Cornell SC Johnson College of Business

INSEAD The Business School for the World®

WIPO WORLD INTELLECTUAL PROPERTY ORGANIZATION

EMBARGO: NOT FOR ANY KIND OF PUBLICATION BEFORE 10 a.m. IN NEW YORK (GMT-4); 4 p.m. IN GENEVA (GMT +2) ON JULY 10, 2018

GLOBAL INNOVATION INDEX 2018

Energizing the World with Innovation

CII Confederation of Indian Industry

strategy& Part of the PwC network

SEBRAE

CNI National Confederation of Industry Brazil

CNI, THE STRENGTH OF THE BRAZILIAN INDUSTRY

Cornell SC Johnson College of Business

INSEAD The Business School for the World®

WIPO WORLD INTELLECTUAL PROPERTY ORGANIZATION

GLOBAL INNOVATION INDEX 2018

Energizing the World with Innovation

11TH EDITION

Soumitra Dutta, Bruno Lanvin, and **Sacha Wunsch-Vincent**
Editors

CII Confederation of Indian Industry

strategy&
Part of the PwC network

SEBRAE

CNI
National Confederation of Industry Brazil
CNI, THE STRENGTH OF THE BRAZILIAN INDUSTRY

The Global Innovation Index 2018: Energizing the World with Innovation is the result of a collaboration between Cornell University, INSEAD, and the World Intellectual Property Organization (WIPO) as co-publishers, and their Knowledge Partners.

The report and any opinions expressed in this publication are the sole responsibility of the authors. They do not purport to reflect the opinions or views of WIPO Member States or the WIPO Secretariat.

The terms 'country', 'economy', and 'nation' as used in this report do not in all cases refer to a territorial entity that is a state as understood by international law and practice. The terms cover well-defined, geographically self-contained economic areas that may not be states but for which statistical data are maintained on a separate and independent basis. Any boundaries and names shown and the designations used on any visual maps do not imply official endorsement or acceptance by any of the co-publishers. Chapters 2–13 may deviate from UN terminology for countries and regions.

Suggested citation: Cornell University, INSEAD, and WIPO (2018): *The Global Innovation Index 2018: Energizing the World with Innovation.* Ithaca, Fontainebleau, and Geneva.

ISSN 2263-3993
ISBN 979-10-95870-09-8

Printed and bound in Geneva, Switzerland, by the World Intellectual Property Organization (WIPO), and in New Delhi, India, by the Confederation of Indian Industry (CII).

Cover design by Neil Weinberg Design Group LLC; cover image courtesy of oliviercefai.com based on a photo from @sachleno.

CONTENTS

RANKINGS

KEY FINDINGS

CHAPTERS

(Continued on next page)

SPECIAL SECTION: CLUSTERS

APPENDICES

PREFACE

RELEASING THE GLOBAL INNOVATION INDEX 2018: ENERGIZING THE WORLD WITH INNOVATION

©WIPO 2018. Photo by Emmanuel Berrod.

We are pleased to present the 2018 edition of the Global Innovation Index (GII) on the theme 'Energizing the World with Innovation'.

Energy demand is reaching unprecedented levels as a result of a growing world population, rapid urbanization, and industrialization. Higher levels of technological and non-technological innovation are required to meet this demand, both on the production side of the energy equation (alternative sources, smart grids, and new advanced energy-storage technologies) and on the consumption side (smart cities, homes, and buildings; energy-efficient industries; and transport and future mobility). Innovation plays key roles in addressing both sides of that equation. However, technological innovation alone is rarely the solution. Changes in societal norms and cultures along with innovations in organizational processes are also essential.

The GII 2018 analyses the energy innovation landscape of the next decade and identifies possible breakthroughs in fields such as energy production, storage, distribution, and consumption. It also looks at how breakthrough innovation occurs at the grassroots level and describes how small-scale renewable systems are on the rise.

Last year marked the 10th edition of the report. Work in the context of the GII continues on two important fronts: assisting countries to better assess their innovation performance by collecting innovation metrics according to international standards, and helping empower countries to improve their innovation policies while leveraging their strengths and overcoming challenges. On both fronts, national GII events have made substantial progress. First, technical sessions across national capitals with data and innovation experts have elaborated on how to close gaps in countries' innovation metrics. Second, high-level meetings with a cross-section of innovation stakeholders have expanded on countries' innovation performance and possible sectoral priorities, often leading to concrete innovation policy agendas.

Despite the decade-long positive influence of the GII, significant progress is needed on key questions related to innovation metrics. How should one better measure innovation and intangible assets in the services sector? How can linkages between innovation actors be better quantified and assessed? How can the more open nature of innovation processes be captured? Discussions in capitals and in academic settings, and related experimentation with new indicators in the context of the GII, offer a welcome opportunity to shape future innovation metrics.

The GII 2018 again includes a ranking of the world's largest clusters of science and technology activity. As last year, this ranking relies on international patent filings to identify such clusters. This year, the report introduces scientific publishing activity as a second measure of cluster performance. While still a long way from fully capturing innovation performance at the city and regional level, we hope that this big data approach to measurement offers an increasingly useful complement to the country-based ranking that forms the core of the GII.

We thank our Knowledge Partners, the Confederation of Indian Industry (CII), PwC's Strategy&, the National Confederation of Industry Brazil (CNI) and the Brazilian Service of Support to Micro and Small Enterprises (Sebrae), for their support of this year's report.

We also thank our prominent Advisory Board, which has been enriched by three new members this year: Audrey Azoulay, Director-General, United Nations Educational, Scientific and Cultural Organization (UNESCO); Philippe Kuhutama Mawoko, Executive Secretary, the African Observatory for STI, African Union Commission; and Sergio Mujica, Secretary-General, International Organization for Standardization (ISO).

Soumitra Dutta
Former Dean and Professor of Operations, Technology and Information Management, Cornell SC Johnson College of Business, Cornell University

Francis Gurry
Director General, World Intellectual Property Organization (WIPO)

Bruno Lanvin
Executive Director for Global Indices, INSEAD

FOREWORD

INNOVATION: A KEY TO ENERGY SECURITY

In today's connected world, increasingly driven by technology, communication, and super human intelligence, energy is the fundamental element that makes everything possible. Without energy there can be no development. The growth of any nation therefore demands adequate available energy.

In India, that adequacy has eluded us thus far by a wide margin. Our per capita energy consumption needs to grow four times to enable us to be level with the world's most advanced countries in terms of the Human Development Index. Even at India's current low consumption levels, more than 42% of our energy requirements are met by imports. To boost consumption, contain imports, and increase domestic production, it is imperative to look at innovative ways to generate, store, and transmit electricity.

Recent government efforts have the nation inching closer to 100% electrification. The latest innovations in solar energy and light emitting diodes (LED) have significantly lowered consumption in terms of wattage and at the same time improved luminescence. But a lot remains to be done. The theme of this year's Global Innovation Index (GII), 'Energizing the World with Innovation', is very apt for India as well as the rest of the developing world. It captures the pulse of the key enablers of growth and economic development. Working towards ensuring energy security is a key agenda for the Confederation of Indian Industry (CII), in close partnership with the government and industry.

India's position on the GII has been keenly monitored by the Indian government for the past few years. Joint efforts of CII and the publishers of the GII, including WIPO, have led to significant collaboration on improving Indian innovation metrics and identifying innovation challenges and opportunities. Since 2016, the report has also launched separately in India at an event jointly organized by the Department of Industrial Policy and Promotion, the National Institution for Transforming India, and CII. In 2016 India's Minister of State for Commerce and Industry instituted a high-level Task Force on Innovation to suggest ways to improve the innovation ecosystem. As a follow-up, the first international consultative exercise was organized in January 2017 in New Delhi to address existing data gaps in the GII. Moreover, the first India Innovation Index—focused on ranking Indian states—was conceptualized in 2017 and reviewed along with India's performance in the GII at the Indian Innovation Summit in Delhi in October 2017. As a result, a State Innovation Index is now in the works. It is hoped that it will spur states to improve their innovation ecosystems.

Based on this year's theme, Chapter 8 presents India's energy story. This has largely been a quest for sustainable development with strained resources. Rising energy demand coupled with a less-than-adequate increase in domestic production has led to an alarming increase in the import component of India's energy basket. Tackling that challenge requires innovative thinking and a smart push towards technologies and services that provide maximum impact.

CII's partnership with GII continues to grow strong and I see it consolidating in years to come. I congratulate the GII team for their sustained efforts and untiring rigor in producing this latest edition of the index, which is based on a very apt theme and will lead to significant improvement in world energy scenario.

Chandrajit Banerjee
Director General
Confederation of Indian Industry

FOREWORD

TOWARDS THE GOAL OF ENERGY FOR ALL

Innovation lies at the core of any solution to the challenges facing our world today. Whether it's the creation of new technologies that can help us stretch the limits of what is possible, or the development of new business models that make our world more efficient and interconnected, it is our business imperative as leaders to continuously reinvent, rethink, and reimagine.

The Global Innovation Index (GII), by creating metrics through which innovation can be measured across the globe, helps identify ways that innovation can better serve society and the challenges we face. At Strategy&, PwC's strategy consulting business, we are proud to be included as contributors to this volume for the second consecutive year.

Our purpose at PwC is to build trust in society and solve important problems—problems that erode trust, prevent expanding economic opportunity for all, and threaten the fabric of our society and culture. These are problems that require people to come together, bringing their best ideas and creativity to the table. The GII brings strategy and execution together to advance innovation in the service of making our world better.

The theme of the 2018 GII, 'Energizing the World with Innovation', offers an opportunity for some of the world's greatest minds to apply themselves to the critical issue of access to energy—from production to storage, from transport and distribution to consumption patterns. Supply has not kept pace with demand, and there is a growing need for sustainable solutions. In PwC's chapter, 'Energy for All: How Innovation Is Democratizing Electricity', Norbert Schwieters, Barry Jaruzelski, and Robert Chwalik report that an estimated 1.2 billion people worldwide are living without electricity, and 2.8 billion without clean and safe cooking facilities. This certainly represents a crisis of global concern.

But as we go on to discuss, innovations in energy sources such as renewables, as well as distribution and storage solutions such as micro-grids, batteries, and smart technologies, can be game-changers. In regions where centralized power grids are inefficient and unreliable, distributed energy systems can be built from the ground up, thanks to off-grid renewable energy technology. Even in developed countries, where the shift is happening more slowly because centralized power generation via long-distance power grids is well established, customers are installing solar panels, producing their own energy, and sending unused energy back to the grid.

It's clear that, across the globe, traditional energy frameworks are witnessing a fundamental change. Private-sector investment will play a significant role as these new systems take shape, both from traditional utilities—many of which are seeing this new way forward as an opportunity rather than as disruption—and from the start-ups and entrepreneurs developing and applying new technologies in the renewables space. Around the globe companies are implementing projects, often in close coordination with public-sector partners, that demonstrate the transformative potential of these innovations.

The realization of 'energy for all' is a powerful and worthy goal, and one that we owe ourselves and future generations to continue to pursue. As a GII Knowledge Partner, we hope to contribute to bridging the gap between innovation goals and tangible societal benefits.

Tim Ryan
U.S. Chairman and Senior Partner
PwC

FOREWORD

INNOVATION: CENTRAL TO BRAZIL'S ENERGY SECTOR

Sustainable development is a priority for the Brazilian National Confederation of Industry (CNI), the Social Service of Industry (SESI), the National Service of Industrial Training (SENAI), the Brazilian the Brazilian Micro and Small Business Support Service (Sebrae), and the Entrepreneurial Mobilization for Innovation (MEI). Sustainable development demands innovation and, since 2008, Brazilian business leaders, including those from the energy sector, have been promoting innovation as the centre of business strategy, aiming to increase the strength and efficiency of innovation policies in Brazil.

The energy sector is essential for sustainable development. The rational use of natural resources has room to improve significantly, and the use of renewable sources is increasing fast. Those processes can contribute to making good on the commitments undertaken by Brazil in the Paris Agreement. The goal is to promote the reduction of greenhouse gas emissions as part of a transition towards a low-carbon economy.

The theme of this year´s Global Innovation Index, 'Energizing the World with Innovation', deals with a crucial issue for the world´s industry: the role of innovation to promote a cost-effective energy transition. The great challenge in energy transition is to reduce the trade-off between energy cost and environmental impacts. This challenge is being tackled with the help of new vectors of technological innovation, which are helping transform the technological basis and the structures of energy supply and demand.

Each country's endowment of energy resources and demand allow multiple strategies and policies to meet this challenge. In this context, Brazil has lessons to offer and new challenges to overcome. The size of its national energy sector, as well as its diversity and unique circumstances, impose important technological challenges that have been met with an important innovation effort. The result is an energy matrix with a large share of renewable energy in transport and electricity. In 2016 renewable energy supplied 43.5% of the country's total energy consumption needs. Sugarcane products used for transport (ethanol) and for heat and electricity generation (bagasse) provided 17% of total energy supply. Hydropower dominates Brazil's electricity generation, at 13% of total supply.

Brazil has been able to build a complex ecosystem of innovation in the energy sector. To adapt to new challenges of energy transition, however, this ecosystem must adopt an energy and innovation policy compatible with the energy, business, and institutional challenges, and with the need to include small businesses in the process.

The adoption of technological solutions supported by digital tools is an important driver for business strategies and government policies in the medium and long term. Three trends stand out: fostering the intelligent management of complex systems, increasing the sophistication of the data analytics tools, and instituting new paradigms of automation.

Based on this new technological foundation, important transformations in the energy industry can be induced that facilitate the diffusion of renewable sources (wind, solar, and biomass) and the necessary intelligent management of the electric system to make distributed generation possible.

The theme of Global Innovation Index this year represents an excellent opportunity to assess the Brazilian experience of innovation in the energy sector and draw lessons for an innovation strategy compatible with the major challenges imposed by energy transition on the national and worldwide economy.

Robson Braga de Andrade
President, CNI; Director, SESI;
and President, SENAI's National Council

Heloisa Menezes
Technical Director in the
Exercise of the Presidency of SEBRAE

CONTRIBUTORS TO THE REPORT

The Global Innovation Index 2018: Energizing the World with Innovation was developed under the general direction of **Francis GURRY** (Director General, World Intellectual Property Organization), and the editors of the report, **Soumitra DUTTA, Bruno LANVIN,** and **Sacha WUNSCH-VINCENT.**

The report was prepared and coordinated by a core team comprising:

CORE TEAM

Soumitra DUTTA, Former Dean and Professor, Cornell SC Johnson College of Business, Cornell University

Rafael ESCALONA REYNOSO, GII Lead Researcher, Cornell SC Johnson College of Business, Cornell University

Francesca GUADAGNO, Consultant, Cornell University and WIPO

Bruno LANVIN, Executive Director for Global Indices, INSEAD

Lorena RIVERA LEON, Program Officer, Composite Indicator Research Section, Economics and Statistics Division, WIPO

Kritika SAXENA, GII Project Manager, Cornell SC Johnson College of Business, Cornell University

Sacha WUNSCH-VINCENT, Head, Composite Indicator Research Section, Economics and Statistics Division, WIPO

The following people and institutions have supported the production of the GII:

CO-PUBLISHERS

Cornell University

Sarah MAGNUS-SHARPE, Director, PR & Media Relations, Cornell SC Johnson College of Business, Cornell University

Rohit VERMA, Dean of External Relations and Executive Director, Cornell Institute for Healthy Futures, Cornell SC Johnson College of Business, Cornell University

Mark YEAGER, Event Coordinator, Office of External Relations, Cornell SC Johnson College of Business, Cornell University

INSEAD

Sophie BADRE, Director, Media Relations Europe & Asia

Virginie BONGEOT-MINET, Senior Coordinator

Chris HOWELLS, Managing Editor, INSEAD Knowledge

Aileen HUANG, Associate Director, Media Relations, Asia

Robert LOXHAM, Community Manager

Rachael NOYES, Europe Editor, INSEAD Knowledge

Axel TAGLIAVINI, Chief Communications Officer

World Intellectual Property Organization (WIPO)

Carsten FINK, Chief Economist, Economics and Statistics Division

Communications Division

Conference and General Services Division

Economics and Statistics Division

External Relations Division

Global Challenges Division

Global Infrastructure Sector

WIPO Printing Plant

WIPO Regional Bureaus, External Offices, and WIPO Coordination Office in New York

KNOWLEDGE PARTNERS

Confederation of Indian Industry

Anjan DAS, Executive Director

Jibak DASGUPTA, Director

Gaurav GUPTA, Executive Officer

Shalini S. SHARMA, Senior Consultant

CNI/Sebrae

Gianna SAGAZIO, Innovation Director, Innovation Directory, National Confederation of Industry (CNI)

Suely LIMA, Innovation Manager, Innovation Directory, National Confederation of Industry (CNI)

Julieta Costa CUNHA, Project Manager, Innovation Directory, National Confederation of Industry (CNI)

Idenilza MIRANDA, Industrial Development Specialist, Innovation Directory, National Confederation of Industry (CNI)

Edmar Luiz Fagundes De ALMEIDA, Consultant, Innovation Directory, National Confederation of Industry (CNI)

Helder Queiroz PINTO Jr., Consultant, Innovation Directory, National Confederation of Industry (CNI)

Luciano LOSEKANN, Consultant, Innovation Directory, National Confederation of Industry (CNI)

Guilherme Afif DOMINGOS, Chief Executive Officer, Brazilian Micro and Small Business Support Service (Sebrae)

Heloisa MENEZES, Technical Director, Brazilian Micro and Small Business Support Service (Sebrae)

Vinicius LAGES, Chief Management and Financial Officer, Brazilian Micro and Small Business Support Service (Sebrae)

Kelly SANCHES, Industry Unit Manager, Technical Directory, Brazilian Micro and Small Business Support Service (Sebrae)

Analuiza LOPES, Industry Unit Substitute, Manager, Technical Directory, Brazilian Micro and Small Business Support Service (Sebrae)

Eliane Lobato Peixoto BORGES, Energy National Program Coordinator, Brazilian Micro and Small Business Support Service (Sebrae)

Cristina Vieira ARAÚJO, Project Manager, Brazilian Micro and Small Business Support Service (Sebrae)

Charles de Souza e SILVA, Project Manager, Brazilian Micro and Small Business Support Service (Sebrae)

PwC's Strategy&

Alessandro BORGOGNA, Partner, PwC Middle East

Barry JARUZELSKI, Principal, PwC US

Norbert SCHWIETERS, Partner, PwC Germany

Robert CHWALIK, Principal, PwC US

Olesya HATOP, Director, PwC Germany

Jenny KOEHLER, Partner, PwC US

Tim RYAN, US Chairman and Senior Partner, PwC US

Ivan De SOUZA, Partner, PwC Brazil

Steven VELDHOEN, Partner, PwC Japan

Laura W. GELLER, Senior Manager, PwC US

Nimish VORA,Associate Director, PwC India

Georg BAECKER, Associate Director, PwC South Africa

Annie PHAN, Manager, PwC US

DIRECT COLLABORATORS

Antanina GARANASVILI, PhD Candidate in Economics, University of Padova and Queen Mary, University of London

Juan MATEOS-GARCIA, Head of Innovation Mapping, Nesta; and **Chantale TIPPETT,** Principal Researcher (Innovation Systems), Innovation Mapping, Nesta

Yann MÉNIÈRE, Chief Economist; **Ilja RUDYK,** Senior Economist; **Geert BOEDT,** Business Analyst; and **Alessia VOLPE,** Co-ordinator Public Policy Issues and International Organisations, all from the European Patent Office (EPO)

Michaela SAISANA, Head of the Competence Centre on Composite Indicators & Scoreboards (COIN), European Commission, Joint Research Centre (JRC); and **Marcos DOMINGUEZ-TORREIRO** and **Daniel VÉRTESY,** Competence Centre on Composite Indicators & Scoreboards (COIN), European Commission, Joint Research Centre (JRC).

Pía SUÁREZ SÁNCHEZ, Formerly with the Ministry of Energy, Chile

Hope STEELE, Principal and Editor, Steele Editorial Services

Neil WEINBERG, Principal, Neil Weinberg Design Group LLC

We are also grateful to the following persons/institutions for their collaboration with specific data requests:

DATA COLLABORATORS

Erkko AUTIO, Professor at the Imperial College London; **Zoltan ACS,** Professor at the London School of Economics; **Mark HART,** Professor at the University of Aston; and **Laszlo SZERB,** Professor at the University of Pecs, all from The Global Entrepreneurship Index

David BESCOND, Statistician; **Steven KAPSOS,** Head of Unit; **Yves PERARDEL,** Senior Econometrician; and **Marie-Claire SODERGREN,** Senior Economist, all at the Data Production and Analysis Unit (DPAU), Department of Statistics, International Labour Office (ILO)

Daniel Wolf BLOEMERS, European Innovation Scoreboards Coordinator, Policy Officer for Innovation Policy, European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, and **Oliver HALL-ALLEN,** Minister Counsellor, European Union Delegation to the United Nations and other international organizations in Geneva

Mohsen BONAKDARPOUR, Managing Director, IHS Markit; **Karen CAMPBELL,** Senior Consultant, IHS Markit

Barbara D'ANDREA, Senior Statistician, International Trade Statistics Section, and **Adelina MENDOZA,** Senior Statistical Officer, Market Access Intelligence Section, both from the Economic Research and Statistics Division, World Trade Organization (WTO)

Klass DE VRIES, Associate Economist at the Conference Board

Thierry GEIGER, Head of Analytics and Quantitative Research; **Roberto CROTTI,** Economist, Global Competitiveness and Risks; **Silja BALLER,** Practice Lead, Digital Economy and Innovation; and **Ciara PORAWSKI,** Head of Engagement, Future of Economic Progress, all from the Word Economic Forum

Dong GUO, Statistician; **Rita LANG,** Senior Statistical Assistant; **Jürgen MUTH,** Senior Statistical Assistant; and **Valentin TODOROV,** Senior Information Management Officer, all from the Statistics Division, Department of Policy, Research and Statistics, United Nations Industrial Development Organization (UNIDO)

Héctor HERNANDEZ, Project Leader – Scoreboard, Territorial Development Unit; and **Alexander TÜBKE,** Team Leader – Industrial Research & Innovation and Technology Analysis, Territorial Development

Unit, both from the European Commission, Joint Research Centre, Directorate for Growth and Innovation

Richard LAMBERT, Manager, Global Government IP Sales, and **Simon THOMSON,** Senior Scientific Analyst, both from Clarivate Analytics

Rati SKHIRTLADZE, Head; Esperanza **MAGPANTAY**, Senior Statistician; **Martin SCHAAPER,** Senior ICT Analyst and **Nathalie DELMAS,** Assistant, all at the ICT Data and Statistics Division (IDS), Telecommunication Development Bureau (BDT), International Telecommunication Union (ITU)

Randy NELSON, Head of Mobile Insights, Sensor Tower

Florian RENNBERGER, Market Intelligence Consultant; and **Roxanne KINGSMAN,** PR Manager EMEA, both at App Annie.

Metri SANTHOSH, Global Head of IP Products and Solutions, and **Petra STEINER,** Regional Head of Government and Public Sector, both from Bureau van Dijk Electronic Publishing GmbH

Ben SOWTER, Head of Division; **David REGGIO FRSA,** Global Head of Consulting; and **Selina GRIFFIN,** Rankings Manager, all from QS Intelligence Unit, QS Quacquarelli Symonds Ltd

Saïd Ould A. VOFFAL, Programme Specialist, **Elise LEGAULT,** Programme Specialist, **Chiao-Ling CHIEN,** Assistant Programme Specialist, and **Imededdine JERBI,** Statistician, Education Indicators and Data Analysis Section; **Lydia DELOUMEAUX,** Assistant Programme Specialist, and **Lisa BARBOSA,** Statistical Assistant, Culture Unit; **Talal EL HOURANI,** Statistician, Education Survey Section; **José PESSOA,** Head of Section, Science, Culture and Communication Statistics; and **Rohan PATHIRAGE,** Assistant Programme Specialists, Science, Technology and Innovation Unit, all from the United Nations Educational, Scientific and Cultural Organization (UNESCO) Institute for Statistics (UIS)

Leila ZIA, Senior Research Scientist, Research Team, and **Dan ANDREESCU,** Senior Software Engineer, Analytics Team, both at Wikimedia Foundation

Matthew ZOOK, Professor at the University of Kentucky and President, ZookNIC Inc.

Energy Data Centre, headed by Duncan Millard, International Energy Agency (IEA)

United Nations Commodity Trade Statistics Database, Department of Economic and Social Affairs/Statistics Division, http://comtrade.un.org/db/

PwC Global entertainment and media outlook 2017–2021, www.pwc.com/outlook

UN Public Administration Network (UPAN)
http://unpan3.un.org/egovkb/en-us/Data-Center

ADVISORY BOARD TO THE GLOBAL INNOVATION INDEX

In 2011, an Advisory Board was set up to provide advice on the research underlying the Global Innovation Index (GII), generate synergies at its stages of development, and assist with the dissemination of its messages and results. The Advisory Board is a select group of leading international practitioners and experts with unique knowledge and skills in the realm of innovation. Its members, while coming from diverse geographical and institutional backgrounds (international organizations, the public sector, non-governmental organizations, business, and academia), participate in their personal capacity. We are grateful for the time and support provided by the Advisory Board members.

In 2018, we welcome three new members to the Advisory Board: Audrey Azoulay, Director-General of the United Nations Educational, Scientific and Cultural Organization (UNESCO); Philippe Kuhutama Mawoko, Executive Secretary, the African Observatory for STI, African Union Commission; and Sergio Mujica, Secretary-General, International Organization for Standardization (ISO).

We would also like to express our gratitude to Irina Bokova, former Director-General of the United Nations Educational, Scientific and Cultural Organization (UNESCO), for her thoughtful contributions to previous editions of the GII as a member of the Advisory Board.

ADVISORY BOARD MEMBERS

Robert D. ATKINSON
President, The Information Technology and Innovation Foundation (ITIF), United States of America

Audrey AZOULAY
Director-General of the United Nations Educational, Scientific and Cultural Organization (UNESCO)

Dongmin CHEN
Professor/Dean, School of Innovation and Entrepreneurship, and Director, Office of Business Development for Science and Technology, Peking University, China

Fabiola GIANOTTI
Director-General of the European Organization for Nuclear Research (CERN)

Leonid GOKHBERG
First Vice-Rector, Higher School of Economics (HSE), and Director, HSE Institute for Statistical Studies and Economics of Knowledge, Russian Federation

Yuko HARAYAMA
Executive Member, Council for Science, Technology and Innovation, Cabinet Office, Government of Japan, Japan

Hugo HOLLANDERS
Senior Researcher, UNU-MERIT (Maastricht University), Netherlands

Beethika KHAN
Program Director, National Science Foundation (NSF), United States of America

Chuan Poh LIM
Chairman, Agency for Science, Technology and Research (A*STAR), Singapore

Raghunath Anant MASHELKAR
Bhatnagar Fellow, National Chemical Laboratory, Council of Scientific and Industrial Research (CSIR); Chairperson, National Innovation Foundation; and President, Global Research Alliance, India

Philippe Kuhutama MAWOKO
Executive Secretary, the African Observatory for STI, African Union Commission

Sergio MUJICA
Secretary-General, International Organization for Standardization (ISO)

Mary O’KANE
Professor, NSW Chief Scientist and Engineer, Australia

Sibusiso SIBISI
Former President and Chief Executive Officer, Council for Scientific and Industrial Research (CSIR), South Africa

Pedro WONGTSCHOWSKI
Member of the Board of Directors of Ultrapar Participações S.A. and of Embraer S.A.; Chairman of the Board of Directors of the Brazilian Enterprise for Research and Innovation (EMBRAPII) and of the Brazilian Association of Innovative Companies (ANPEI), Brazil

Houlin ZHAO
Secretary-General, International Telecommunication Union (ITU)

RANKINGS

Global Innovation Index 2018 rankings

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Efficiency Ratio	Rank	Median: 0.61
Switzerland	68.40	1	HI	1	EUR	1	0.96	1	
Netherlands	63.32	2	HI	2	EUR	2	0.91	4	
Sweden	63.08	3	HI	3	EUR	3	0.82	10	
United Kingdom	60.13	4	HI	4	EUR	4	0.77	21	
Singapore	59.83	5	HI	5	SEAO	1	0.61	63	
United States of America	59.81	6	HI	6	NAC	1	0.76	22	
Finland	59.63	7	HI	7	EUR	5	0.76	24	
Denmark	58.39	8	HI	8	EUR	6	0.73	29	
Germany	58.03	9	HI	9	EUR	7	0.83	9	
Ireland	57.19	10	HI	10	EUR	8	0.81	13	
Israel	56.79	11	HI	11	NAWA	1	0.81	14	
Korea, Republic of	56.63	12	HI	12	SEAO	2	0.79	20	
Japan	54.95	13	HI	13	SEAO	3	0.68	44	
Hong Kong (China)	54.62	14	HI	14	SEAO	4	0.64	54	
Luxembourg	54.53	15	HI	15	EUR	9	0.94	2	
France	54.36	16	HI	16	EUR	10	0.72	32	
China	53.06	17	UM	1	SEAO	5	0.92	3	
Canada	52.98	18	HI	17	NAC	2	0.61	61	
Norway	52.63	19	HI	18	EUR	11	0.64	52	
Australia	51.98	20	HI	19	SEAO	6	0.58	76	
Austria	51.32	21	HI	20	EUR	12	0.64	53	
New Zealand	51.29	22	HI	21	SEAO	7	0.62	59	
Iceland	51.24	23	HI	22	EUR	13	0.76	23	
Estonia	50.51	24	HI	23	EUR	14	0.82	12	
Belgium	50.50	25	HI	24	EUR	15	0.70	38	
Malta	50.29	26	HI	25	EUR	16	0.84	7	
Czech Republic	48.75	27	HI	26	EUR	17	0.80	17	
Spain	48.68	28	HI	27	EUR	18	0.70	36	
Cyprus	47.83	29	HI	28	NAWA	2	0.79	18	
Slovenia	46.87	30	HI	29	EUR	19	0.74	27	
Italy	46.32	31	HI	30	EUR	20	0.70	35	
Portugal	45.71	32	HI	31	EUR	21	0.71	34	
Hungary	44.94	33	HI	32	EUR	22	0.84	8	
Latvia	43.18	34	HI	33	EUR	23	0.69	39	
Malaysia	43.16	35	UM	2	SEAO	8	0.66	48	
Slovakia	42.88	36	HI	34	EUR	24	0.74	28	
Bulgaria	42.65	37	UM	3	EUR	25	0.79	19	
United Arab Emirates	42.58	38	HI	35	NAWA	3	0.50	95	
Poland	41.67	39	HI	36	EUR	26	0.69	42	
Lithuania	41.19	40	HI	37	EUR	27	0.63	58	
Croatia	40.73	41	UM	4	EUR	28	0.70	37	
Greece	38.93	42	HI	38	EUR	29	0.59	74	
Ukraine	38.52	43	LM	1	EUR	30	0.90	5	
Thailand	38.00	44	UM	5	SEAO	9	0.71	33	
Viet Nam	37.94	45	LM	2	SEAO	10	0.80	16	
Russian Federation	37.90	46	UM	6	EUR	31	0.58	77	
Chile	37.79	47	HI	39	LCN	1	0.60	68	
Moldova, Republic of	37.63	48	LM	3	EUR	32	0.89	6	
Romania	37.59	49	UM	7	EUR	33	0.66	47	
Turkey	37.42	50	UM	8	NAWA	4	0.75	25	
Qatar	36.56	51	HI	40	NAWA	5	0.57	81	
Montenegro	36.49	52	UM	9	EUR	34	0.63	56	
Mongolia	35.90	53	LM	4	SEAO	11	0.72	30	
Costa Rica	35.72	54	UM	10	LCN	2	0.68	43	
Serbia	35.46	55	UM	11	EUR	35	0.63	57	
Mexico	35.34	56	UM	12	LCN	3	0.59	72	
India	35.18	57	LM	5	CSA	1	0.65	49	
South Africa	35.13	58	UM	13	SSF	1	0.55	83	
Georgia	35.05	59	LM	6	NAWA	6	0.58	79	
Kuwait	34.43	60	HI	41	NAWA	7	0.74	26	
Saudi Arabia	34.27	61	HI	42	NAWA	8	0.47	104	
Uruguay	34.20	62	HI	43	LCN	4	0.64	51	
Colombia	33.78	63	UM	14	LCN	5	0.50	94	

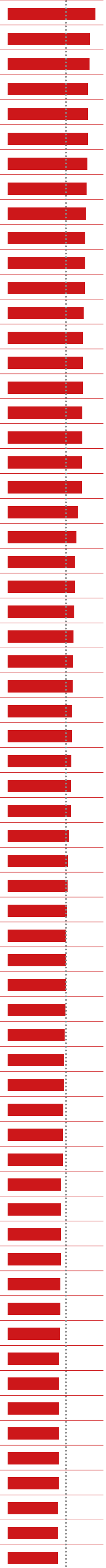
(Continued on next page)

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Efficiency Ratio	Rank	Median: 0.61
Brazil	33.44	64	UM	15	LCN	6	0.54	85	
Iran, Islamic Republic of	33.44	65	UM	16	CSA	2	0.82	11	
Tunisia	32.86	66	LM	7	NAWA	9	0.63	55	
Brunei Darussalam	32.84	67	HI	44	SEAO	12	0.31	124	
Armenia	32.81	68	LM	8	NAWA	10	0.80	15	
Oman	32.80	69	HI	45	NAWA	11	0.51	92	
Panama	32.37	70	UM	17	LCN	7	0.61	64	
Peru	31.80	71	UM	18	LCN	8	0.47	100	
Bahrain	31.73	72	HI	46	NAWA	12	0.55	84	
Philippines	31.56	73	LM	9	SEAO	13	0.61	62	
Kazakhstan	31.42	74	UM	19	CSA	3	0.44	111	
Mauritius	31.31	75	UM	20	SSF	2	0.47	105	
Morocco	31.09	76	LM	10	NAWA	13	0.61	65	
Bosnia and Herzegovina	31.09	77	UM	21	EUR	36	0.50	97	
Kenya	31.07	78	LM	11	SSF	3	0.69	41	
Jordan	30.77	79	LM	12	NAWA	14	0.65	50	
Argentina	30.65	80	UM	22	LCN	9	0.51	91	
Jamaica	30.39	81	UM	23	LCN	10	0.57	80	
Azerbaijan	30.20	82	UM	24	NAWA	15	0.49	99	
Albania	29.98	83	UM	25	EUR	37	0.44	110	
The former Yugoslav Republic of Macedonia	29.91	84	UM	26	EUR	38	0.47	103	
Indonesia	29.80	85	LM	13	SEAO	14	0.61	66	
Belarus	29.35	86	UM	27	EUR	39	0.37	119	
Dominican Republic	29.33	87	UM	28	LCN	11	0.60	71	
Sri Lanka	28.66	88	LM	14	CSA	4	0.58	78	
Paraguay	28.66	89	UM	29	LCN	12	0.54	86	
Lebanon	28.22	90	UM	30	NAWA	16	0.50	98	
Botswana	28.16	91	UM	31	SSF	4	0.39	118	
Tanzania, United Republic of	28.07	92	LI	1	SSF	5	0.72	31	
Namibia	28.03	93	UM	32	SSF	6	0.41	116	
Kyrgyzstan	27.56	94	LM	15	CSA	5	0.45	106	
Egypt	27.16	95	LM	16	NAWA	17	0.66	45	
Trinidad and Tobago	26.95	96	HI	47	LCN	13	0.43	114	
Ecuador	26.80	97	UM	33	LCN	14	0.51	93	
Cambodia	26.69	98	LM	17	SEAO	15	0.61	60	
Rwanda	26.54	99	LI	2	SSF	7	0.31	125	
Senegal	26.53	100	LI	3	SSF	8	0.60	70	
Tajikistan	26.51	101	LM	18	CSA	6	0.60	67	
Guatemala	25.51	102	LM	19	LCN	15	0.56	82	
Uganda	25.32	103	LI	4	SSF	9	0.45	108	
El Salvador	25.11	104	LM	20	LCN	16	0.43	112	
Honduras	24.95	105	LM	21	LCN	17	0.47	101	
Madagascar	24.75	106	LI	5	SSF	10	0.69	40	
Ghana	24.52	107	LM	22	SSF	11	0.51	90	
Nepal	24.17	108	LI	6	CSA	7	0.45	107	
Pakistan	24.12	109	LM	23	CSA	8	0.66	46	
Algeria	23.87	110	UM	34	NAWA	18	0.42	115	
Cameroon	23.85	111	LM	24	SSF	12	0.58	75	
Mali	23.32	112	LI	7	SSF	13	0.59	73	
Zimbabwe	23.15	113	LI	8	SSF	14	0.60	69	
Malawi	23.09	114	LI	9	SSF	15	0.52	89	
Mozambique	23.06	115	LI	10	SSF	16	0.52	88	
Bangladesh	23.06	116	LM	25	CSA	9	0.53	87	
Bolivia, Plurinational State of	22.88	117	LM	26	LCN	18	0.43	113	
Nigeria	22.37	118	LM	27	SSF	17	0.50	96	
Guinea	20.71	119	LI	11	SSF	18	0.47	102	
Zambia	20.66	120	LM	28	SSF	19	0.45	109	
Benin	20.61	121	LI	12	SSF	20	0.35	123	
Niger	20.57	122	LI	13	SSF	21	0.36	120	
Côte d'Ivoire	19.96	123	LM	29	SSF	22	0.40	117	
Burkina Faso	18.95	124	LI	14	SSF	23	0.28	126	
Togo	18.91	125	LI	15	SSF	24	0.36	121	
Yemen	15.04	126	LM	30	NAWA	19	0.36	122	

Notes: World Bank Income Group Classification (July 2017): LI = low income; LM = lower-middle income; UM = upper-middle income; and HI = high income. Regions are based on the United Nations Classification: EUR = Europe; NAC = Northern America; LCN = Latin America and the Caribbean; CSA = Central and Southern Asia; SEAO = South East Asia, East Asia, and Oceania; NAWA = Northern Africa and Western Asia; SSF = Sub-Saharan Africa. See Chapter 1, Annexes 1–3, for methodological considerations that impact the rankings.

Innovation Input Sub-Index rankings

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Median: 42.51
Singapore	74.23	1	HI	1	SEAO	1	
Switzerland	69.67	2	HI	2	EUR	1	
Sweden	69.21	3	HI	3	EUR	2	
United Kingdom	67.89	4	HI	4	EUR	3	
Finland	67.88	5	HI	5	EUR	4	
United States of America	67.81	6	HI	6	NAC	1	
Denmark	67.43	7	HI	7	EUR	5	
Hong Kong (China)	66.71	8	HI	8	SEAO	2	
Netherlands	66.45	9	HI	9	EUR	6	
Canada	65.67	10	HI	10	NAC	2	
Australia	65.66	11	HI	11	SEAO	3	
Japan	65.41	12	HI	12	SEAO	4	
Norway	64.18	13	HI	13	EUR	7	
Korea, Republic of	63.42	14	HI	14	SEAO	5	
New Zealand	63.41	15	HI	15	SEAO	6	
France	63.31	16	HI	16	EUR	8	
Germany	63.27	17	HI	17	EUR	9	
Ireland	63.14	18	HI	18	EUR	10	
Israel	62.76	19	HI	19	NAWA	1	
Austria	62.61	20	HI	20	EUR	11	
Belgium	59.53	21	HI	21	EUR	12	
Iceland	58.22	22	HI	22	EUR	13	
Spain	57.15	23	HI	23	EUR	14	
United Arab Emirates	56.80	24	HI	24	NAWA	2	
Luxembourg	56.19	25	HI	25	EUR	15	
Estonia	55.64	26	HI	26	EUR	16	
China	55.13	27	UM	1	SEAO	7	
Malta	54.74	28	HI	27	EUR	17	
Italy	54.37	29	HI	28	EUR	18	
Czech Republic	54.26	30	HI	29	EUR	19	
Slovenia	53.92	31	HI	30	EUR	20	
Portugal	53.60	32	HI	31	EUR	21	
Cyprus	53.36	33	HI	32	NAWA	3	
Malaysia	52.07	34	UM	2	SEAO	8	
Latvia	51.09	35	HI	33	EUR	22	
Lithuania	50.61	36	HI	34	EUR	23	
Brunei Darussalam	50.05	37	HI	35	SEAO	9	
Poland	49.41	38	HI	36	EUR	24	
Slovakia	49.34	39	HI	37	EUR	25	
Greece	49.11	40	HI	38	EUR	26	
Hungary	48.94	41	HI	39	EUR	27	
Croatia	47.94	42	UM	3	EUR	28	
Russian Federation	47.89	43	UM	4	EUR	29	
Bulgaria	47.61	44	UM	5	EUR	30	
Chile	47.17	45	HI	40	LCN	1	
Saudi Arabia	46.73	46	HI	41	NAWA	4	
Qatar	46.63	47	HI	42	NAWA	5	
South Africa	45.36	48	UM	6	SSF	1	
Romania	45.34	49	UM	7	EUR	31	
Colombia	45.04	50	UM	8	LCN	2	
Montenegro	44.75	51	UM	9	EUR	32	
Thailand	44.49	52	UM	10	SEAO	10	
Georgia	44.44	53	LM	1	NAWA	6	
Mexico	44.32	54	UM	11	LCN	3	
Kazakhstan	43.56	55	UM	12	CSA	1	
Serbia	43.50	56	UM	13	EUR	33	
Oman	43.43	57	HI	43	NAWA	7	
Brazil	43.40	58	UM	14	LCN	4	
Peru	43.12	59	UM	15	LCN	5	
Belarus	43.00	60	UM	16	EUR	34	
Mauritius	42.72	61	UM	17	SSF	2	
Turkey	42.64	62	UM	18	NAWA	8	
India	42.53	63	LM	2	CSA	2	



(Continued on next page)

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Median: 42.51
Costa Rica	42.49	64	UM	19	LCN	6	
Viet Nam	42.17	65	LM	3	SEAO	11	
Mongolia	41.73	66	LM	4	SEAO	12	
Uruguay	41.62	67	HI	44	LCN	7	
Bosnia and Herzegovina	41.57	68	UM	20	EUR	35	
Albania	41.56	69	UM	21	EUR	36	
Bahrain	41.05	70	HI	45	NAWA	9	
The former Yugoslav Republic of Macedonia	40.74	71	UM	22	EUR	37	
Argentina	40.55	72	UM	23	LCN	8	
Rwanda	40.49	73	LI	1	SSF	3	
Botswana	40.48	74	UM	24	SSF	4	
Ukraine	40.45	75	LM	5	EUR	38	
Azerbaijan	40.39	76	UM	25	NAWA	10	
Tunisia	40.25	77	LM	6	NAWA	11	
Panama	40.19	78	UM	26	LCN	9	
Moldova, Republic of	39.85	79	LM	7	EUR	39	
Namibia	39.61	80	UM	27	SSF	5	
Kuwait	39.50	81	HI	46	NAWA	12	
Philippines	39.14	82	LM	8	SEAO	13	
Jamaica	38.75	83	UM	28	LCN	10	
Morocco	38.69	84	LM	9	NAWA	13	
Kyrgyzstan	37.99	85	LM	10	CSA	3	
Trinidad and Tobago	37.82	86	HI	47	LCN	11	
Lebanon	37.74	87	UM	29	NAWA	14	
Jordan	37.36	88	LM	11	NAWA	15	
Paraguay	37.23	89	UM	30	LCN	12	
Indonesia	37.12	90	LM	12	SEAO	14	
Kenya	36.85	91	LM	13	SSF	6	
Dominican Republic	36.77	92	UM	31	LCN	13	
Iran, Islamic Republic of	36.71	93	UM	32	CSA	4	
Armenia	36.40	94	LM	14	NAWA	16	
Sri Lanka	36.26	95	LM	15	CSA	5	
Ecuador	35.48	96	UM	33	LCN	14	
El Salvador	35.05	97	LM	16	LCN	15	
Uganda	34.96	98	LI	2	SSF	7	
Honduras	33.90	99	LM	17	LCN	16	
Algeria	33.67	100	UM	34	NAWA	17	
Nepal	33.32	101	LI	3	CSA	6	
Senegal	33.19	102	LI	4	SSF	8	
Cambodia	33.06	103	LM	18	SEAO	15	
Tajikistan	33.04	104	LM	19	CSA	7	
Egypt	32.69	105	LM	20	NAWA	18	
Tanzania, United Republic of	32.68	106	LI	5	SSF	9	
Guatemala	32.67	107	LM	21	LCN	17	
Ghana	32.41	108	LM	22	SSF	10	
Bolivia, Plurinational State of	31.99	109	LM	23	LCN	18	
Benin	30.58	110	LI	6	SSF	11	
Malawi	30.45	111	LI	7	SSF	12	
Mozambique	30.41	112	LI	8	SSF	13	
Niger	30.27	113	LI	9	SSF	14	
Bangladesh	30.11	114	LM	24	CSA	8	
Cameroon	30.09	115	LM	25	SSF	15	
Nigeria	29.85	116	LM	26	SSF	16	
Burkina Faso	29.59	117	LI	10	SSF	17	
Mali	29.41	118	LI	11	SSF	18	
Madagascar	29.30	119	LI	12	SSF	19	
Pakistan	29.05	120	LM	27	CSA	9	
Zimbabwe	28.93	121	LI	13	SSF	20	
Côte d'Ivoire	28.60	122	LM	28	SSF	21	
Zambia	28.55	123	LM	29	SSF	22	
Guinea	28.19	124	LI	14	SSF	23	
Togo	27.86	125	LI	15	SSF	24	
Yemen	22.18	126	LM	30	NAWA	19	

Notes: World Bank Income Group Classification (July 2017): LI = low income; LM = lower-middle income; UM = upper-middle income; and HI = high income. Regions are based on the United Nations Classification: EUR = Europe; NAC = Northern America; LCN = Latin America and the Caribbean; CSA = Central and Southern Asia; SEAO = South East Asia, East Asia, and Oceania; NAWA = Northern Africa and Western Asia; SSF = Sub-Saharan Africa. See Chapter 1, Annexes 1–3, for methodological considerations that impact the rankings.

Innovation Output Sub-Index rankings

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Median: 25.39
Switzerland	67.13	1	HI	1	EUR	1	
Netherlands	60.19	2	HI	2	EUR	2	
Sweden	56.94	3	HI	3	EUR	3	
United Kingdom	52.37	6	HI	6	EUR	6	
Germany	52.79	5	HI	5	EUR	5	
United States of America	51.81	7	HI	7	NAC	1	
Luxembourg	52.87	4	HI	4	EUR	4	
Finland	51.38	8	HI	8	EUR	7	
China	50.98	10	UM	1	SEAO	1	
Israel	50.83	11	HI	10	NAWA	1	
Korea, Republic of	49.84	12	HI	11	SEAO	2	
Ireland	51.25	9	HI	9	EUR	8	
Denmark	49.34	13	HI	12	EUR	9	
Iceland	44.26	19	HI	18	EUR	13	
Estonia	45.39	17	HI	16	EUR	12	
France	45.40	16	HI	15	EUR	11	
Malta	45.84	14	HI	13	EUR	10	
Japan	44.49	18	HI	17	SEAO	4	
Czech Republic	43.23	20	HI	19	EUR	14	
Austria	40.02	28	HI	27	EUR	19	
Belgium	41.47	23	HI	22	EUR	15	
Singapore	45.43	15	HI	14	SEAO	3	
Slovenia	39.82	29	HI	28	EUR	20	
Hong Kong (China)	42.53	21	HI	20	SEAO	5	
New Zealand	39.17	30	HI	29	SEAO	6	
Norway	41.08	24	HI	23	EUR	16	
Cyprus	42.30	22	HI	21	NAWA	2	
Australia	38.30	31	HI	30	SEAO	7	
Spain	40.20	27	HI	26	EUR	18	
Canada	40.28	26	HI	25	NAC	2	
Italy	38.28	32	HI	31	EUR	21	
Bulgaria	37.68	34	UM	2	EUR	23	
Hungary	40.95	25	HI	24	EUR	17	
Portugal	37.82	33	HI	32	EUR	22	
Ukraine	36.59	35	LM	1	EUR	24	
Slovakia	36.42	36	HI	33	EUR	25	
Moldova, Republic of	35.41	37	LM	2	EUR	26	
Latvia	35.27	38	HI	34	EUR	27	
Viet Nam	33.70	41	LM	3	SEAO	9	
Poland	33.92	40	HI	35	EUR	28	
Croatia	33.52	42	UM	4	EUR	29	
Turkey	32.19	43	UM	5	NAWA	3	
Malaysia	34.26	39	UM	3	SEAO	8	
Lithuania	31.77	44	HI	36	EUR	30	
Thailand	31.51	45	UM	6	SEAO	10	
Iran, Islamic Republic of	30.16	46	UM	7	CSA	1	
Mongolia	30.06	47	LM	4	SEAO	11	
Romania	29.84	48	UM	8	EUR	31	
Armenia	29.21	50	LM	5	NAWA	5	
Montenegro	28.23	55	UM	10	EUR	33	
Greece	28.75	52	HI	38	EUR	32	
Costa Rica	28.95	51	UM	9	LCN	1	
India	27.83	57	LM	6	CSA	2	
Serbia	27.42	58	UM	12	EUR	35	
Russian Federation	27.91	56	UM	11	EUR	34	
United Arab Emirates	28.36	54	HI	40	NAWA	6	
Mexico	26.35	61	UM	13	LCN	4	
Kuwait	29.36	49	HI	37	NAWA	4	
Chile	28.41	53	HI	39	LCN	2	
Uruguay	26.77	59	HI	41	LCN	3	
Tunisia	25.47	63	LM	8	NAWA	9	
Kenya	25.30	64	LM	9	SSF	1	
Qatar	26.49	60	HI	42	NAWA	7	

(Continued on next page)

Country/Economy	Score (0–100)	Rank	Income	Rank	Region	Rank	Median: 25.39
Georgia	25.65	62	LM	7	NAWA	8	
Jordan	24.19	67	LM	10	NAWA	10	
South Africa	24.89	65	UM	14	SSF	2	
Panama	24.55	66	UM	15	LCN	5	
Philippines	23.98	68	LM	11	SEAO	12	
Tanzania, United Republic of	23.47	71	LI	1	SSF	3	
Morocco	23.50	69	LM	12	NAWA	11	
Brazil	23.49	70	UM	16	LCN	6	
Bahrain	22.41	74	HI	43	NAWA	12	
Dominican Republic	21.89	77	UM	19	LCN	9	
Indonesia	22.47	73	LM	13	SEAO	13	
Oman	22.18	75	HI	44	NAWA	13	
Colombia	22.52	72	UM	17	LCN	7	
Jamaica	22.03	76	UM	18	LCN	8	
Saudi Arabia	21.81	78	HI	45	NAWA	14	
Egypt	21.62	79	LM	14	NAWA	15	
Sri Lanka	21.06	80	LM	15	CSA	3	
Argentina	20.75	81	UM	20	LCN	10	
Bosnia and Herzegovina	20.60	82	UM	21	EUR	36	
Peru	20.48	83	UM	22	LCN	11	
Paraguay	20.09	86	UM	23	LCN	12	
Cambodia	20.32	84	LM	16	SEAO	14	
Madagascar	20.21	85	LI	2	SSF	4	
Senegal	19.87	90	LI	3	SSF	6	
Mauritius	19.90	89	UM	25	SSF	5	
Pakistan	19.19	92	LM	18	CSA	6	
The former Yugoslav Republic of Macedonia	19.09	93	UM	27	EUR	37	
Ecuador	18.11	97	UM	30	LCN	14	
Guatemala	18.35	96	LM	19	LCN	13	
Kazakhstan	19.28	91	UM	26	CSA	5	
Albania	18.39	95	UM	29	EUR	38	
Ghana	16.63	102	LM	22	SSF	10	
Lebanon	18.70	94	UM	28	NAWA	17	
Tajikistan	19.98	88	LM	17	CSA	4	
Cameroon	17.60	98	LM	20	SSF	7	
Azerbaijan	20.00	87	UM	24	NAWA	16	
Zimbabwe	17.36	99	LI	4	SSF	8	
Mali	17.23	100	LI	5	SSF	9	
Trinidad and Tobago	16.08	104	HI	46	LCN	15	
Kyrgyzstan	17.14	101	LM	21	CSA	7	
Namibia	16.44	103	UM	31	SSF	11	
Malawi	15.72	108	LI	6	SSF	13	
Bangladesh	16.01	105	LM	23	CSA	8	
Uganda	15.69	111	LI	8	SSF	15	
Belarus	15.70	110	UM	33	EUR	39	
Mozambique	15.71	109	LI	7	SSF	14	
Honduras	15.99	106	LM	24	LCN	16	
Nigeria	14.89	115	LM	26	SSF	16	
El Salvador	15.17	113	LM	25	LCN	17	
Botswana	15.85	107	UM	32	SSF	12	
Zambia	12.77	119	LM	28	SSF	18	
Algeria	14.07	116	UM	34	NAWA	18	
Brunei Darussalam	15.63	112	HI	47	SEAO	15	
Bolivia, Plurinational State of	13.77	117	LM	27	LCN	18	
Guinea	13.24	118	LI	10	SSF	17	
Nepal	15.03	114	LI	9	CSA	9	
Rwanda	12.59	120	LI	11	SSF	19	
Côte d'Ivoire	11.32	121	LM	29	SSF	20	
Niger	10.87	122	LI	12	SSF	21	
Benin	10.64	123	LI	13	SSF	22	
Burkina Faso	8.30	125	LI	15	SSF	24	
Yemen	7.90	126	LM	30	NAWA	19	
Togo	9.96	124	LI	14	SSF	23	

Notes: World Bank Income Group Classification (July 2017): LI = low income; LM = lower-middle income; UM = upper-middle income; and HI = high income. Regions are based on the United Nations Classification: EUR = Europe; NAC = Northern America; LCN = Latin America and the Caribbean; CSA = Central and Southern Asia; SEAO = South East Asia, East Asia, and Oceania; NAWA = Northern Africa and Western Asia; SSF = Sub-Saharan Africa. See Chapter 1, Annexes 1–3, for methodological considerations that impact the rankings.

KEY FINDINGS

Figure A.
Global leaders in innovation in 2018

Every year, the Global Innovation Index ranks the innovation performance of nearly 130 economies around the world.

Top innovation regions by GII score

NORTHERN AMERICA — 56

U.S.	59.81
Canada	52.98

EUROPE — 47

Switzerland	68.40
Netherlands	63.32 ↑
Sweden	63.08 ↓

NORTHERN AFRICA AND WESTERN ASIA — 34

Israel	56.79
Cyprus	47.83
UAE	42.58

SOUTH EAST ASIA, EAST ASIA, AND OCEANIA — 44

Singapore	59.83
Republic of Korea	56.63
Japan	54.95

LATIN AMERICA AND THE CARIBBEAN — 30

Chile	37.79
Costa Rica	35.72
Mexico	35.34

SUB-SAHARAN AFRICA — 25

South Africa	35.13
Mauritius	31.31
Kenya	31.07

CENTRAL AND SOUTHERN ASIA — 28

India	35.18
Iran	33.44
Kazakhstan	31.42

Innovation leaders by income group

HIGH INCOME (ABOVE $12,236)
- Switzerland.......68.40
- Netherlands......63.32 ↑
- Sweden............63.08 ↓

UPPER-MIDDLE INCOME ($3,956–12,235)
- China.................53.06
- Malaysia.............43.16 ↑
- Bulgaria.............42.65 ↓

LOWER-MIDDLE INCOME ($1,006–3,955)
- Ukraine ....38.52 ↑
- Viet Nam .... 37.94 ↓
- Moldova .... 37.63 ★

LOW INCOME (UNDER $1,005)
- Tanzania............ 28.07
- Rwanda.............26.54
- Senegal.............26.53

Source: See Figure 7 in Chapter 1.

KEY FINDINGS OF THE GLOBAL INNOVATION INDEX (GII) 2018

The main messages of the Global Innovation Index 2018 can be summarized in seven key findings.

1: Becoming optimistic about global innovation and growth is possible

After almost a decade of uneven progress, a broad-based global economic growth momentum is now in place. The current challenge is for the global economy to reach a comfortable cruising speed that can be sustained for the next several years.

In this context, there is a renewed need to prioritize policies that foster new sources of innovation-driven growth. Investments in innovation are central in this goal.

Certainly, according to the GII estimates, year-on-year growth of corporate and public R&D spending is still mostly lower than it was before the crisis (see Figure B). There are also downward risks to economic projections and innovation in the months to come.

Yet many considerations also allow for considerable optimism. The global landscape of investment in science and technology as well as in education and human capital has undergone important positive shifts over the last three decades. Today innovation and research and development (R&D) are a serious policy ambition in most developed and developing economies and in all world regions. Global R&D expenditures have continued to rise, more than doubling over the 20-year period between 1996 and 2016; businesses increasingly account for most R&D investments.

In 2016, worldwide total R&D expenditure (GERD) grew at 3% (Figure B). Global R&D intensity too has been stable or it even has intensified over recent years. Intellectual property (IP) filings too have reached record levels in 2016; that growth is mainly driven by China.

Another positive message can be found on the business front. Global business R&D spending increased at faster pace in 2016 (4.2%) than in 2015. The top 1,000 R&D companies raised their R&D expenditures between 2015 and the first half of 2017.

Building on this movement, and overcoming the global innovation divide, there is potential to ramp up innovation in most middle-income economies as well as to progressively increase innovation in low-income economies.

Looking forward, what if innovation expenditures are aligned with economic growth over the next few years? What if India and other emerging countries in Asia, and hopefully also in other world regions such as Latin America, Central Asia, and Africa—the regions that currently lag in comparison—follow the dynamic innovation trajectory of China in the next several years? What if increased protectionism—in particular protectionism that impacts technology-intensive sectors, IP, and knowledge flows across the board—could be contained in the months ahead?

Such dynamics could create the basis for productive knowledge spillovers and opportunities for collaboration and the generation of new knowledge and innovation.

2: Continued investments in breakthrough energy innovations are essential for global growth and to avert an environmental crisis

Projections indicate that by 2040 the world will require up to 30% more energy than it needs today. Conventional approaches to energy supply are unsustainable in the face of climate change. The chapters of the 11th edition of the GII explore how innovation contributes to addressing and solving the energy equation in specific geographies and contexts.

Five messages emerge from this year's GII thematic focus, namely:

1. Innovation has a key role in meeting increasing global energy demand.
2. Energy innovations are happening globally, while objectives differ across countries.
3. New energy innovation systems need to emerge, with efforts along all stages, including energy distribution and storage.
4. Obstacles to the adoption and diffusion of energy innovations remain numerous.
5. Public policy plays a central role in driving the energy transition.

To start with, significant progress has been achieved recently in energy innovation. For example, lower costs of renewable energy technologies have combined with increasing energy efficiencies. Today offshore wind and concentrated solar power technologies are relevant energy supply options. Ultra-high voltage lines and smart grids are opening the possibility that power and electricity can be transported across long distances.

Furthermore, innovation in the energy sector is not the privilege of high-income economies alone. India and China are delving deeper into the downstream applications of photovoltaic technologies. Energy innovation is happening at the grassroots level too. For example, small-scale systems to provide electricity for people living far from the grid are on the rise.

Yet to realize their full potential, new energy innovation systems, coupled with intense innovation efforts, are needed at all stages of the energy system value chain.

Higher levels of technological and non-technological innovation are required on diverse fronts:

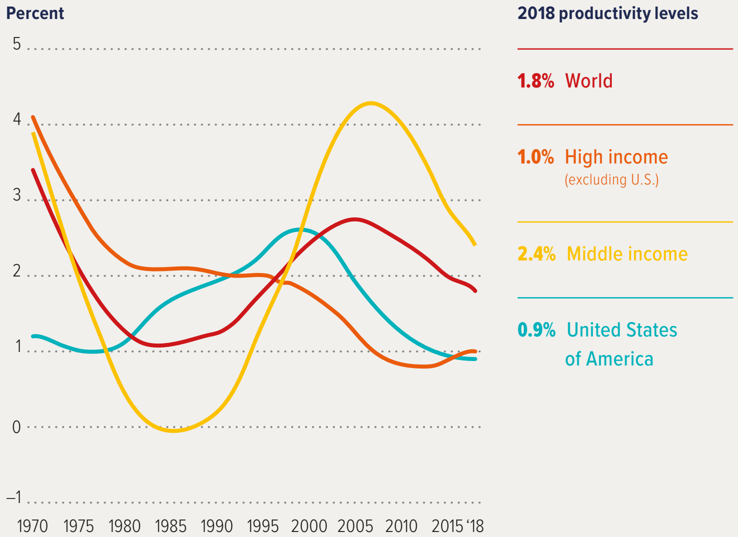
- on the supply side of the energy equation, including cleaner energy sources;
- on the demand side, including smart cities, homes and buildings, energy efficient industries, and transport and future mobility; and
- in enabling technologies for the optimization of energy systems, including smart grids and advanced storage technologies.

In this context, however, Chapter 1 of the GII 2018 notes that green investment growth has slowed on the basis of available figures; energy-related patenting has also stagnated and even declined in recent years following a period of accelerated growth. Moreover, at the moment, innovation has been uneven across the different stages of the energy system value chain, with more attention needed to be paid to energy storage technologies and energy transmission technologies.

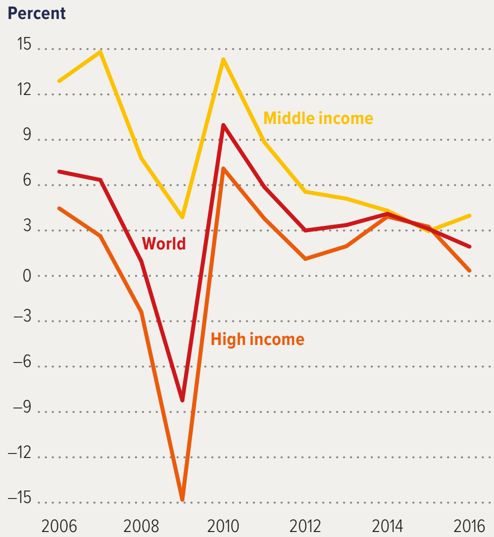
According to an analysis done by the World Intellectual Property Organization (WIPO) for the GII 2018, the total number of patent families and PCT international patent applications in energy technologies almost doubled between 2005 and 2013 (see Figure D). Yet this period of accelerated growth in the number of patented green energy inventions has been followed

Figure B.
Global productivity, investment, and business R&D falling short?

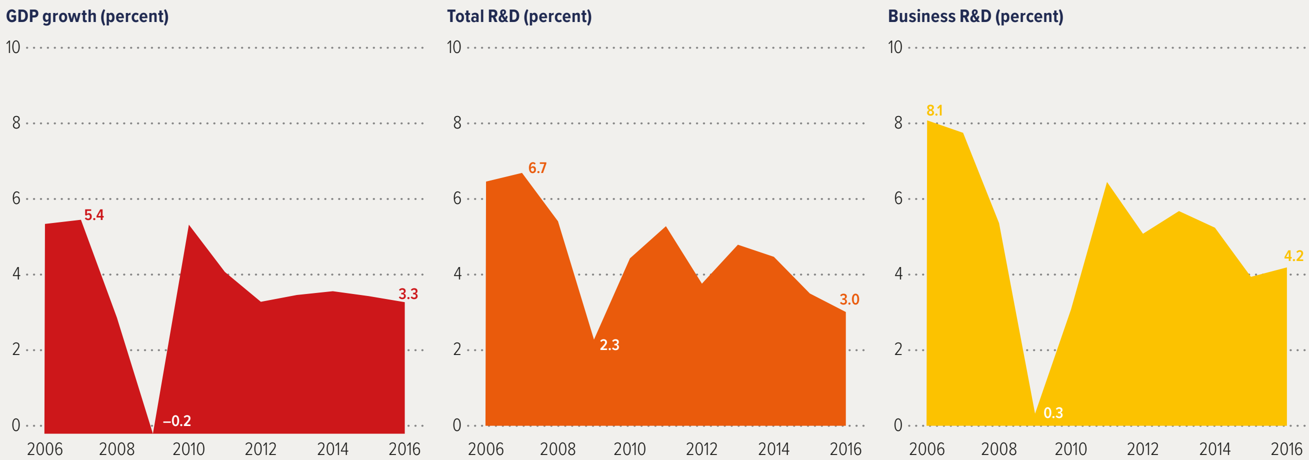
Productivity growth, 1970–2018



Investment growth, 2006–16



Global R&D expenditures growth, 2006–16



Source: See Figure 1 in Chapter 1.

Figure C.
Movement in the GII top 10

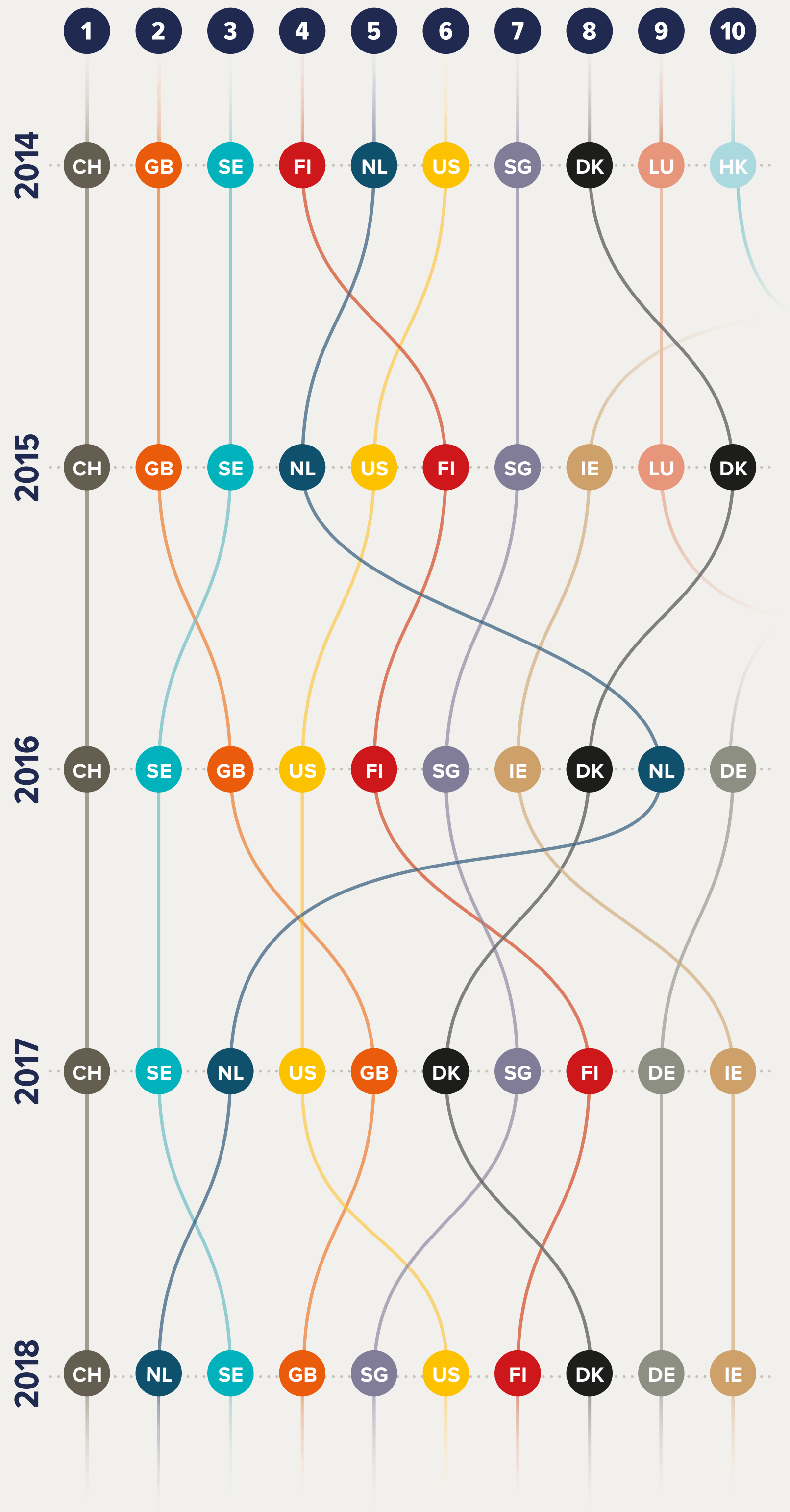
Since 2011 Switzerland has ranked 1st in the GII every year.

In 2015 Ireland entered the top 10 and Hong Kong (China) exited.

After 2016 no country has entered or exited the top 10.

Sweden maintained 2nd place for the second time in 2017.

In 2018 the Netherlands and Sweden traded 2nd and 3rd place.



KEY

DK Denmark	**HK** Hong Kong (China)	**NL** Netherlands	**CH** Switzerland
FI Finland	**IE** Ireland	**SG** Singapore	**GB** United Kingdom
DE Germany	**LU** Luxembourg	**SE** Sweden	**US** United States of America

Source: See Figure 5 in Chapter 1.

by a period of deceleration and, indeed, a slow decline. The number of green patent families peaked in 2012—with the underlying invention usually happening about 18 months before the patent publication. Hence the peak of inventive activity was around 2010. Since then a decrease in the absolute number of patent families has been observed every year until 2015, a reduction from peak to bottom of close to 4% percent—from 113,547 green patent families in 2012 to 109,266 families in 2015. Similarly, published PCT international patent applications peaked in 2013, and were followed by a decrease of about 11 % between 2013 and 2017.

With regard to patent families, although most green energy technologies saw a downward trend in the annual number of patents granted since 2012, the decline has been most pronounced in nuclear power generation technologies and alternative energy production technologies. The latter include notably renewable energy technologies, such as solar energy, wind energy, and fuel cells. In contrast, inventions in energy conservation technologies and green transportation technologies have continued growing but at a slower pace. An analysis conducted by the European Patent Office (EPO) for the GII 2018 confirms the above-mentioned slowdown for smart grid technology.

Moving beyond the actual invention of technologies, one of the biggest challenges with respect to energy innovation seems to be on the side of diffusion and adoption and the fact that incentives to address this need are missing. The challenges and costs linked to the commercialization and uptake of energy innovations are mostly underestimated.

Finally, the role of government is central to implementing strong incentives and regulations to drive the transition. Governments often play the role of risk taker by promoting mechanisms that stimulate investment and the diffusion of technologies with disruptive potential. Policy incentives are particularly lacking in sectors with the least progress in innovation for decarbonization, such as the heavy industries, freight transport, and aviation. Innovation efforts around grid infrastructure need additional support. At the same time, the role of the effect of subsidies on innovation is currently underappreciated. Although subsidies might be critical to fostering the uptake of, for example, solar energy panels by private households, their role in driving innovation on the supply-side across this and other energy technologies is unclear.

3: China's rapid rise shows the way for other middle-income economies

The global innovation divide remains wide, with high-income economies leading the innovation landscape and big gaps in terms of nearly all innovation input and output metrics between these leaders and other less-developed countries.

In this context, China's rise in the GII rankings over the last few years has been spectacular. Since 2016 China has featured in the top 25 group and has consistently moved upward in the rankings to 17th this year. The only middle-income economy that continues to edge closer to the top 25 is Malaysia (35th).

China's innovation prowess becomes evident in various areas. It shows some of its greatest improvements in global R&D companies, high-tech imports, the quality of its publications, and tertiary enrolment. In absolute values, and in areas such as R&D expenditures and the number of researchers, patents, and publications, China is now 1st or 2nd in the world, with volumes that overshadow most high-income economies (see Figure G).

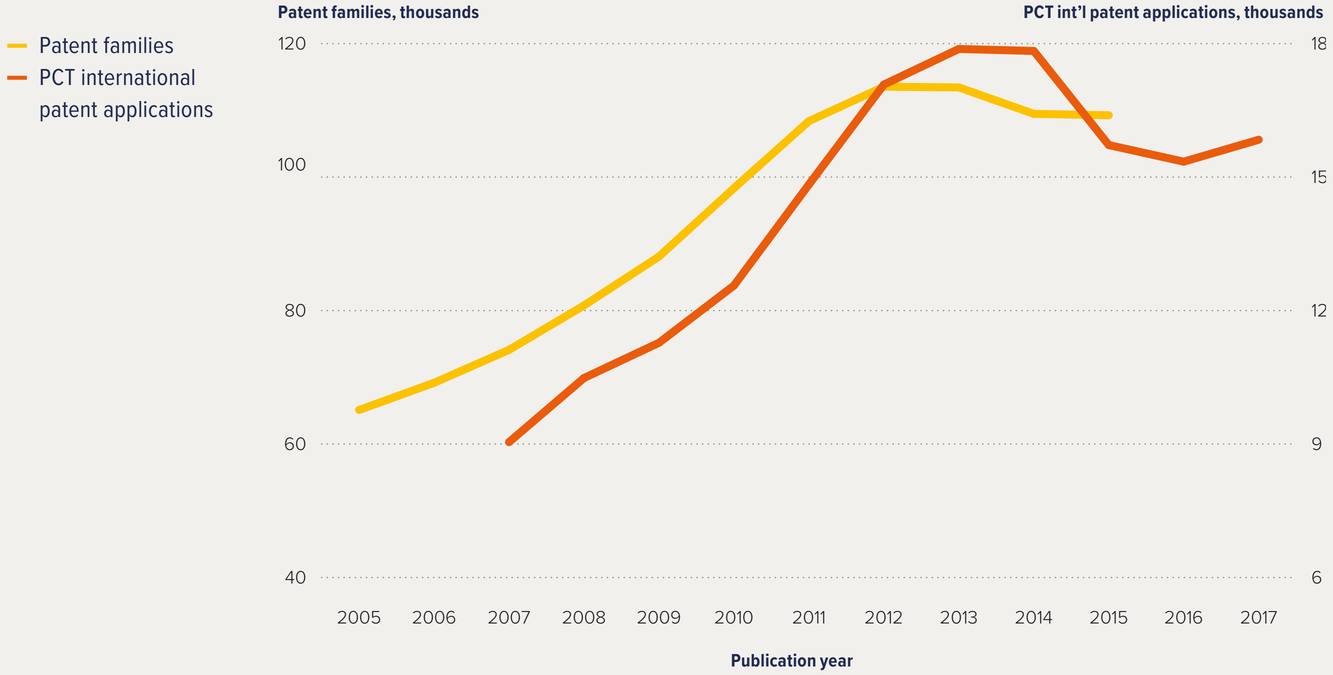
Indeed, China presents an impressive example for other middle-income countries to follow as they seek to join the echelons of high-income economies. With this success in mind, China's attention is now turning to the quality and impact of innovation.

The GII 2018 also identifies 20 countries that outperform on innovation relative to their level of development (see Figure E and Table A). New entrants include Colombia, Tunisia, South Africa, Costa Rica, Serbia, Montenegro, Thailand, Georgia, and Mongolia. Among these, Colombia, Tunisia, and South Africa enter this group for the first time.

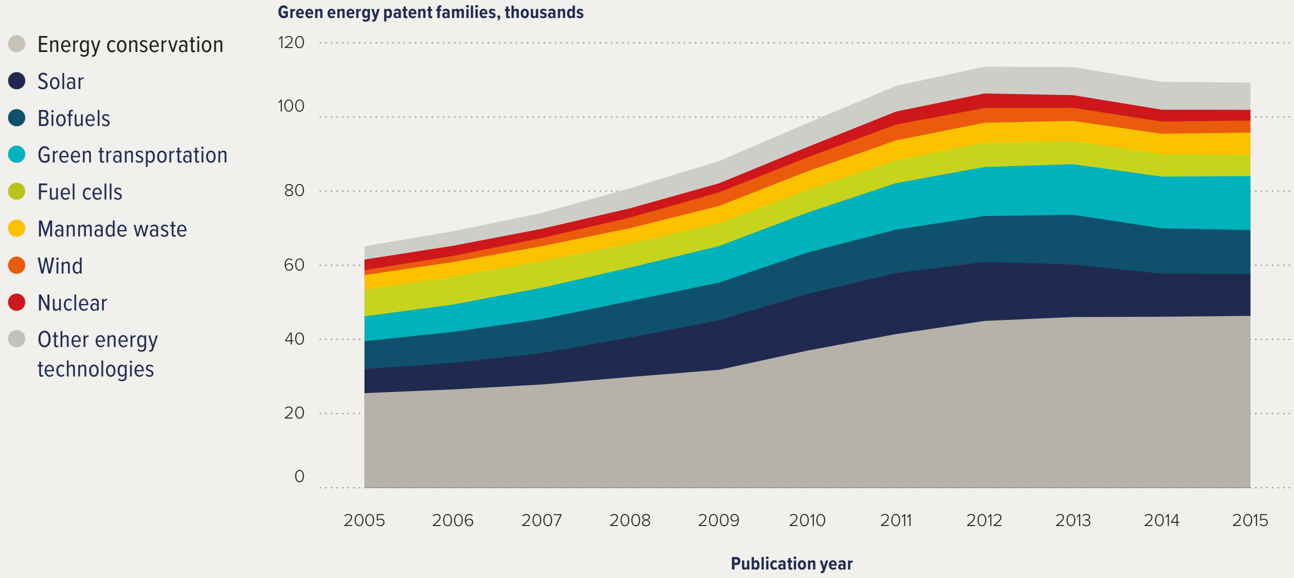
Of these 20 economies—six in total, the most from any region—come from Sub-Saharan Africa. Importantly, Kenya, Rwanda, Mozambique, Malawi, and Madagascar stand out for being innovation achievers at least three times in the previous eight years. For the very first time, South Africa also joins this group of achievers from the Sub-Saharan Africa region. In other regions, this year Mongolia, Thailand, and Montenegro make a comeback.

Figure D.
Green energy patent filings

Number of patent families and PCT int'l patent applications in green energy technologies, 2005–17



Total number of patent families in green energy technologies, 2005–15



Source: See Figure 3 in Chapter 1.

Table A: Innovation achievers: Income group, region, and years as an innovation achiever

Economy	Income group	Region	Years as an innovation achiever (total)
Moldova, Rep.	Lower-middle income	Europe	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Viet Nam	Lower-middle income	South East Asia, East Asia, and Oceania	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
India	Lower-middle income	Central and Southern Asia	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Kenya	Lower-middle income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Armenia	Lower-middle income	Northern Africa and Western Asia	2018, 2017, 2016, 2015, 2014, 2013, 2012 (7)
Ukraine	Lower-middle income	Europe	2018, 2017, 2016, 2015, 2014, 2012 (6)
Mongolia	Lower-middle income	South East Asia, East Asia, and Oceania	2018, 2015, 2014, 2013, 2012, 2011 (6)
Malawi	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Mozambique	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Rwanda	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Georgia	Lower-middle income	Northern Africa and Western Asia	2018, 2014, 2013, 2012 (4)
Thailand	Upper-middle income	South East Asia, East Asia, and Oceania	2018, 2015, 2014, 2011 (4)
Montenegro	Upper-middle income	Europe	2018, 2015, 2013, 2012 (4)
Bulgaria	Upper-middle income	Europe	2018, 2017, 2015 (3)
Madagascar	Low income	Sub-Saharan Africa	2018, 2017, 2016 (3)
Serbia	Upper-middle income	Europe	2018, 2012 (2)
Costa Rica	Upper-middle income	Latin America and the Caribbean	2018, 2013 (2)
South Africa	Upper-middle income	Sub-Saharan Africa	2018 (1)
Tunisia	Lower-middle income	Northern Africa and Western Asia	2018 (1)
Colombia	Upper-middle income	Latin America and the Caribbean	2018 (1)

Source: See Table 2 in Chapter 1.

India is consistently an overachiever relative to its level of development, although it is making progress in its rankings year on year. Given its size, India has the potential to make a true difference to the global innovation landscape in the years to come.

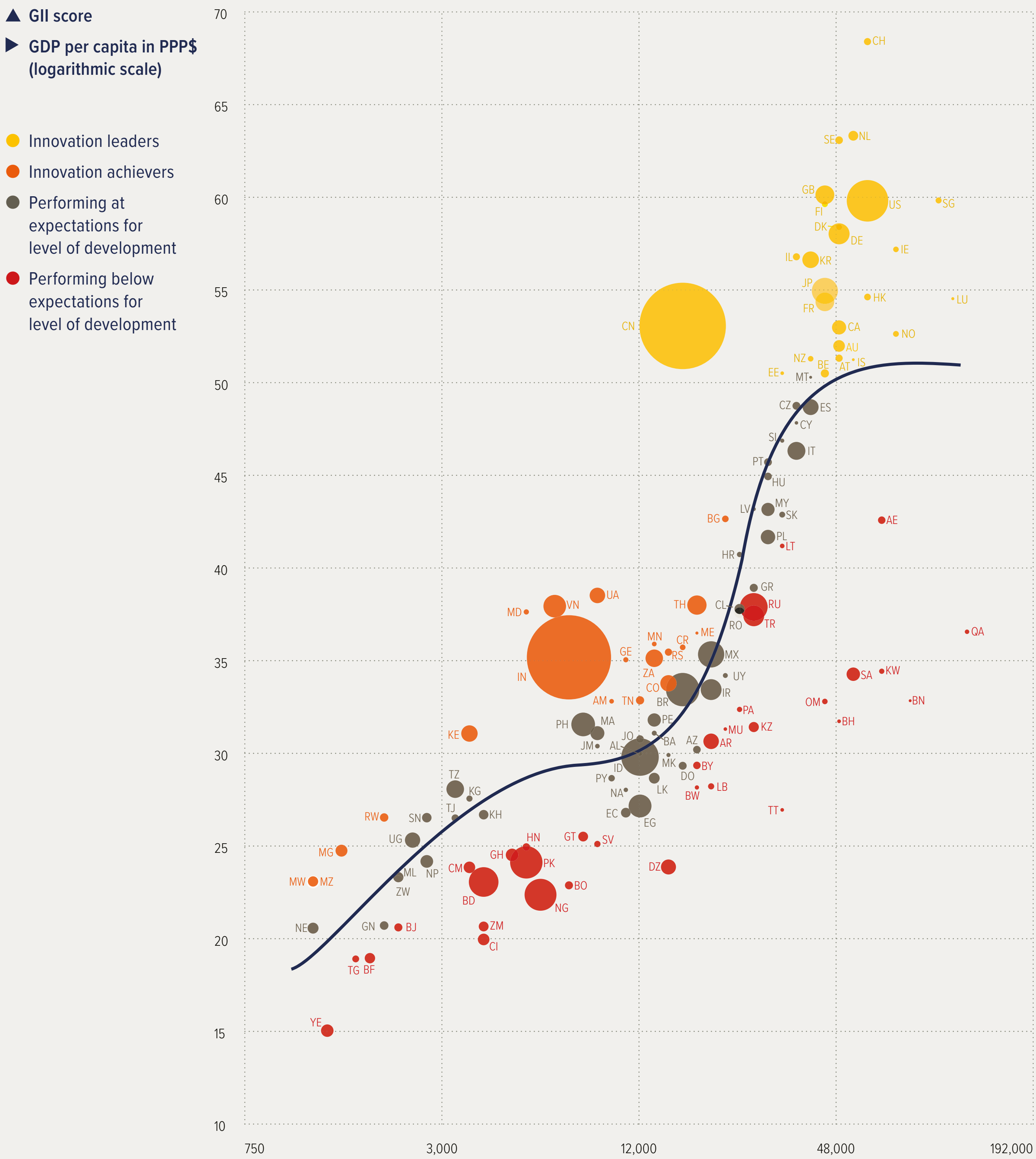
4: Richer economies, with more diverse industry and export portfolios, are likelier to score high in innovation

A look at the 2018 league table of the GII confirms the surprising presence of several countries or economies with small populations or relatively small economies (see Figure C). Among the GII top 20, one can find, for example, the Netherlands, the Nordic EU countries, Singapore, Israel, and Luxembourg—in spite of the fact that large economies such as the United States of America (U.S.), Germany, and now China are also part of this top-ranked group. Thus the question has legitimately been asked: Does being small give a country a positive advantage in the innovation rankings?

For this edition of the GII, the statistical relationship of the GII score relative to country features has been assessed. The core findings—which do not imply causality in either direction but correlation—are as follows:

1. All editions of the GII demonstrate the positive link between innovation performance and an economy's level of development as measured by GDP per capita, aka the 'GII bubble chart' (Figure E). Still, some economies stand out because they overperform relative to their levels of development (see key finding 3).
2. All factors considered, country size as reflected by population size is not correlated with the GII score in a statistically significant way. Both large and small countries have a good shot at scoring high on the GII; small countries do not unduly lead the rankings.
3. High-income economies are more innovative when their economic structures—and thus their industry portfolios—are more diverse.
4. Similarly, economies at all levels of development happen to be more innovative when they have a more diversified export portfolio.

Figure E.
GII scores and GDP per capita in PPP$ (bubbles sized by population)



Source: See Figure 9 in Chapter 1.

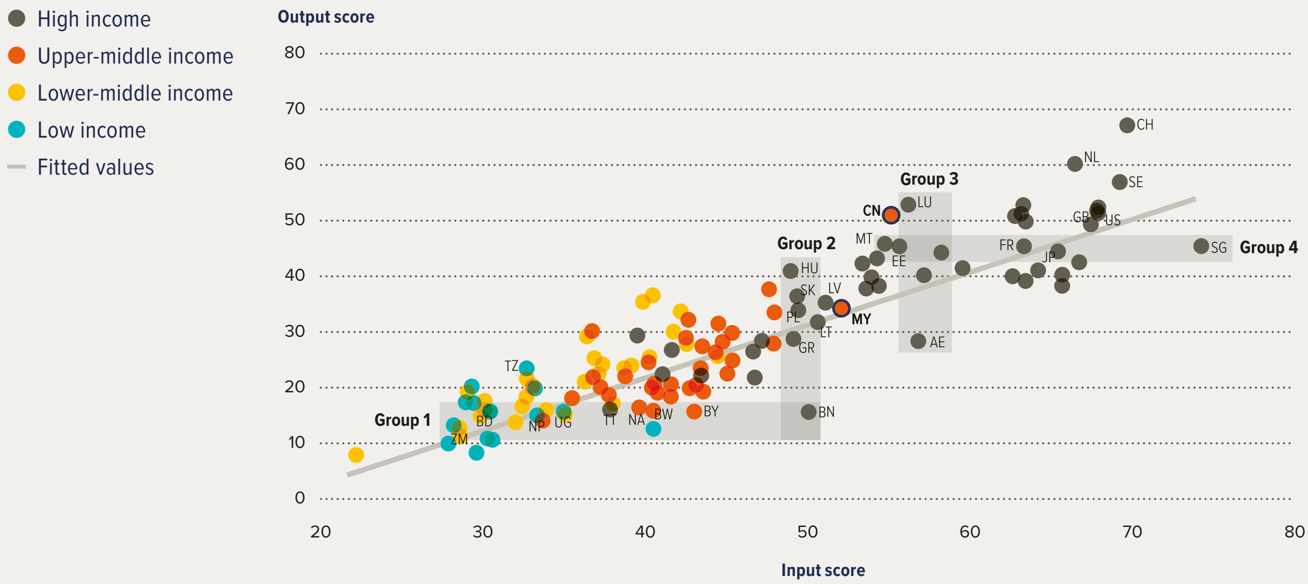
ISO-2 Country Codes

Code	Country/Economy
AE	United Arab Emirates
AL	Albania
AM	Armenia
AR	Argentina
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BD	Bangladesh
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BH	Bahrain
BJ	Benin
BN	Brunei Darussalam
BO	Bolivia, Plurinational State of
BR	Brazil
BW	Botswana
BY	Belarus
CA	Canada
CH	Switzerland
CI	Côte d'Ivoire
CL	Chile
CM	Cameroon
CN	China
CO	Colombia
CR	Costa Rica
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
DO	Dominican Republic
DZ	Algeria
EC	Ecuador
EE	Estonia
EG	Egypt
ES	Spain
FI	Finland
FR	France
GB	United Kingdom
GE	Georgia
GH	Ghana

Code	Country/Economy
GN	Guinea
GR	Greece
GT	Guatemala
HK	Hong Kong (China)
HN	Honduras
HR	Croatia
HU	Hungary
ID	Indonesia
IE	Ireland
IL	Israel
IN	India
IR	Iran, Islamic Republic of
IS	Iceland
IT	Italy
JM	Jamaica
JO	Jordan
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KH	Cambodia
KR	Korea, Republic of
KW	Kuwait
KZ	Kazakhstan
LB	Lebanon
LK	Sri Lanka
LT	Lithuania
LU	Luxembourg
LV	Latvia
MA	Morocco
MD	Moldova, Republic of
ME	Montenegro
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MT	Malta
MU	Mauritius
MW	Malawi
MX	Mexico
MY	Malaysia
MZ	Mozambique
NA	Namibia

Code	Country/Economy
NE	Niger
NG	Nigeria
NL	Netherlands
NO	Norway
NP	Nepal
NZ	New Zealand
OM	Oman
PA	Panama
PE	Peru
PH	Philippines
PK	Pakistan
PL	Poland
PT	Portugal
PY	Paraguay
QA	Qatar
RO	Romania
RS	Serbia
RU	Russian Federation
RW	Rwanda
SA	Saudi Arabia
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SV	El Salvador
TG	Togo
TH	Thailand
TJ	Tajikistan
TN	Tunisia
TR	Turkey
TT	Trinidad and Tobago
TZ	Tanzania, United Republic of
UA	Ukraine
UG	Uganda
US	United States of America
UY	Uruguay
VN	Viet Nam
YE	Yemen
ZA	South Africa
ZM	Zambia
ZW	Zimbabwe

Figure F.
Innovation Output Sub-Index score vs Innovation Input Sub-Index score by income group, 2018



Source: See Figure 8 in Chapter 1.

5: Focusing on translating innovation investments into results is key

What is the best way to translate investments on education, a high number of qualified researchers, and high R&D expenditures into high-quality innovation outputs? Despite significant investment in innovation inputs, some economies do not generate a corresponding level of innovation outputs.

Most economies have a linear relationship between innovation inputs and outputs (see Figure F). But there are important outliers that strongly over- or under-deliver with respect to obtaining a 'bang for their buck'.

- Among high-income countries, Switzerland, the Netherlands, Sweden, Germany, Ireland, Luxembourg, and also Hungary stand out for producing many outputs for their given level of inputs. Singapore, Australia, Japan, Hong Kong (China), Canada, New Zealand, and Norway, as well as many resource-rich economies such as Saudi Arabia, Qatar, and Trinidad and Tobago stand out as high-income economies that—assuming that both inputs and outputs are properly measured—tend to perform worse.
- Among upper-middle-income countries, China strongly overperforms in the said efficiency relationship, whereas Malaysia slightly underperforms.
- Among lower-middle economies, Ukraine, the Republic of Moldova, and Viet Nam stand out as performing better than would be expected by their levels of inputs.

Another frequent policy ambition is to achieve innovation inputs and outputs of high quality. Rather than targeting quantity in terms of university spending, publications, or patents, the focus is on top-ranked universities, much-cited publications, or patents that go international. The top 5 high-income economies in the quality of innovation in 2018 are Japan, Switzerland, the U.S., Germany, and the United Kingdom (U.K.) (see Figure 5.1 in Box 5 of Chapter 1). The Republic of Korea moves up in the quality of innovation, overtaking Sweden this year, while France enters the top 10 for the first time.

Among the middle-income group, the top 5 remain steady with China, India, and the Russian Federation at the top, followed by Brazil and Argentina. Mexico and Malaysia are advancing the most in this group.

6: Strong regional innovation imbalances persevere, hampering economic and human development

Regional performance as measured by the average scores shows that (1) Northern America is the top performer with top scores for all pillars, followed by (2) Europe, (3) South East Asia, East Asia, and Oceania, (4) Northern Africa and Western Asia, (5) Latin America and the Caribbean, (6) Central and Southern Asia, and, finally, (7) Sub-Saharan Africa (see Figure A).

Northern America—the U.S. and Canada—make up the top-performing region. The U.S. ranks 6th in the GII this year. Its position deteriorates in both the innovation input and output sides, driven by declines in Human capital and research, Infrastructure, and Creative outputs. Despite these downward movements, the U.S.—in conjunction with China—remains among the largest world contributors in all dimensions of absolute, unscaled innovation inputs and outputs, including R&D expenditures and patent applications (see Figure G). The U.S. also still harbours most top innovation clusters such as Silicon Valley. If parts of the San Jose/San Francisco or the Boston area in the U.S. were countries, they could top most, if not all, innovation rankings.

Europe is catching up with Northern America in terms of average GII scores, coming in 2nd. Although often underappreciated, 15 of the top 25 economies come from Europe, and most belong to the European Union (EU).

The GII, however, also documents some longstanding innovation policy concerns of the EU. First, it showcases the persistent differences in innovation performance within the EU region. While the above-mentioned EU countries are in the top 10, others are in the top 30 and 40, or even in the top 50. Second, the GII also shows the important strengths that the EU harbours on the side of innovation inputs versus lower performance on business R&D or innovation outputs. Third, the GII also attests that entrepreneurial activity is sometimes more constrained than would be ideal. Recent years, however, have witnessed a renewed start-up spurt in European capitals—a trend that is worth amplifying.

In 3rd place comes South East Asia, East Asia, and Oceania—the region showing the most progress again this year, driven mainly by the Association of Southeast Asian Nations (ASEAN) region. Seven of this region's 15 economies rank in the top 25 of the GII: Singapore (5th), the Republic of Korea (12th), Japan (13th), Hong Kong (China) (14th), China (17th), Australia (20th), and New Zealand (22nd).

Malaysia moves up two positions to 35th. Thailand jumps forward seven positions, reaching the 44th place. Viet Nam gains another two positions, ranking 45th this year.

ASEAN economies are making great progress in innovation indicators, yet with significant differences in performance. Singapore has the highest scores among ASEAN members in many of the selected indicators, excluding expenditure on education (topped again by Viet Nam), tertiary enrolment (where Thailand leads the ASEAN countries), gross capital formation (topped again by Brunei Darussalam), ICT service exports (topped again by the Philippines), and trademarks by origin (topped by Viet Nam this year).

In 4th place is Northern Africa and Western Asia. Israel (11th, up by six), has the most striking upward movement in the region. Following Cyprus (29th), the United Arab Emirates (38th) is 3rd in the region.

Latin America and the Caribbean comes in at 5th place. Although important regional potential exists, the GII rankings of countries in Latin America relative to other regions have not steadily improved. Chile continues to lead the region in the GII rankings for another year, while Mexico has consistently moved upward in recent years. Brazil is ranked 64th in the GII 2018. This year Costa Rica and Colombia are identified as innovation achievers.

Figure G.

Large high-income economies, and upper-middle income China, overshadow small countries in absolute innovation performance

Source: See Figure 6 in Chapter 1.

In 6th place is Central and Southern Asia, which is a rather heterogeneous region. India is the only economy from the region in the top half of the GII, gaining positions since 2016. At the indicator level, India ranks well in a number of important indicators, including graduates in science and engineering, productivity growth, and ICT services exports, where it ranks number 1 in the world. The Islamic Republic of Iran, which is moving closer to the top half of the GII this year, has also improved its ranking remarkably since 2014. The other economies in the region— in particular Kazakhstan, Sri Lanka, Nepal, Pakistan, and Bangladesh—which rank lower, will benefit from more innovation in the future.

Finally, Sub-Saharan Africa is last as a region, despite the strong performance of individual countries. As last year, this year South Africa takes the top spot among all economies in the region (58th), followed by Mauritius (75th), Kenya (78th), and Botswana (91st). Since 2012, most countries among the group of innovation achievers have been from Sub-Saharan Africa (see key finding 3 and Table A). It will be important for Africa to preserve this innovation momentum.

Table B: Top cluster of economies or cross-border regions within the top 50

Rank	Cluster name	Economies
1	Tokyo–Yokohama	JP
2	Shenzhen–Hong Kong	CN/HK
3	Seoul	KR
4	San Jose–San Francisco, CA	US
5	Beijing	CN
9	Paris	FR
15	London	GB
17	Amsterdam–Rotterdam	NL
20	Cologne	DE
22	Tel Aviv–Jerusalem	IL
28	Singapore	SG
29	Eindhoven	BE/NL
30	Moscow	RU
31	Stockholm	SE
33	Melbourne	AU
37	Toronto, ON	CA
38	Madrid	ES
44	Tehran	IR
45	Milan	IT
48	Zurich	CH/DE

Source: See Table 2 in the Special Section Annex.
Note: Codes refer to the ISO-2 codes; see page xxxvii for a full list.

7: Most top science and technology clusters are in the U.S., China, and Germany; Brazil, India, and Iran also make the top 100 list

Countries have shown particular interest in assessing and monitoring innovation performance at the sub-national level in clusters in their states, regions, or cities. The challenge is that official data on the existence and performance of innovation clusters at the international level are hard to come by.

For the second year in a row, the Special Section on Clusters includes a ranking of the world's largest clusters of science and technology activity (see Figure H and Table B). As last year, this ranking relies on international patent filings to identify such clusters. But in addition, this year the cluster ranking introduces scientific publishing activity as an additional measure of cluster performance.

The high-levels results are:

- Again, Tokyo–Yokohama tops this ranking, followed by Shenzhen–Hong Kong.
- The U.S., with 26 clusters, accounts for the highest number, followed by China (16), Germany (8), the U.K. (4), and Canada (4).
- In addition to China, there are clusters from five middle-income countries—Brazil, India, the Islamic Republic of Iran, the Russian Federation, and Turkey—in the top 100.

Figure H.
PCT patent density and SCIE publication density per 100 square kilometres

PCT patent density per 100 square kilometres

SCIE publication density per 100 square kilometres

Source: See Figures 1 and 2 in the Special Section Annex.

CHAPTERS

CHAPTER 1

THE GLOBAL INNOVATION INDEX 2018: ENERGIZING THE WORLD WITH INNOVATION

Soumitra Dutta, Rafael Escalona Reynoso, Antanina Garanasvili, and **Kritika Saxena,**
SC Johnson College of Business, Cornell University
Bruno Lanvin, INSEAD
Sacha Wunsch-Vincent, Lorena Rivera León, and **Francesca Guadagno***, WIPO

Since the release of the Global Innovation Index (GII) last year, the initial upswing in the global economy has been transforming into momentum for more broad-based global economic growth. Current economic figures show a level of optimism that has been long awaited. The global economy might well have taken off with a, sometimes surprising, significant growth performance in various countries and a partial reversal of their faltering levels of productivity.

Now the challenge is for the global economy to reach a comfortable cruising speed that can be upheld for the next several years.

Key findings in brief

The seven key findings of the GII 2018 are:

1. Becoming optimistic about global innovation and growth is possible.
2. Continued investments in breakthrough energy innovations are essential for global growth and to avert an environmental crisis.
3. China's rapid rise shows the way for other middle-income economies.
4. Richer economies, with more diverse industry and export portfolios, are likelier to score high in innovation.
5. Focusing on translating innovation investments into results is key.
6. Strong regional innovation imbalances persevere, hampering economic and human development.
7. Most top science and technology clusters are in the U.S., China, and Germany; Brazil, India, and Iran also make the top 100 list.

Sustaining the resumption of global growth

As the GII 2018 goes to print, and after almost a decade of uneven, often unsustained, progress, the global economy is now picking up speed and showing more broad-based growth. The world's leading economic institutions predict that global economic activity will strengthen, reaching almost 4% in 2018 and 2019.[1] Initial forecasts keep being revised upward, producing the best result since 2011. World trade and the ratio of trade growth to GDP growth are also set for recovery after a decade of lower trend growth.[2]

Growth in emerging economies, on one hand, and the closing of output gaps in high-income economies relative to the post-crisis years on the other hand, are among the drivers of this upswing.

Low- and middle-income economies are foreseen to grow close to 5% on average in 2018 and 2019.[3] China and, increasingly, India make an overarching contribution to sustaining this trend.[4] Certain countries part of the Association of Southeast Asian Nations (ASEAN)—notably Cambodia, the Philippines, and Viet Nam, as well as other Asian countries such as Bangladesh, Myanmar, and Pakistan—also sustain this expansion.[5] That aside, economic growth is also predicted to be relatively strong in several Sub-Saharan African economies, including Ethiopia, Kenya, Rwanda, and Senegal.[6] Commodity-exporting countries, notably Brazil and the Russian Federation (Russia)—which are overcoming recessions—also benefit from a swift turnaround driven by rising commodity prices.[7] If fundamentals remain positive, Latin America might experience more positive prospects in the next couple of years.

The revised global economic situation is mainly driven by an improved, sometimes striking, recovery in high-income economies, in particular in the United States of America (U.S.), Australia, and many countries in Western Europe, including Germany and France. Among high-income countries, however, some witness a further faltering of economic activity (e.g., Canada; Japan; and the United Kingdom [U.K.]), while others see no upward revisions in the last projections (see, for example, the Republic of Korea).[8]

In terms of more medium- and long-term fundamentals, global growth rates experienced before the economic crisis remain distant for nearly all countries. This is also a result of a decade of sub-par investment and lower productivity that has accompanied the global economy's holding pattern.[9] Worse, it is currently unclear whether the global economy will reach a robust cruising speed and altitude for a sufficient length of time to ensure sustained global growth.[10]

The concerns expressed in last year's GII have not faded. It is fair to say that the following points deserve continued attention.

First, at the global level, investment and productivity growth rates are still historically low. The welcome news is that productivity growth in high-income economies is now more rapid. This change in trend is also fortunately reinforced by a tangible upsurge in total factor productivity.[11] Yet it is too early to rejoice. At the global level, the 'productivity crisis' is not over (see 'Productivity growth, 1970–2018', Figure 1)—the productivity pick-up might be only cyclical in nature.[12] It is true that perceptions of slower average productivity growth might be due to measurement issues and related structural changes such as a shift to digital transactions and services.[13] Yet more fundamental drivers are probably at stake. For one, global foreign direct investment fell strongly by 16% between 2016 and 2017.[14] The low levels of investment at the national level are equally striking (see 'Investment growth, 2006–16', Figure 1); investment is simply not picking up at the same speed as economic growth or trade, lowering prospects of future potential growth. And then there has been another debate over whether modern technology creation and diffusion is effective enough to rival growth rates of previous decades, going back to the Industrial Revolution.[15]

Second, similar to last year when the first green spurts of growth surfaced, we are still wary of the potential downside risks that could affect the global outlook in the years to come. For many economic and geopolitical reasons—such as the build-up of financial vulnerabilities and increased protectionism—the global economy might well descend again before it truly operates at a full speed.[16]

Although most analysts concur with this unpleasant appraisal, suggestions for how to counter this potential obstacle diverge. As the editors of the GII, we believe that there is a renewed need to better prioritize policies that foster new sources of innovation-driven growth.

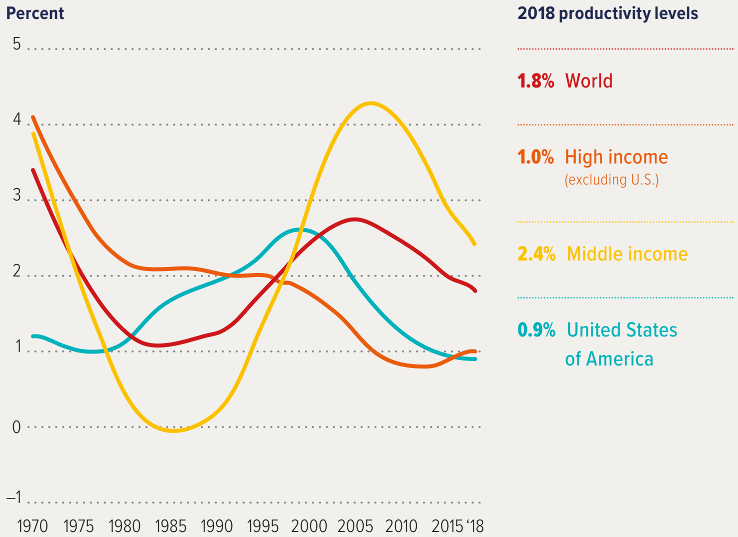
Re-inventing and managing the sources for innovation-driven growth

Laying the foundations for innovation-driven growth is paramount to ensuring that we move beyond a short-lived cyclical recovery.[17]

Investments in innovation and the creation of intangible assets are central to this goal.[18] These investments are crucial to spurring breakthrough technologies and innovations

Figure 1.
Global productivity, investment, and business R&D falling short?

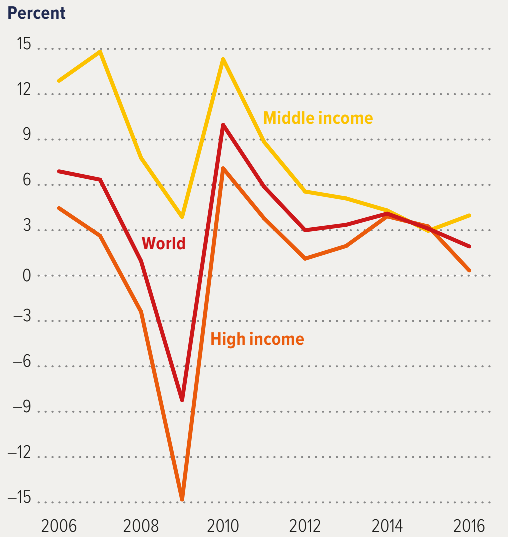
Productivity growth, 1970–2018



Source: Conference Board Total Economy Database, May 2018.

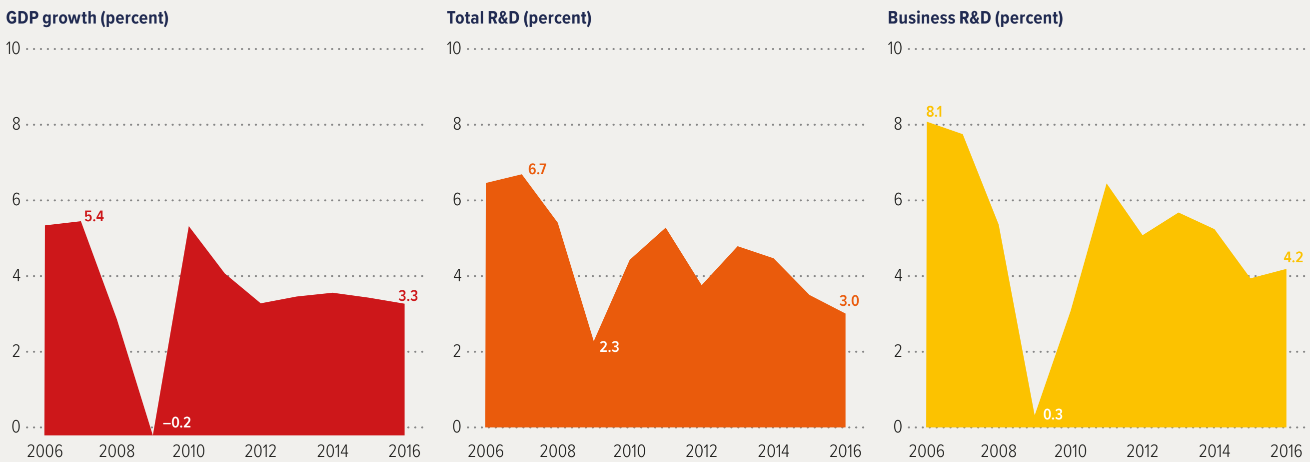
Note: 'Productivity growth' refers to the growth rate of GDP per person employed. The high income category excludes the U.S.

Investment growth, 2006–16



Source: World Bank World Development Indicators database, May 2018.

Global R&D expenditures growth, 2006–16



Source: Authors' estimates, based on the UNESCO Institute for Statistics (UIS) database and the IMF World Economic Outlook database, May 2018.

BOX 1

Mixed post-crisis R&D performance across countries

Countries showed considerable variation in their global R&D expenditure patterns after the 2008–09 financial crisis (Table 1.1).

Countries such as Germany, Israel, Italy, the United Kingdom (U.K.), the United States of America (U.S.), and Brazil experienced a decline in R&D spending in 2009, but their global and business expenditures on R&D (GERD and BERD) had fully recovered by 2016 (the latest year for which data are available). Chile and Colombia saw a steep decline in BERD in 2009 but their BERD growth rates leaped in the aftermath of the crisis.

France, Poland, the Republic of Korea, China, and Costa Rica proved to be among the economies most resilient to the crisis. They saw strong and constant growth in both GERD and BERD during whole 2010–16 period.

Some countries have not yet returned to their pre-crisis R&D spending levels. Finland, Portugal, and Spain still spend less on R&D than they did in 2008. In Latvia, in contrast, GERD and BERD had recovered in 2014 but experienced a new fall in 2016.

Finally, some countries, such as South Africa, still struggle to recover their business R&D spending but demonstrate sound total R&D spending.

Table 1.1: Gross domestic expenditure on R&D (GERD): Crisis and recovery compared

Countries with no fall in GERD during the crisis that have expanded since

	CRISIS		RECOVERY			
	2008	2009	2010–2013*	2014	2015	2016
France	100	104	108	114	115	115[p]
Korea	100	106	139	166	168	173
Mexico	100	105	114	127[ep]	130[ep]	125[ep]
Poland	100	113	150	187	207	n/a
Turkey	100	111	138	171	185	n/a
Argentina	100	117[bp]	138[p]	137[p]	149[p]	n/a
China	100	126	177	231	253	276
Russia	100	111	108	118	118	117
Colombia[†]	100	100	132	201	197	189
Costa Rica[†]	100	133	147	177	n/a	n/a
Egypt[†]	100	168	222	284	334	344
India[†]	100	106	118	n/a	119	n/a

Countries with a fall in GERD during the crisis but above pre-crisis levels in 2016

	CRISIS		RECOVERY			
	2008	2009	2010–2013*	2014	2015	2016
Austria	100	97	110[e]	122[e]	123	126[p]
Chile	100	92[b]	108	123[b]	129	125[bp]
Estonia	100	94	146	118	123	108
Germany	100	99	109	116	120	123[e]
Greece	100	90[e]	84	94	108	111[p]
Israel	100	96[d]	106[d]	120[d]	125[d]	129[de]
Italy	100	99	102	107[e]	108	104[p]
Slovak Republic	100	97	162	206	286	199
Sweden	100	94	96[p]	96[p]	104	107[p]
United Kingdom	100	99[e]	101[e]	108[e]	111	114[p]
United States	100	99[d]	101[d]	107[d]	110[dp]	112[dp]
Brazil[†]	100	99	115	133	128	n/a
Singapore	100	82	96	115	n/a	n/a
South Africa	100	93	87	97	102	n/a

Countries with GERD below crisis levels in 2016

	CRISIS		RECOVERY			
	2008	2009	2010–2013*	2014	2015	2016
Finland	100	97	95	84	77	75
Iceland	100	98	79[b]	79	89	92
Latvia	100	67	98	112	105	76
Portugal	100	106	94	83	81	84[p]
Spain	100	99	93	87	88	89[p]
Romania	100	75	75	67	89	93
Mongolia[†]	100	89	91	111	78	94

Source: OECD MSTI, March 2018; data used: Gross domestic expenditure on R&D (GERD) at constant 2010 PPP$, base year = 2008 (index 100).

Notes: *Average values for the 2010–13 period; [†] Country data source is the UNESCO UIS database: UNESCO-UIS Science & Technology Data Center, update from March 2018. Data used: GERD in '000 PPP$ (in constant prices, 2005).

b: time series break; **d:** new OECD definition of data point; **e:** estimated value; **p:** provisional value.

that will have a major impact in the longer term. Given the long cycles from initial concept to successfully deployed breakthrough innovation—sometimes lasting more than four to five decades—the essential groundwork facilitating these radical advances needs to take place now.[19]

In fact, from a historical perspective, the global landscape of investment in science and technology as well as in education and human capital has undergone important positive shifts over the last three decades.[20] Today it is no longer a few high-income economies such as the U.S., Japan, and certain European countries that carry out research and development (R&D), for example. R&D is now a common pursuit or, at a minimum, a serious policy ambition in most economies—including those in Asia where R&D has new momentum. The worldwide estimated total of R&D expenditures has continued to rise, more than doubling over the 20 years between 1996 and 2016, with businesses increasingly bearing the brunt of R&D investments.

This holds true for intellectual property (IP) filings as well, which reached record levels in 2016.[21] The latest figures point to an 8.3% patent filing growth in 2016, much higher than it had been in the previous six years, although that growth is mainly driven by China.[22]

R&D intensity, defined as R&D expenditures divided by GDP, has also been stable or even intensified over recent years, even comparing 2000 with 2016. In terms of world averages, R&D intensity rose from 1.5% to 1.7% in that period.[23] Within the Organisation for Economic Co-operation and Development (OECD) region, growth in R&D intensity has been even more significant—climbing from 2.1% to close to 2.4%, an increase in part also affected by negative or lower GDP growth.[24] Israel and the Republic of Korea have continued to have the highest R&D intensities, at 4.3% and 4.2% respectively. China has maintained its steady increase, reaching 2.1% in 2016.

However, R&D is still highly concentrated in high-income and a very few middle-income economies; the trend is worse for basic R&D, which continues to be conducted mainly in a few high-income economies. Excluding China, in middle-income economies R&D intensity improved only marginally, from 0.5% in 2000 to 0.6% in 2016. Low-income economies still hover around 0.2% to 0.4% across 2000–16, showing how nascent their innovation systems still are. Broadly speaking, the same is true for IP, which is increasingly filed in a growing array of middle- and low-income economies, but nevertheless is still quite concentrated.[25]

Moreover, progress in R&D growth has been less sustained in recent years. R&D growth has slowed and—because of a lag in data—it is still uncertain whether or not the economic upturn for 2017–19 will feed into significantly increased R&D expenditures.

'Global R&D expenditures growth, 2006–16', Figure 1 and Box 1 illustrate R&D developments before and after the economic crisis. Global gross R&D expenditure (GERD) growth fell in the aftermath of the global financial crisis of 2009.[26] In an uncharacteristic anticyclical move, governments stepped in to stimulate R&D effectively.[27] Some slowdown also occurred right after the crisis, with recovery as of 2010 holding up until 2013 but then declining, from 4.8% to 3% in 2016. Tighter government budgets in certain high-income countries and slower spending growth in key emerging countries explain part of this slowdown.

In 2016, GERD grew at 3%, slightly slower than world GDP growth.[28] This rate is also slower than the rate before the crisis, when GERD grew at 6.5% and 6.7% in 2006 and 2007 respectively. Business R&D investments (BERD) returned to faster growth as of 2010. A noticeable slowdown in the following years of 2014 and 2015 occurred, stabilizing at lower levels in 2016 compared with pre-crisis levels.

Across OECD countries, R&D spending grew by only 1.2% in 2016 because of government R&D plateauing; its slight growth was powered by R&D expenditures by higher education institutions.[29] Australia, the Republic of Korea, and the United Arab Emirates are among the high-income countries that markedly increased investments in 2016.[30] In turn, high R&D investing economies such as the U.S., Canada, Israel, Germany, France, and Japan faced a notable drop in R&D expenditure growth in 2016. The U.S., for instance, had only 0.9% growth in BERD (3.1% in 2015) and 1.6% growth in GERD (2.9% in 2015). Related growth in Japan is negative.[31]

Again, not all is doom and gloom. Nine years after the crisis, the worst-case scenario of permanently reduced R&D growth has so far been avoided, thanks to the anticyclical innovation policies and the role of R&D champions such as China, Germany, and the Republic of Korea. Furthermore, R&D funding allocated by governments in the OECD countries showed a strong increase of 2.5% in 2016, with the U.S. being a key driver and with further increases in 2017 for Germany and Japan.[32]

Another partially positive message can be found on the business front. Global business R&D spending is increasing at faster pace in 2016 (4.2%) than in 2015. Thankfully the loss in momentum we feared in the GII 2017 has not materialized for world aggregate spending. In the OECD, however, the opposite is observed. According to the latest OECD data, real business R&D expenditure grew by only 0.9% in 2016, compared with 2.2% in 2015 and 4.1% in 2014.[33]

But is R&D growth currently aligned with growth in the economy in a sustainable way? In the absence of complete aggregate data, solid published data—including from our GII Knowledge Partner PwC's Strategy&—indicate that the top 1,000 and 2,500 world R&D companies raised their R&D expenditures between 2015 and the first half of 2017 as part of six consecutive years of increases in R&D investments by the top private R&D spenders.[34] The R&D expenditures of the top 1,000 R&D spenders reached an all-time high in 2016 and 2017.[35] Relative to revenue, R&D intensity too is actually the same or higher than it was before the crisis.[36]

Nevertheless, year-on-year growth of corporate top R&D spending is still mostly lower than it was before the crisis. Despite the many challenges that warrant faster rather than slower growth in innovation expenditures, companies fear that the increasing prospect of economic nationalism will soon have a sustained negative impact on innovation expenditures.[37] For example, China's corporate R&D spending—having experienced double-digit growth rates for many years—declined for the first time in 2016.

Turning to the future, as governments prepare policies to sustain the current growth momentum, a focus on R&D and innovation should be a priority. Looking forward, if innovation expenditures are aligned with economic growth over the next years, what would this mean for future innovation scenarios? What if India and other emerging countries in Asia, and hopefully also in other world regions, followed the high innovation expenditure and patenting growth of China in the next several years? Such dynamics could create the basis of productive knowledge spillovers as well as opportunities for collaboration and for the generation of new knowledge and innovation.

Part and parcel of encouraging these dynamics is an active approach to better explaining the relationship of innovation in general and R&D expenditures in particular to growth. The second element of this goal is the harder but more important task of practically ensuring that economic gains from innovation are also materializing in terms of employment and wage growth in developed and developing countries alike. At the moment, upcoming new technology advances such as industry 4.0, automatization and robots, and artificial intelligence are often seen more as threats than opportunities.[38]

At its best, innovation is not only a driver of economic growth but also a wellspring of solutions to pressing societal matters such as aging, pollution, and the spread of diseases. The impacts that innovation has achieved and will continue to achieve in the near future are worth more than money and percentage point increases in economic growth. They are central to overcoming important challenges that mankind faces in the 21st century.

With this in mind, the 2018 GII edition on the theme of 'Energizing the World with Innovation' elaborates on the opportunities and challenges of the current and future energy innovation landscape. The world will continue to be powered in the context of increased energy demand and increasing concerns with environmental sustainability. This edition of the GII shows that innovation is squarely in the centre of this effort.

Energizing the world with innovation

Global energy demand is reaching unprecedented levels as a result of a growing world population along with rapid urbanization and industrialization, particularly in developing and emerging economies. Projections indicate that by 2040 the world will require up to 30% more energy than it needs today.[39] At the same time, conventional approaches to energy supply—particularly in cities—are unsustainable in the face of climate change. This requires shifting towards cleaner and more efficient methods of producing energy through traditional sources as well as scaling up the use of renewable sources.[40]

As a result of these challenges, higher levels of technological and non-technological innovation are needed on the supply side of the energy equation (including cleaner energy sources), the demand side (including smart cities, homes, and buildings; energy efficient industries; and transport and future mobility), and in enabling technologies for the optimization of energy

BOX 2

Innovation, energy, and the United Nations

In 2015 the United Nations (UN) Member States adopted the 2030 Agenda for Sustainable Development (the 2030 Agenda) and the Paris Agreement.[1] Both recognize that effective national innovation systems are key to promoting scientific and technological solutions that lead to improvement in energy efficiency systems.

The 2030 Agenda and its 17 Sustainable Development Goals (SDGs) and 232 indicators apply to all countries universally and set out an ambitious global path towards a sustainable future for all. Goal 7 calls for 'access to affordable, reliable, sustainable and modern energy for all'. It highlights international cooperation to facilitate access to clean energy research and technology and promote investment in energy infrastructure and clean energy technology. The UN General Assembly also emphasized the importance of access to energy in a recent resolution.[2] The majority of the 17 SDGs rely on technology and innovation as a means of implementation, and all are interlinked. Goal 9 explicitly refers to innovation and to several specific innovation factors referenced in the GII.[3] The High-level Political Forum (HLPF), which has a central role in the global review of the 2030 Agenda, will meet from 9 to 18 July 2018, coinciding with the GII launch on 10 July 2018.[4]

Energy production and use account for two-thirds of total global greenhouse gas emissions and 80% of CO2; they are closely linked with climate change. The Paris Agreement—which entered into force in 2016 under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC)—brings together countries in a common effort to address climate change. Article 10.5 of the Agreement explicitly recognizes the critical role of technological innovation for an effective response to climate change also helping to accelerate the implementation of nationally determined contributions (NDCs), national adaptation plans, and mid-century (2050) strategies to achieve the Paris Agreement.

The GII provides countries with a data-based tool for policy making and contributes to the shared endeavour of achieving the SDGs and the full implementation of the Paris Agreement. WIPO GREEN also promotes clean energy innovation and diffusion by connecting those seeking solutions with technology and service providers.[5]

Notes

Notes for this box appear at the end of the chapter.

systems (including smart grids and new advanced energy storage technologies).

The chapters of the 11th edition of GII explore these issues and illustrate the contribution innovation makes to addressing and solving the energy equation in specific geographies and contexts. They also take a candid look at the obstacles and rigidities that could stand in the way of such innovations.

Five messages emerge from this year's GII theme:

1. Innovation has a key role in meeting increasing global energy demand.
2. Energy innovations are happening globally, while objectives differ across countries.
3. New energy innovation systems need to emerge, with efforts along all stages, including energy distribution and storage.
4. Obstacles to the adoption and diffusion of energy innovations remain numerous.
5. Public policy plays a central role in driving the energy transition.

Innovation has a key role in meeting increasing global energy demand

Access to energy is a prerequisite for maintaining a basic standard of living and economic development, and—in the context of the GII—is a necessary input for innovation. Yet access to energy eludes millions around the world. For many developing countries, energy access is a basic element of equality (Chapter 13).

Innovation is a major driver in the energy transition currently underway.[41] Technological development is accelerating and renewable energy costs have decreased at a remarkable pace over past decades (Chapter 3).

The Kyoto Protocol and the Paris Climate Change Accord have placed an increased focus on renewable energy, and on its integration with innovative local distribution and storage solutions (see Box 2). This trend reflects a commitment to decarbonize the economy, and is driven by the falling costs and increased competitiveness of these technologies (Chapter 2).

Lower costs of renewable energy technologies have combined with increasing energy efficiencies. Solar photovoltaic (PV) module costs have fallen by about four-fifths in just the six years from 2010 to 2016.[42] Onshore wind is one of the most competitive sources of new generation capacity.[43] Offshore wind and concentrated solar power (CSP) technologies are becoming relevant energy supply options. Technologies for previously fringe energy sources, such as tidal and geothermal power, are entering the market as genuine players in the contemporary energy space (Chapter 6). The potential of biomass as an energy source has significantly heightened as a result of new technologies that can convert a much wider variety of biomass into commercial biofuel. Many economies also see the energy transition as a way to achieve energy independence from external sources (Chapter 8 addresses the example of India).

New energy innovation systems need to emerge.

The transition to a global low-carbon energy sector can stimulate employment and economic growth. Recent employment estimates show that the transition to a green economy would lead to a net increase of approximately 18 million jobs across the world.[44] Increased economic growth would be generated by higher investment in renewables and energy efficiency, and enhanced through pro-growth policies, particularly carbon pricing (Chapter 3).

Energy innovations are happening globally, while objectives differ across countries

Energy innovations can have disruptive effects across many sectors. For example, battery storage technology is acting as a leap enabler, allowing off-grid customer self-sufficiency and self-production thanks to the rapid development of small-scale renewable technologies. A breakthrough in the cost of lithium-ion batteries is effectively transforming the automotive industry. Ultra-high voltage lines and smart grids are opening the possibility that power and electricity can be transported across long distances, even countries.

Distributed energy generation, the digitalization of energy systems, and the coupling of diverse energy applications are major innovation trends that are transforming the energy sector. Smart grids and digital energy in particular are heavily disruptive of current structures and innovation systems. Distributed and decentralized energy generation, combined with information and communication technology (ICT) developments, are transforming the way power systems are operated and regulated (Chapter 3). Power storage technology can play an active role in modulating the supply-demand of renewable energies (Chapter 12). The emergence of intelligent networks has the potential to change the role and business models of distribution companies and present opportunities for small innovative businesses. This is effectively leading to a 'democratization of electricity'. Customers and end-users have unprecedented access, control, and choice (Chapter 2).

Examples of energy innovations flourish around the world, showing that innovation in the energy sector is not the privilege of more advanced or high-income economies. The potential of emerging economies for the adoption and deployment of renewable energy technologies is enormous. China's rapid expansion of PV facilities has attracted worldwide attention.[45] India and China are delving deeper into the downstream applications of PV technologies, including PV-hybrid plants and PV-grid integrations (Chapter 11). PV technologies can supply electricity to populated as well as remote areas due to its modularity.

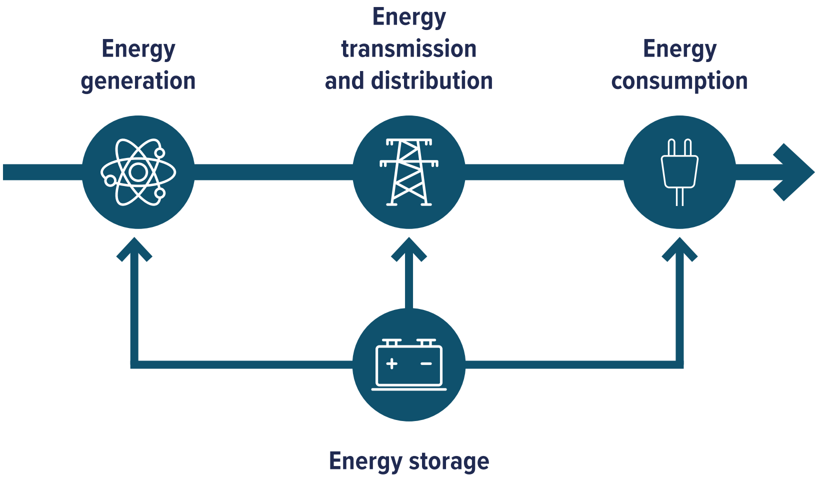
Breakthrough innovation can also happen at the grassroots level. Small-scale renewable systems to provide electricity to people living far from the grid are on the rise. Grassroots communities in Sub-Saharan Africa are applying simple innovations to improve their production and use of woodfuel in ways that address their practical needs while also addressing global challenges (Chapter 9). The adoption of energy innovations in developing countries also offers them the opportunity to leapfrog because conventional energy sources and the associated institutions and regulations are not yet fully installed.

New energy innovation systems need to emerge, with efforts along all stages, including energy distribution and storage

The global energy transition requires a change in innovation systems to one where the production of knowledge and technology for the energy sector is encouraged by means of technological linkages between large companies and their suppliers. Indeed, private-sector investment is of central importance to the new energy ecosystem. This new ecosystem integrates small business innovators through corporate venture capital and with support of technological institutions (Chapter 7). How well companies innovate with new types of energy and distribution technologies will determine their ability to survive the energy transformation

Figure 2.

Stages of the energy system value chain



and to compete against the many start-ups and entrepreneurial firms eyeing the energy market (Chapter 2).

Innovation has been uneven across the different stages of the energy system value chain (Figure 2).[46]

There is an increasing market need for energy storage technologies to act as reliable buffer systems, creating an opportunity for new disruptive technologies to enter the market (Chapter 6). Given the rapid growth of renewable energy development, more energy transmission technologies are needed to cope with the imbalance between energy supply and demand (Chapter 12). This imbalance also calls for more flexible energy systems and for innovation in technology solutions that support the integration of variable renewable energy.[47] Energy waste disposal, including but not limited to nuclear waste or, for example, the recycling of batteries, is also in need of further innovative solutions.

In contrast to global commitments by governments and industry in favour of the energy transition, it is often debated whether the world is investing enough in technologies and projects supporting it, and whether R&D and innovations are being produced at the necessary levels and speed to enable this transition.

Global private-sector investment in green energy sources and inventions (patents filed) in energy technologies have grown at unprecedented levels in the past decade. Both have remained high in recent years, but have experienced slower growth since 2011. This slowdown could be a sign of existing obstacles in the diffusion of energy innovations.[48]

In the period 2004–17, the world invested US$2.9 trillion in renewable energy sources.[49] The period 2004–10 was characterized by a boom in investment, with a compound annual growth rate (CAGR) in investments equal to 32%. In contrast, in the period 2011–17, these investments have stagnated.[50] The levels of investment recorded in 2017 are 2% higher than those registered in 2016, but remain 13% lower than the record set in 2015 of US$323.4 billion of new investment in renewable energy.

The 2018 *Global Landscape of Renewable Energy Finance* also highlights waning growth in annual investments in renewable energy in 2016.[51]

A slowdown can also be observed in the growth of green energy-related patents. WIPO's *World Intellectual Property Indicators 2017* showed that—first and foremost—patent applications in energy-related technologies in categories such as solar energy, fuel cells, wind energy, and geothermal energy significantly increased over recent years, up until 2013.[52] Since then, however, patent applications in the field of energy-related technologies have declined. A decrease has also been observed in the number of cleantech patents granted by the United States Patent and Trademark Office (USPTO): between 2014 and 2016 the number of cleantech patents granted in the U.S. declined by 9%.[53]

According to an analysis done by WIPO for the GII 2018, the total number of patent families and PCT international patent applications in green energy technologies almost doubled between 2005 and 2013.[54] The number of patent families rose from 65,105 in 2005 to 113,457 in 2012, growing annually at about 8.3%. PCT international patent applications rose from 9,043 in 2007 to 17,880 in 2013, growing 12% each year (Figure 3; see also WIPO, 2018b).

Yet this period of accelerated growth in the number of published green energy inventions has been followed by a period of deceleration—even a slow decline. The number of published green energy patent families peaked in 2012—with the underlying invention usually happening about 18 months before the patent publication. Hence the peak of inventive activity was around 2010. Since then, a decrease in the absolute number of patent families has been observed every year until 2015—a reduction from peak to bottom by 3.8%, from 113,547 families in 2012 to 109,266 in 2015.

Similarly, published PCT international patent applications peaked in 2013, followed by a decrease of 11.4% between 2013 and 2017—dropping from 17,880 to 15,840, an annual decrease of 3%.

With regard to patent families, although most green energy technologies have seen a downward trend in the annual number of patents published since 2012, the decline has been most pronounced in nuclear power generation technologies and alternative energy production technologies. The latter notably include renewable energy technologies, such as solar energy, wind energy, and fuel cells. In contrast, inventions in energy conservation technologies and green transportation technologies have continued to grow, but at a slower pace.

An analysis conducted by the European Patent Office (EPO) for the GII 2018 confirms the above-mentioned slowdown for smart-grid technology. Related inventions as measured by numbers of new patent families show accelerated growth followed by deceleration, and even a decline in the number of internationally oriented smart-grid patent families.[55] Accelerated growth was observed between 2005 and 2011. The number of new patent families in smart-grid technologies grew from 441 to 2,500 in 2005–11. In the same time, the number of internationally oriented smart-grid patent families increased six-fold, from fewer than 200 in 2005 to 1,168 in 2011. In 2012 the trend changed. While the growth of new smart-grid patent families slowed, the number of internationally oriented smart-grid patent families dropped considerably by 41%, to 685 by 2014.

Why are these slowdowns or declines in green investment taking place in the face of increased need for energy innovation?

The reasons for green investment and green energy patenting slowdown are not entirely clear. Many factors could be at play, including a lack of prioritization of green energy innovation as a result of declining oil and fossil fuel prices, which decrease the incentives to go green. Also the decreasing profit margins in the area of select renewable energy technologies and the ensuing changing industry structures have led to an overall decrease in patenting, although innovation remains strong.[56] Moreover, potentially the issue is now more one of failing technology adoption than an actual need for a redoubling of innovation. In other words, the green energy technologies required to curb emissions exist, yet the obstacles to their diffusion are manifold.

Obstacles to the adoption and diffusion of energy innovations remain numerous

Energy innovation is taking place mostly on the supply side. One of the biggest challenges with respect to energy innovation seems to be on the side of diffusion and adoption, which are slow and missing incentives. Complementary social and organizational innovations are therefore needed.

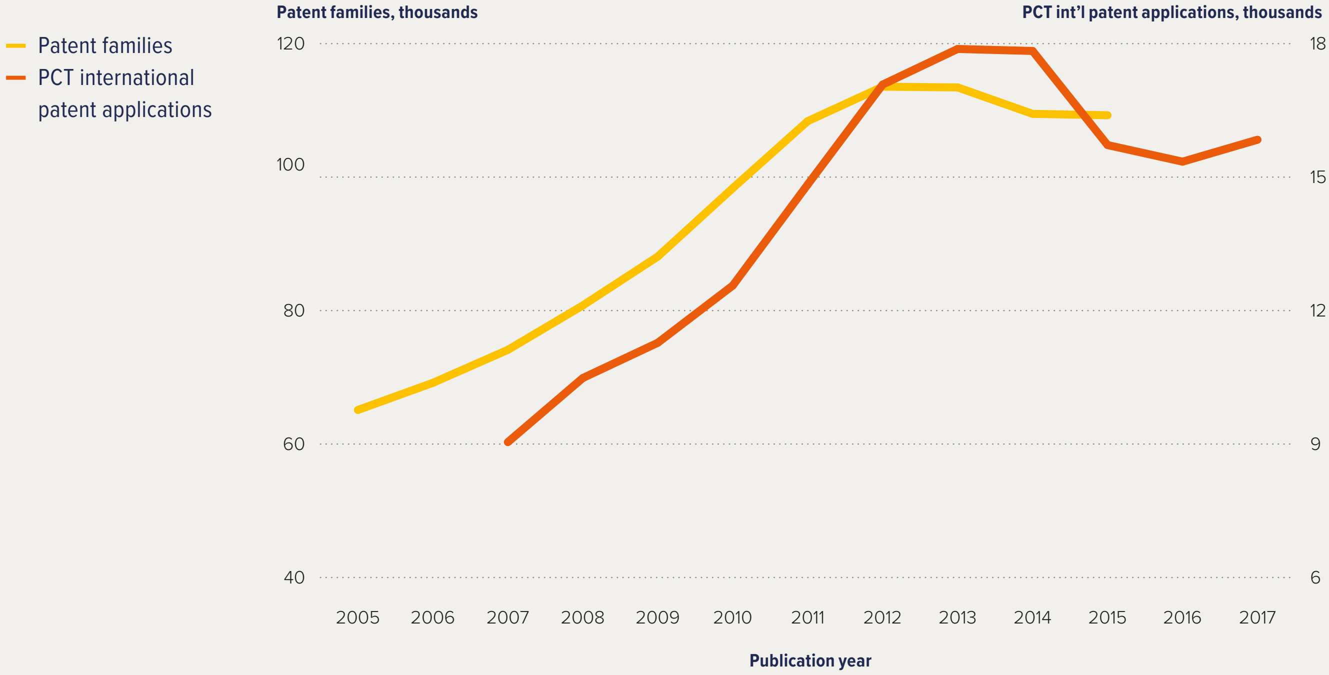
New energy technologies need to demonstrate their viability with respect to their energy performance. The public and private interests that support the dominant—often fossil fuel–based—energy technologies also need to be addressed to allow large-scale adoption.

Moving from research and innovation to the adoption and commercialization of energy innovations remains difficult for developing countries. The costs linked to the commercialization of innovations are often underestimated and under-recorded (Chapter 8).

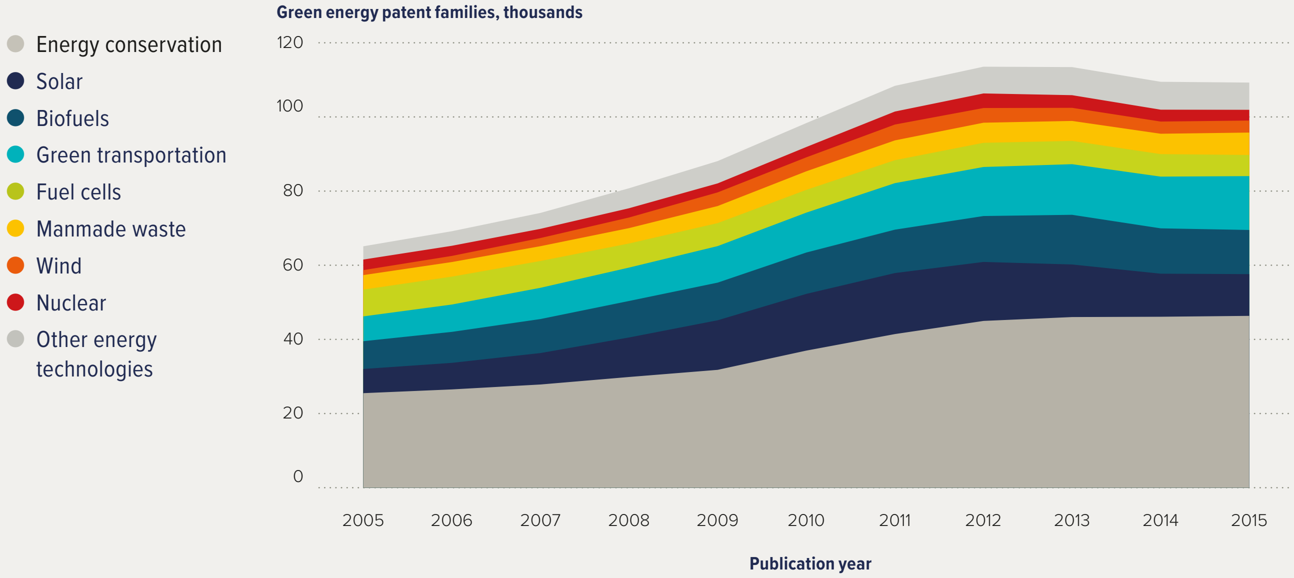
Technology adaptation after technological learning is also very important. This is a challenge that is often underestimated with regard to the availability of skills and technical knowhow in low- and middle-income economies (Chapter 13).

Figure 3.
Green energy patent filings

Number of patent families and PCT int'l patent applications in green energy technologies, 2005–17



Total number of patent families in green energy technologies, 2005–15



Sources: WIPO, Patent families and PCT international patent applications based on WIPO Statistics Database and PATSTAT and WIPO IPC Green Inventory; Total number of patent families based on PATSTAT and WIPO IPC Green Inventory.

Notes: 'Patent families' are those with at least one granted application in one patent office. All patent data refer to published applications.

Innovation efforts around grid infrastructure and grid integration also need additional support both from governments and from industry.[57]

Finally, changes in the consumption behaviour of consumers need to receive strong 'buy in' from society and necessarily must be gradual. This is particularly important for low-income economies that still need to make difficult trade-offs between basic needs (e.g., nutrition, health, housing, education) and energy imperatives. Supplying consumers with the right information about the sustainability of their purchasing decisions, and limiting the ability of firms to 'greenwash' their products and services with false claims, are central to empowering consumer decisions.

The GII helps to create an environment in which innovation factors are continually evaluated.

Public policy plays a central role in driving the energy transition

Delivering on global commitments to mitigate climate change generates additional and positive forces to address the energy equation. However, innovation and technological change alone will not be enough to achieve the energy transition. This transformation requires complementary changes in institutions, business strategies, and user practices.[58] The role of government is vital in implementing strong incentives and regulations to drive the transition. Public policies need to be coherent in supporting this process.

Public authorities therefore play a central role in stimulating energy innovations. Policy makers have a responsibility to provide funding mechanisms that stimulate innovation. Funding mechanisms can take several forms:

- In Viet Nam (Chapter 13), government grants from the Ministry of Industry and Trade and the Ministry of Science and Technology played a central role in stimulating private-sector investments in energy transformation technologies.
- In Brazil, the provisions for mandatory investment in research, development, and innovation (RDI) in the exploration and production of oil contracts and the legislation of mandatory RDI investment in the electric power sector are both successful drivers in making Brazil's power generation the cleanest in the world (Chapter 7).
- Targeted technological innovation programmes can help the development of key and strategic energy technologies (e.g., the Inova Petro programme in Brazil, Chapter 7; and China's Development Plan on Renewable Energy, Chapter 12).
- Government procurement and international collaboration can promote higher levels of private-sector investment in transformational clean energy technologies (Chapter 10).
- Private-sector funding can be incentivized through tax exemptions, favoured tax status for high-tech enterprises and small and medium-sized enterprises, and co-finance loans (Chapter 7, Chapter 10, and Chapter 12).
- The creation of focused research institutes (e.g., the Solar Energy Research Institute of Singapore, or SERIS, is also a possibility (Chapter 11 on Singapore).

Governments often play the role of risk taker both by promoting mechanisms that stimulate investment and the diffusion of technologies with disruptive potential and by supporting projects with high technological risk (Chapter 7). Policy incentives are lacking in sectors with the least progress in innovation for decarbonization such as the heavy industries, freight transport, and aviation (Chapter 3).

Innovations in commercial and financial models are instrumental in the scale-up of renewable energies, which calls for constant innovation in business models and policy design (e.g., renewable energy green power certificates in China, see Chapter 12). Investments in R&D can also scale up grassroots innovations and local communities so that technology development addresses their needs and aspirations, particularly in low- and middle-income economies (Chapter 9).

Technological cooperation and innovation networks are an important element of an innovation ecosystem.[59] International cooperation is often used by emerging economies as a way to learn from other countries and ensure technology diffusion and transfer (Chapter 11, Chapter 12, and Chapter 13). Initiatives that include small businesses in the innovation processes of large companies have succeeded in fostering learning and technology transfer within national innovation systems (Chapter 7 on Brazil).

It is important to seek R&D efficiencies (Chapter 7). Policy monitoring is thus central to understanding whether public and private resources are being properly employed to fulfil a successful energy transition.

The energy transition hence requires much more than technological innovation. It also demands the invention and promotion of innovative organizational, institutional, social, and political structures.

Favourable regulatory frameworks can incentivize energy innovations. Improving national legal and regulatory frameworks can support innovation and contribute to a more conducive environment (Chapter 11). This can also increase investor confidence and favour investments in disruptive technologies. A robust regulatory framework enables new energy technologies to play a significant part in the future of a country's energy supply. For example, a positively evolving regulatory environment has made Australia an ideal place for the rapid penetration of battery technologies into its national energy landscape (Chapter 6). Prescribing a reduction in specific energy consumption norms for energy-intensive industries has resulted in large savings of electricity in India (Chapter 8).

The role of the effect of subsidies on innovation is currently underappreciated. Although subsidies might be critical to fostering the uptake of, for example, solar energy panels by private households, their role in driving innovation on the supply-side across this and other energy technologies is unclear.

IP rights and IP protection can also encourage innovation in renewable energy technologies (Chapter 11 on Singapore and Chapter 12 on China).

The GII 2018 conceptual framework

The GII helps to create an environment in which innovation factors are continually evaluated. It provides a key tool of detailed metrics for 126 economies this year, representing 90.8% of the world's population and 96.3% of the world's GDP (in current US dollars).

Four measures are calculated: the overall GII, the Input and Output Sub-Indices, and the Innovation Efficiency Ratio (Figure 4).

- **The overall GII score** is the simple average of the Input and Output Sub-Index scores.
- **The Innovation Input Sub-Index** is comprised of five input pillars that capture elements of the national economy that enable innovative activities: (1) Institutions, (2) Human capital and research, (3) Infrastructure, (4) Market sophistication, and (5) Business sophistication.
- **The Innovation Output Sub-Index** provides information about outputs that are the results of innovative activities within the economy. There are two output pillars: (6) Knowledge and technology outputs and (7) Creative outputs.
- **The Innovation Efficiency Ratio** is the ratio of the Output Sub-Index score to the Input Sub-Index score. It shows how much innovation output a given country is getting for its inputs.

Each pillar is divided into three sub-pillars and each sub-pillar is composed of individual indicators, for a total of 80 indicators this year.

Further details on the GII framework and the indicators used are provided in Annex 1. It is important to note that each year the variables included in the GII computation are reviewed and updated to provide the best and most current assessment of global innovation. Other methodological issues—such as missing data, revised scaling factors, and countries added or removed from the sample—also impact year-on-year comparability of the rankings (details of these changes to the framework and factors impacting year-on-year comparability are provided in Annex 2).

Most notably, a more stringent criterion for the inclusion of countries in the GII was adopted in 2016, following the Joint Research Centre (JRC) recommendation of past GII audits (see Annex 3 in this report and in previous years' editions). Economies and countries were included in the GII 2018 only if 66% of data were available within each of the two sub-indices and if at least two of sub-pillars in each pillar could be computed. This more stringent criterion for inclusion in the GII ensures that country scores for the GII and for the two Input and Output Sub-Indices are not particularly sensitive to the missing values. As noted by the audit, this more stringent threshold notably improved the confidence in the country ranks for the GII and the two sub-indices, and thus the reliability of the GII rankings (see Annex 3). Although this year these remain constant, the rules on missing data and minimum coverage per sub-pillar will be progressively tightened, leading to the exclusion of countries that fail to meet the desired minimum coverage in any sub-pillar (see Annex 2 for more details).

In addition, this year Annex 1 introduces a box, produced by Nesta, on big data. This new element offers an overview of how new measures based on big data may provide better measurement indicators in the future. The box further delves into how, as our world becomes more digitalized and new data sources become

Figure 4.
Framework of the Global Innovation Index 2018

available, big data is creating opportunities for a more complete understanding of both existing and previously unexplored questions that are difficult or impossible to capture with traditional metrics.

The Global Innovation Index 2018 results

The Rankings section beginning on page xix presents the results in tabular form of all economies included in the GII 2018 for the GII and the Input and Output Sub-Indices. The GII 2018 results have shown consistency in areas such as top rankings and the innovation divide. However, there have also been some new high-level developments this year, as described below.

Movement at the top, led by Switzerland, the Netherlands, and Sweden

In 2018 the GII shows interesting changes in the top 10. Switzerland leads the rankings for the eighth consecutive year, while the Netherlands and Sweden swap their positions, ranking 2nd and 3rd respectively. The U.K. gains one spot, moving to the 4th position. Singapore jumps to the 5th spot, moving up two positions since last year. The U.S., which had been stable at the 4th spot for the last two years, moves down to the 6th this year. Finland follows, gaining one position since 2017 and taking the 7th place. Denmark, which has moved up two positions each year since 2016, loses two positions this year, ranking 8th. Germany and Ireland, instead, remain stable at the 9th and 10th spots respectively.

Figure 5 shows movement in the top 10 ranked economies over the last four years:

1. *Switzerland*
2. *Netherlands*
3. *Sweden*
4. *United Kingdom*
5. *Singapore*
6. *United States of America*
7. *Finland*
8. *Denmark*
9. *Germany*
10. *Ireland*

The top 25 of the GII 2018 also show interesting movement. Among the most significant, Israel moves up by six positions this year, almost reaching the top 10 (11th). China, which entered the top 25 in 2016, continues its spectacular rise and moves up by five places this year, becoming the 17th most innovative economy in the world. Apart from these large movements, the Republic of Korea now takes the 12th place, losing one position, while Japan gains one position, making it to 13th place. After leaving the top 10 in 2015, Hong Kong (China) ranks 14th, gaining two positions since last year. France moves down one spot, now ranking 16th. Canada (18th) and Norway (19th) remain stable, while Australia moves up three places, ranking 20th, after previously falling in the rankings for two consecutive years. In turn, Austria (21st) and New Zealand (22nd) lose one spot each; Estonia improves its ranking by one, taking the 24th place and displacing the Czech Republic, which leaves the top 25 this year. Belgium (25th) returns to the top 25 this year after two years.

2018 results: The world's top innovators

The following section describes and analyses the prominent features of the GII 2018 results for the global leaders in each component of the GII and the best performers in light of their income level.[60] A short discussion of the rankings at the regional level follows.[61]

The top 10 in the Global Innovation Index

Switzerland earns the number 1 position in the GII for the eighth consecutive year. It has maintained this top spot since 2011, as well as its number 1 position in the Innovation Output Sub-Index and in the Knowledge and technology outputs pillar since 2012. This year it also gains the 1st spot in the Creative outputs pillar, consolidating its leadership in innovation outputs. Switzerland becomes the 2nd economy in the world in innovation quality, taking the spot of Japan, which ranks 1st this year (see Box 5 on innovation quality). Despite these important achievements, Switzerland loses positions in all innovation inputs pillars except for Human capital and research, where it gains two spots. In this pillar, Switzerland improves in the sub-pillar Research and development (R&D), where it gains six positions and ranks 2nd. At the indicator level, its rank in researchers and R&D expenditures improves considerably and its 3rd positions in global R&D companies and the quality of universities are preserved. Thanks to these gains, the country improves its ranking in the Innovation Input Sub-Index, where it moves to 2nd place, and in

Figure 5.
Movement in the GII top 10

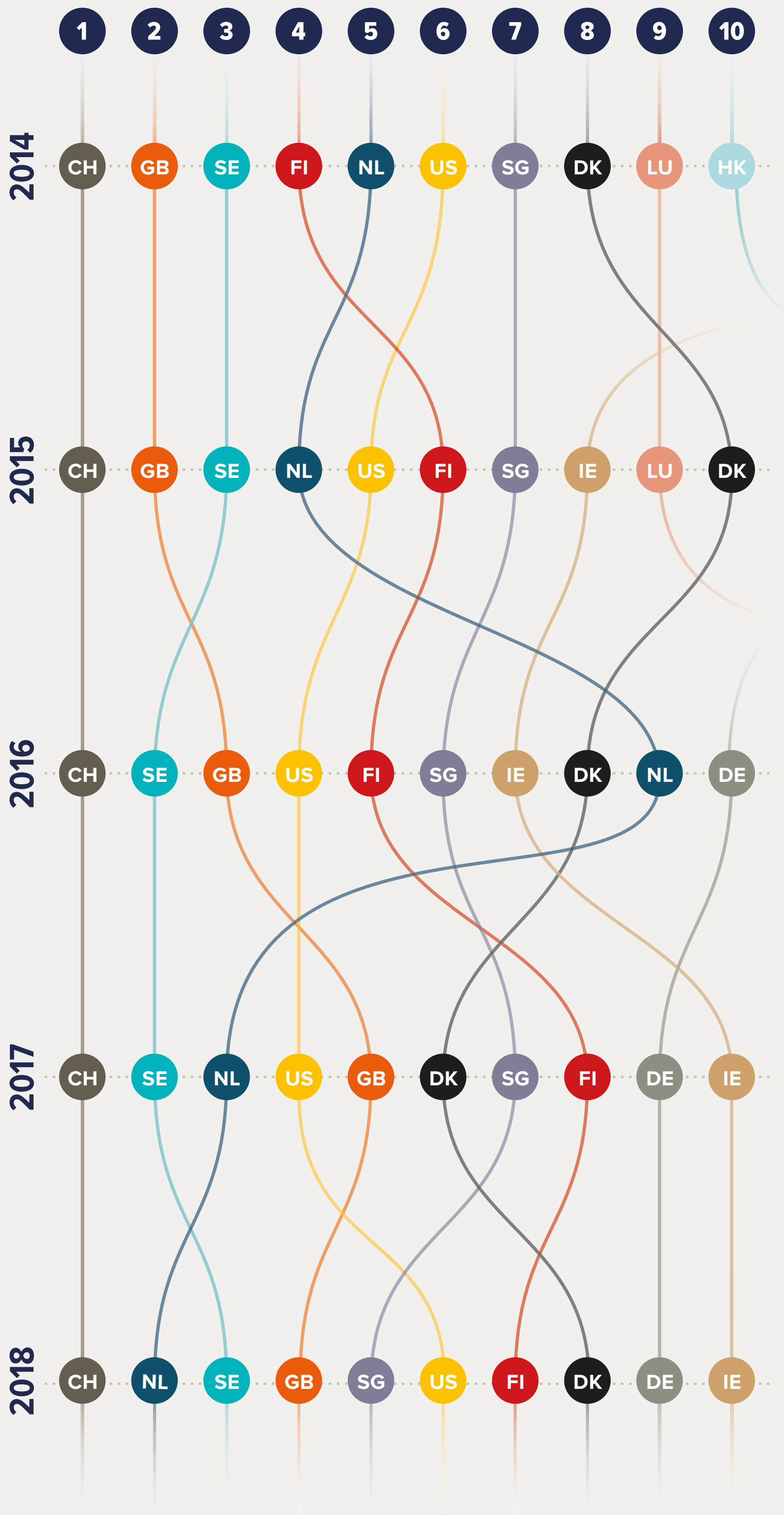
Since 2011 Switzerland has ranked 1st in the GII every year.

In 2015 Ireland entered the top 10 and Hong Kong (China) exited.

After 2016 no country has entered or exited the top 10.

Sweden maintained 2nd place for the second time in 2017.

In 2018 the Netherlands and Sweden traded 2nd and 3rd place.



KEY

DK Denmark	**HK** Hong Kong (China)	**NL** Netherlands	**CH** Switzerland
FI Finland	**IE** Ireland	**SG** Singapore	**GB** United Kingdom
DE Germany	**LU** Luxembourg	**SE** Sweden	**US** United States of America

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Note: Year-on-year GII rank changes are influenced by performance and methodological considerations; see Annex 2. ISO-2 codes are used to identify economies.

the Innovation Efficiency Ratio, where it gains the 1st spot this year. As in previous years, it ranks among the top 25 in all sub-pillars, with only three exceptions: Business environment (44th), Education (32nd), and Information and communication technologies (ICTs, 30th). Switzerland ranks 1st in several important indicators, including patent families in 2 or more offices, PCT patent applications by origin, and IP receipts, while it loses its 1st rank in high- and medium-high-tech manufactures. With its solid output performance and increasingly diversified range of high-quality outputs, Switzerland remains the most innovative economy in the world. Switzerland also presents a few areas of weakness, especially on the input side. These include ease of starting a business, expenditure on education, productivity growth, and ease of getting credit.

Despite the exceptional relative performance of Switzerland and other small countries—as measured by population—in the top 20 (see also Box 3), it is evident that in terms of absolute, unscaled innovation inputs and outputs, large countries overshadow small countries (see Figure 6). In other words, while the innovation performance of Switzerland, Israel, or smaller countries such as Singapore, Malta, Honk Kong (China) relative to their GDP or other scaling factors is outstanding or at least noteworthy, their overall shares in the number of global researchers, global R&D expenditures, total number of patent applications by origin, and publications worldwide is less impressive, particularly relative to the U.S. and China, which dominate these rankings by far.

The Netherlands moves up one spot in 2018, becoming the 2nd most innovative economy in the world. It ranks 2nd in the Innovation Output Sub-Index and 4th in the Innovation Efficiency Ratio. The Netherlands strengthens its already-strong output pillars, maintaining 2nd position in Knowledge and technology outputs and gaining the 3rd spot in Creative outputs. The country keeps its 9th position in the Innovation Input Sub-Index, albeit gaining seven positions in Human capital and research (12th) and four in Institutions (7th). In the former, it improves in all sub-pillars, most significantly in Education (8th), but also in the graduates in science and engineering and tertiary inbound mobility indicators. In Institutions, the Netherlands gains positions in its Regulatory environment and Business environment, especially in regulatory quality and ease of starting a business. On the innovation input side, its best ranks are in Business sophistication, where the Netherlands keeps its 1st spot. In this pillar, it maintains its 1st rank in Knowledge absorption, where it ranks 1st in IP payments and in ICT services imports. This year the Netherlands also gains the 1st position in Online creativity and the 2nd spot in Knowledge diffusion, where it ranks 1st in IP receipts and FDI outflows. Areas of weakness persist and include the sub-pillar Tertiary education (48th) and indicators pupil-teacher ratio, gross capital formation, ease of getting credit, and productivity growth.

Sweden moves down to the 3rd position this year, albeit remaining the top Nordic economy in the GII 2018. It ranks among the top 10 in all pillars except for Market sophistication (12th) where it loses two positions since last year. Sweden also ranks lower in Human capital and research (7th) and Business sophistication (5th). As a result of these downward movements, its rank in the Innovation Input Sub-Index moves down from the 2nd to the 3rd position. Its Innovation Output Sub-Index remains stable at the 3rd spot. Indeed, on the output side, Sweden gains five positions in Creative outputs (6th) and keeps its 3rd spot in Knowledge and technology outputs. In the former, it shows a remarkable improvement in Online creativity, where it ranks 3rd globally. Other sub-pillars where Sweden makes considerable progress are Ecological sustainability (12th, up by eight positions) and Trade, competition, and market scale (24th, up four). At the indicator level, the country keeps its 1st position in PCT patent applications by origin and gains a 1st rank in IP receipts and rule of law. Finally, and as in previous years, areas of weakness include pupil-teacher ratio, GDP per unit of energy use, ease of getting credit, GERD financed by abroad, FDI inflows, and productivity growth.

The United Kingdom (U.K.) moves to 4th place this year, getting closer to the top 3. The U.K. gains three positions in the Innovation Input Sub-Index and keeps its 6th spot in the Innovation Output Sub-Index. The pillar where the U.K. improves its rank is Business sophistication (12th), especially thanks to the gains in Knowledge absorption (24th). At the sub-pillar level, other significant increases are in Knowledge diffusion (16th), Investment (8th), and Creative goods and services (2nd). FDI inflows, market capitalization, cultural and creative services exports, and printing and other media manufactures are among the indicators that contributed to these improved ranks.[62] Despite these important gains, the U.K. loses between two and five positions in Institutions (14th), Human capital and research (8th), and Infrastructure (7th). Items such as ease of getting credit, expenditure on education, and ICT services imports and exports lose the most positions. The U.K. maintains its 1st spot in

Figure 6.

Large high-income economies, and upper-middle income China, overshadow small countries in absolute innovation performance

Source: Authors, researchers and R&D expenditures based on the UNESCO Institute for Statistics (UIS) database; Patents by origin based on WIPO Statistics Database; Scientific and technical publications based on Clarivate Analytics, special tabulations from Thomson Reuters, Web of Science, Science Citation Index (SCI), and Social Sciences Citation Index (SSCI).

quality of scientific publications, government's online service, and e-participation; it loses its 1st spot in ICT and business model creation. Thanks to its historic universities and the quality of its scientific publications, the U.K. is still the 5th world economy in quality of innovation (see Box 5 on the quality of innovation).

Singapore moves up two positions and takes the 5th spot this year. It keeps its top spot in the Innovation Input Sub-Index and gains two positions in the Innovation Output Sub-Index (15th). Singapore ranks in the top 5 in all input pillars, confirming its 1st position in Institutions and gaining a top rank in Human capital and research too, although this is partly due to data becoming unavailable on two indicators—government funding per pupil and school life expectancy. It also holds 2nd position in Business sophistication. In terms of innovation outputs, Singapore maintains its 11th position in Knowledge and technology outputs, while losing three spots in Creative outputs (35th). At the sub-pillar level, Singapore still holds a top rank in Political environment, Regulatory environment, and Tertiary education, while losing it in Investment (2nd this year). Indicators identified as relative weaknesses include expenditure on education, pupil-teacher ratio, environmental performance, productivity growth, and trademarks and industrial designs by origin. Apart from these areas of opportunity, Singapore keeps its 1st place in various indicators, including government effectiveness, regulatory quality, PISA results, IP payments, and FDI outflows. This year Singapore also gains (or re-gains) a top rank in five other indicators: political stability and safety, market capitalization, FDI inflows, high- and medium-high-tech manufactures, and high-tech exports.

The United States of America (U.S.) ranks 6th in the GII this year. Its position deteriorates in both the innovation input and output sides, losing one and two positions in the Innovation Input Sub-Index (6th) and Output Sub-Index (7th) respectively. At the pillar level, the U.S. loses ground in Human capital and research (21st), Infrastructure (24th), and Creative outputs (14th). In Human capital and research, Tertiary education (88th) moves down mainly because data on tertiary enrolment for the U.S. were unavailable this year. In Infrastructure, General infrastructure (21st) is the sub-pillar that loses most spots, with gross capital formation dropping by 10. In Creative outputs, Online creativity (19th) moves down 12 positions as a result of the substitution of the indicator video uploads on YouTube (where the U.S. ranked 1st last year) with a new variable, mobile app creation (14th). Despite these downward movements, the U.S. remains among the largest world contributors in all dimensions of innovation inputs and outputs, including R&D expenditures, patent applications by origin, and scientific and technical publications (see Figure 6). The U.S. also keeps its top ranking in pillar 4—Market sophistication—and improves its position in Institutions (13th) and Knowledge and technology outputs (6th), where it gains 3rd spots in Business environment and Knowledge impact. In the former, it improves in both its indicators. In the latter, the U.S. keeps its 1st place in computer software spending while improving in high- and medium-high-tech manufactures. Other sub-pillars where the country makes some progress are Regulatory environment (12th), ICTs (10th), Knowledge creation (6th), and Intangible assets (35th). The country holds the top rank in many important indicators, including global R&D companies expenditures, quality of universities, venture capital deals, state of cluster development (see also the special section on clusters, which shows that the U.S. has largest number of clusters in the world), quality of scientific publications, computer software spending, IP receipts, ICTs and organizational model creation, and cultural and creative services exports. It also gains a top rank in entertainment and media market.

Finland moves up to 7th position this year from 8th in 2017. Finland's upward movement is the result of improvements on the innovation output side that more than compensate for the drops on the input side. Indeed, Finland drops one spot in the Innovation Input Sub-Index (5th) and gains five positions in the Output Sub-Index (8th). On the input side, it loses between nine and two positions in Human capital and research (4th), Infrastructure (17th), and Market sophistication (15th). At the sub-pillar level, 7 out of 15 input sub-pillars move down, while the sub-pillar Innovation linkages moves from the 5th to the 2nd position. The largest drops are in Investment (15th), Ecological sustainability (39th), and Knowledge absorption (15th). On the output side, Finland gains two positions in Knowledge and technology outputs (8th) and seven positions in Creative outputs (11th). Finland maintains a top spot in patent families and also gains the 1st rank in PCT patent applications by origin and IP receipts and the 2nd rank in the newly introduced indicator, mobile app applications. Weak indicators include pupil-teacher ratio, gross capital formation, GDP per unit of energy use, ease of getting credit, and creative goods exports.

Denmark ranks 8th in this year's GII, dropping two positions from last year. This downward

BOX 3

Do small countries unduly top innovation rankings? They don't.

Whether small countries unduly lead innovation rankings is a legitimate question. This question is regularly brought up as part of technical discussions about innovation rankings or, indeed, any rankings on topics ranging from connectivity to competitiveness.[1]

A look at the 2018 league table of the Global Innovation Index (GII) confirms the surprising presence of a number of countries or economies with small populations, small geographic sizes, or—when compared with large ones such as the United States of America (U.S.) or China—relatively small economies as defined by gross domestic product (GDP). Among the GII top 20, one can find, for example, the Netherlands, the Nordic EU countries,[2] Singapore, Israel, and Luxembourg—in spite of the fact that large economies such as the U.S., Germany, and now China are also part of this top-ranked group. Small economies are equally present among the top-ranked economies in the World Economic Forum's Global Competitiveness Index and the International Telecommunication Union's ICT Development Index, for instance.[3]

Beyond the mere observation that these economies score high, there are at least two reasons to suspect a 'small country advantage'.

- The first reason relates to sheer size issues and the characteristics of innovation systems, which might advantage small countries to perform better at innovation, mostly as a result of agglomeration effects. In country rankings, averages in terms of innovation metrics and not the top scores of the country's most innovative cities or regions are used to assess innovation performance. This might favour really small economies or city states because geographic differences or innovation imbalances are often less accentuated in small economies than in large ones, so a more uniform performance on innovation inputs and outputs prevails across their territories. This holds true for economies with small populations such as Cyprus, Honk Kong (China), Luxembourg, Malta, and Singapore. The small size advantage is most glaring in infrastructure or ICT indices. Connecting households in large, less densely populated territories to broadband, for example, is frequently harder than it is in small city states or small countries. In the case of innovation, a series of spatial factors (e.g., distance, density, factor mobility, governance structure) may facilitate the accumulation, transfer, and absorption of knowledge and increase innovation potential.

  Large countries in turn often have top innovation clusters with top innovation performance, but other regions are less endowed. Take the U.S. It achieves top scores in education, quality of research, excellence of start-ups, and most innovation inputs and outputs in its top innovation clusters such as Silicon Valley. If parts of California or Boston were countries, they could top most, if not all, innovation rankings. Nonetheless, the national performance of the U.S. as measured in the GII is based on average performance across all U.S. states, which is naturally lower. As a result, the U.S. scores lower than Switzerland in the GII.

- The second reason to suspect a small country advantage is more a measurement issue. To make economies comparable in international rankings, composite indices typically scale many if not all of the underlying input and output performance data by size factors. The idea is not to compare absolute innovation inputs or outputs; the objective is to compare relative innovation intensity and performance. For example, rather than comparing the number of researchers or patents from Germany or China directly to the numbers from Iceland and Luxembourg, these data are scaled by population or GDP.[4] The key assumption behind the scaling approach is that there is a (log) linear or proportional relationship between country size and innovation performance. Arguably, however, this proportionality assumption might not be always true, with biases possible in either direction.

Whether or not these two factors actually lead to a significant small country bias or advantage is an empirical question.

For this edition of the GII and based on the 2017 dataset, the statistical independence of the GII score and the GII ranks relative to country size (proxied by population size—but also product and trade diversification, which are proxies for the homogeneity of the country's economic structures) was tested. The core findings of this analysis, described more fully in a paper on uncovering the effects of country-specific characteristics on innovation performance on the GII website,[5] are as follows:

- All editions of the GII demonstrate the positive link between innovation performance and the economy's level of development as measured by GDP per capita, aka the 'GII bubble chart' (Figure 9). In other words, the top-ranked economies, whether large or small, are mostly high-income countries at higher levels of development. What drives which side of the equation is a chicken-and-egg causality dilemma: across countries, higher levels of economic development are associated with higher levels of innovation; and more innovation is associated with higher levels of economic development.
- Turning to the size factors, country size as reflected by population size is not correlated with

the GII score in a statistically significant way. In contrast, when we look only at high-income economies, we note a positive and statistically significant correlation between country size and innovation performance, even when controlling for levels of development proxied by GDP per capita.[6]

When one simply plots the (log of) population of all countries covered in the GII 2017 and high-income countries only against their scores (see Figure 3.1) there appears to be a slight negative relationship between the two variables. However, this correlation is not statistically significant. To the contrary, when controlling for levels of development, a positive but non-significant correlation is seen between country size and innovation performance. Put simply: among all economies, a small size bias does not exist. In contrast, when one only looks at high-income economies, we note a positive and statistically significant correlation between country size and innovation performance when running tests for all relevant economies. In brief: among rich countries, and without implying causality, more densely populated larger economies score better on the GII (red line).[7]

When one deletes oil exporters among resource-rich economies, this finding also applies (pink line). In contrast, when one excludes 'small natural resource–endowed countries'—defined as resource-rich and having fewer than 5 million inhabitants, such as Bahrain or Trinidad and Tobago—mostly at the bottom left of Figure 3.1's high-income panel, the positive relationship becomes statistically insignificant (solid blue line).[8]

The analysis performed for this year's GII then turns to the question of whether countries with more homogeneous economies—that have less diverse sectors and fewer products, and a correspondingly less diversified export portfolio—perform better or worse in terms of innovation performance.

In a nutshell, this analysis finds a negative correlation between a country's GII score and its product concentration.[9] Quite intuitively, the more diversified a country's economy is, the better it does on innovation. When controlled for levels of development proxied by GDP per capita, however, this relationship is non-significant when all countries are included. It remains significant for the group of high-income countries alone. Put simply, and without implying causality, richer economies happen to be more innovative when their economic structures are more diverse.

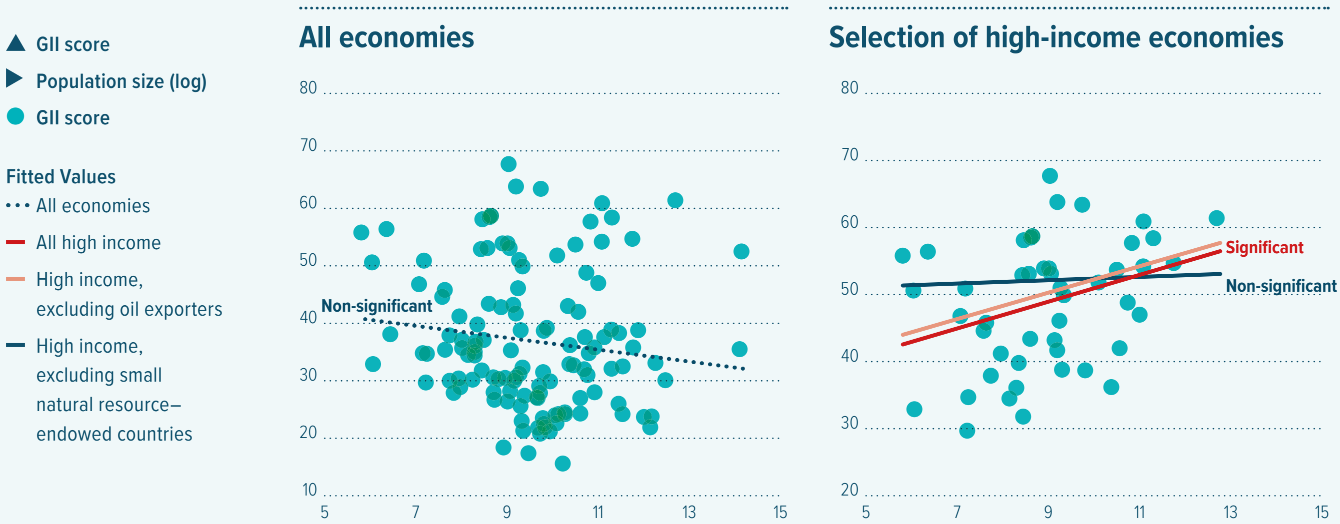
The same holds true for export product concentration but even more strongly.[10] There is a statistically significant and strong negative correlation between a country's GII score and its export product concentration. That is, the more diversified a country's export basket is, the higher its innovation performance as measured by its GII score. This is valid both for all countries and for high-income countries.

Notes

Notes for this box appear at the end of the chapter.

Figure 3.1: GII score vs population size: All economies and a selection of high-income economies

Source: Authors' calculations based on the GII 2017 database and World Population Prospects for population size, available at https://esa.un.org/unpd/wpp/.
Note: All economies panel includes 127 economies; Selection of high-income economies panel includes 48 economies.



movement halts a notable forward shift within the top 10 that began in 2015. This year Denmark loses one spot in both the Innovation Input and Output Sub-Indices, where it ranks 7th and 13th respectively. Downward movements in two input pillars—Human capital and research (6th) and Business sophistication (14th)—contribute to Denmark's fall. The country, however, improves in Knowledge and technology outputs (15th, up one). At the sub-pillar level, Denmark gains the most positions in Knowledge impact (22nd), Knowledge absorption (26th), and Political environment (9th). It ranks in the top 3 in a number of indicators, including researchers, ICT use, environmental performance, and scientific and technical publications. It also achieves a good rank in the new indicator, mobile app creation. Opportunities for further improvement still exist, notably in Tertiary education (25th), General infrastructure (43rd), Trade, competition, and market scale (37th), and Knowledge absorption (26th). As in previous years, relatively weak indicators include graduates in science and engineering, gross capital formation, utility models by origin, productivity growth, and trademarks by origin.

Germany maintains its 9th spot this year, keeping its 17th position in the Innovation Input Sub-index and gaining two places in the Innovation Output Sub-Index (5th). It ranks in the top 25 economies across all pillars and in the top 10 for both output pillars. This year Germany safeguards most of its respectable positions while improving in Institutions (16th), Infrastructure (19th), and Business sophistication (13th). In these three pillars it improves the most in Business environment (15th), Ecological sustainability (31st), Innovation linkages (14th), and Knowledge absorption (22nd). On the output side, Germany gains only in the sub-pillar Knowledge impact (17th, up four). As in previous years, Germany is 1st in logistics performance and patent applications by origin, 2nd in global R&D companies expenditures, and 3rd in state of cluster development and quality of scientific publications. Thanks to these excellent ranks, Germany maintains its 4th spot in the quality of innovation aggregate (Box 5). Despite these important achievements, the country has still opportunity for improvement in areas such as ease of starting a business, expenditure on education, gross capital formation, GERD financed by abroad, FDI inflows, productivity growth, new businesses, and printing and other media manufactures.

Ireland maintains its 10th position this year. On the input side, it improves in Infrastructure (4th) and Human capital and research (17th). On the output side, it gains one spot in Knowledge and technology outputs (4th) and loses six in Creative outputs (19th). As a result of these movements, Ireland exits the top 10 for the Innovation Efficiency Ratio, ranking 13th this year. Ireland ranks in the top 25 across all pillars except Market sophistication (29th), where it loses four positions. At the sub-pillar level, Ireland is still number 1 in Knowledge diffusion, thanks to its 1st spots in FDI outflows and ICT services exports. The country holds top positions in IP payments and FDI inflows and shows a better ranking than in 2017 in a number of important indicators, including tertiary enrolment, researchers, gross capital formation, environmental performance, and high-tech exports. Ireland shows weakness in some particular indicators, including expenditure on education, government funding per pupil, domestic credit to private sector, intensity of local competition, industrial designs by origin, and cultural and creative services exports.

The top 10 in the Innovation Input Sub-Index

The Innovation Input Sub-Index considers the elements of an economy that enable innovative activity across five pillars. The top 10 economies in the Innovation Input Sub-Index are Singapore, Switzerland, Sweden, the U.K., Finland, the U.S., Denmark, Hong Kong (China), the Netherlands, and Canada. Hong Kong (China) and Canada are the only economies in this group that are not also in the GII top 10.

Hong Kong (China) keeps the 8th spot in the Innovation Input Sub-Index this year and ranks 14th overall, up from 16th in 2017. It retains its good position in Market sophistication (2nd) and gains the 1st spot in Infrastructure. Hong Kong (China) improves also in Human capital and research (25th) and Business sophistication (15th), bringing all its input pillars into the top 25. The economy, however, falls seven positions in Institutions, where it moves to the 10th spot. While all the sub-pillars within Institutions move down, the fall in this pillar is also the result of the removal of the variable ease of paying taxes. In six of the 15 input sub-pillars, Hong Kong (China) ranks in the top 10, holding high spots in Regulatory environment (3rd), Ecological sustainability (2nd), Credit (2nd), and Knowledge absorption (3rd). It also gains several places in Education (52nd), thanks to its 2nd spot in PISA results and a newly available indicator, school life expectancy. Weak indicators on the input side include expenditure on education, global R&D companies expenditures, GERD financed by abroad, IP payments, and ICT services imports. Despite these weaknesses, Hong Kong (China) ranks in the top 3 in a number of important indicators, including regulatory quality, ease of starting a business, PISA results, GDP per unit of energy use, market capitalization, JV-strategic alliance deals, high-tech imports, and FDI inflows.

Canada remains in the 10th position in the Innovation Input Sub-Index, maintaining also its 18th spot in the GII rankings. Canada's strength on the input side is a result of having top 25 rankings in all input pillars. Canada shows particular strengths in Institutions (5th) and Market sophistication (3rd), while further improving in Human capital and research (18th). Top 10 sub-pillar rankings for Canada this year are all Institution sub-pillars—Political environment (5th), Regulatory environment (8th), and Business environment (5th); all Market sophistication sub-pillars—Credit (8th), Investment (1st), and Trade, competition, and market scale (7th); and General infrastructure (8th). All these sub-pillars are also identified as relative strengths for Canada. At the indicator level, Canada keeps top 3 ranks in ease of starting a business and venture capital deals.

The top 10 in the Innovation Output Sub-Index

The Innovation Output Sub-Index variables provide information on elements that are the result of innovation within an economy. Although scores on the Input and Output Sub-Indices might differ substantially, leading to important shifts in rankings from one sub-index to another for particular countries, the data confirm that efforts made to improve enabling environments are rewarded with better innovation outputs. The top 10 economies in the Innovation Output Sub-Index this year are Switzerland, the Netherlands, Sweden, Luxembourg, Germany, the U.K., the U.S., Finland, Ireland, and China.

The 10 economies leading the Innovation Output Sub-Index remain broadly consistent with their rankings in 2017, with few shifts and two substitutions: Germany moves upward within the top 10, while the U.S. and Ireland move downward. Finland and China enter the top 10, while the Republic of Korea and Iceland exit. Eight of these economies are ranked in the GII top 10; the profiles of the other two economies, Luxembourg and China, are discussed below.

Luxembourg ranks 4th in the Innovation Output Sub-Index in 2018 and 15th in the overall GII. On the output side, Luxembourg gains one position in Knowledge and technology outputs (14th) and loses the 1st place in Creative outputs (2nd this year). At the indicator level, the country maintains its strengths in cultural and creative services exports, national feature films, and generic top-level domains (TLDs); it also gains strength in PCT patent applications by origin, FDI outflows, and ICTs and business model creation. The only weak indicator among Luxembourg's output indicators is creative goods exports.

China attains 10th position in the Innovation Output Sub-Index this year, up by one from 2017. Indeed, it is the first time that China enters a top 10 ranking in one of the main indices of the GII. China also gains many spots in the GII ranking, moving up to the 17th place this year (see also Box 4 on the innovation divide). Its weight in both the input and output sides of the innovation process is huge. As Figure 6 shows, in absolute terms, China's number of patent applications by origin and scientific and technical publications, as well as its number of researchers, is the highest in the world. China ranks 5th in Knowledge and technology outputs, down one from last year, and gains five spots in Creative outputs (21st). In Knowledge and technology outputs, it moves up in Knowledge creation (4th, up one place) and Knowledge diffusion (22nd, up two places), but loses one position in Knowledge impact (2nd). These positive movements are due in particular to some variables, such as scientific and technical publications (up 12), as well as FDI outflows, computer software spending, and ISO 9001 quality certificates. In the same pillar, China ranks 1st in several important indicators: patents and utility models by origin and high-tech exports. In Creative outputs, China goes up in all sub-pillars, especially in Online creativity (84th, up 20 positions). Looking at single indicators within Creative outputs, China keeps its top spot in two indicators—industrial designs and creative goods exports—and gains the 3rd spot in trademarks by origin. Thanks to these good ranks, the country maintains its first spot among middle-income economies in the quality of innovation aggregate (for more details, see Box 5). Areas of improvement that could help China progress in its rise in the GII ranks are cultural and creative services exports, national feature films, printing and other media manufactures, and Wikipedia edits.

[2018] is the first time that China enters a top 10 ranking in one of the main indices of the GII.

BOX 4

The global innovation divide

With the single exception of China—an upper-middle income economy—a stable group of high-income economies composes the top 25 of the GII.[1] China entered this group in 2016 and has consistently moved up in the rankings to reach 17th place this year. Methodological changes to the GII aside, China's innovation prowess is evident in various areas; it shows some of its strongest improvements in global R&D companies, high-tech imports, the quality of its scientific publications, and tertiary enrolment. China also improves its performance in various key areas of innovation (see Figure 6 and the discussion on the top 10 in this chapter's main text). In particular, China's score in Knowledge and technology outputs continues to be above that of the top 10 group average. This year the difference in scores between China and the top 10 is closing in Institutions, both Market and Business sophistication, and Creative outputs, but it is increasing in Human capital and research and Infrastructure. Within the 11–25 group, China continues to perform above its peers in Business sophistication and Knowledge and technology outputs.

The distance between the top 25 group and the groups that follow remains evident. Figure 4.1 shows the average scores for six groups: (1) the top 10, composed of all high-income economies; (2) ranks 11 through 25, which are also all high-income economies with the sole exception of upper-middle-income China; (3) other high-income economies; (4) upper-middle-income economies; (5) lower-middle-income economies; and (6) low-income economies.

The top 10 and the rest of the top 25

The performance of the top 10 economies continues to be above that of all other economies in the top 25 in most indicators. Yet various economies in the 11 through 25 group show scores above those of the top 10 in at least one pillar. Hong Kong (China) (14th) is the sole economy in that cluster that shows scores higher than those of economies in the top 10 in three pillars: Institutions, Infrastructure, and Market sophistication. Conversely, France (16th) and Belgium (25th) are the only two economies in this cluster with scores below those of the top 10 in every pillar.

This year the Czech Republic drops out of the top 25 group; improved scores in Business environment and a consistent strength in Human capital and research puts Belgium back in the group. In this group Israel (11th) is the fastest mover closing into the top 10. This year Israel's score in Business sophistication is not only above the average of the top 10 but also above that of number 1 ranked Switzerland.

Middle-income economies: China alone in the top 25 with Malaysia and Bulgaria edging closer

Aside from China, which is already in the top 25, the only middle-income economies that continue to edge closer to this group are Malaysia (35th) and Bulgaria (37th). This year Malaysia moves ahead in the rankings with strengths in Tertiary education, Knowledge diffusion, and Creative goods and services. In particular, Malaysia shows top 5 rankings for graduates in science and engineering, ease of protecting minority investors, high-tech imports and exports, and creative goods exports.

Aside from Malaysia and Bulgaria, the divide between the top 11 through 25 group and the other high-income economies and the upper-middle income group remains as wide as in previous years. In most pillars—with the two exceptions of Institutions and the Human capital and research—partly driven by potential methodological considerations, this difference is actually larger than the divide noted in 2017. The few economies in the upper-middle-income group that are among the top 50 are Croatia (41st), Thailand (44th), the Russian Federation (46th), Romania (49th), and Turkey (50th). Lower-middle-income countries in the top 50 are Ukraine (43rd), Viet Nam (45th), and the Republic of Moldova (48th). Among these, Thailand, the Islamic Republic of Iran (65th), and Viet Nam are three middle-income economies noted as climbing in the rankings since 2016. The consistent improvement in performance that is evident in Institutions, Human capital and research, Knowledge and technology outputs (Thailand); in Institutions, Knowledge and technology outputs, and Creative outputs (the Islamic Republic of Iran); and in Institutions for Viet Nam is behind these advances.

Top performers by income group

Analysing economies in relation to their income-group peers can illustrate important relative competitive advantages and help decision makers glean important lessons for improved performance that are applicable on the ground. The GII also assesses results relative to the development stages of countries. This assessment is shown in Figure 7.

Table 1 shows the 10 best-ranked economies in each index by income group. Switzerland, the Netherlands, and Sweden are among the high-income top 10 on the three main indices, and the top 3 in one of them—the Innovation Output Sub-Index.

Interestingly, only a few of these countries perform above the high-income group average—and this occurs in only four pillars. Croatia and the Russian Federation perform higher in Infrastructure; Thailand, South Africa (58th), Colombia (63rd), Peru (71st), Kazakhstan (74th), Mauritius (75th), Azerbaijan (82nd), and Albania (83rd) in Market sophistication; the Russian Federation, Colombia, and Brazil (64th) in Business sophistication; and Croatia, Thailand, Romania, and Islamic Republic of Iran in Knowledge and technology outputs.

Low-income economies show effort but lose momentum

This year the difference in performance between the low-income economies and the lower-middle-income group is less than the one noted in 2017 in four pillars: Infrastructure, Market sophistication, Knowledge and technology outputs, and Creative outputs. In addition, the low-income group performs above the lower-middle-income group in Institutions. Although this may reflect efforts to improve overall performance, a previously bridged gap between both of these groups in Business sophistication opens again this year. This could suggest that previously achieved gains in strengthening institutions might require revisiting in order to keep promoting stronger business environments.

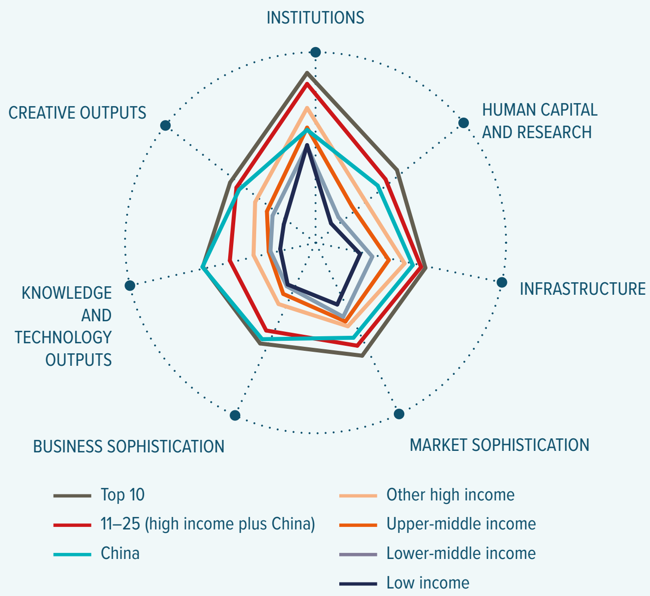
The regional innovation divide

Regional performance as measured by average scores shows that the Northern America is the top performing region (average score of 56.4, 2 economies) with top average scores for all pillars. This region, however, also shows the largest average score reduction this year, followed by Latin America and the Caribbean. Europe (46.67, 39 economies), catching up with Northern America, comes in 2nd, followed by South East Asia, East Asia, and Oceania (43.88, 15 economies), and Northern Africa and Western Asia (33.76, 19 economies). Latin America and the Caribbean (30.31, 18 economies) is in the 5th position, followed by Central and Southern Asia (28.24, 9 economies), and Sub-Saharan Africa (24.53, 24 economies).

This year these scores show that South East, East Asia, and Oceania has the greatest average improvement, followed by Central and Southern Asia, with improved scores in Institutions, Market sophistication, and Knowledge and technology outputs.

Figure 4.1: Innovation divide: Stable at top 10, China moving up

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.



Note

1 The only non-European economies in the top 25 this year are Canada and the U.S. (Northern America); Israel (Northern Africa and Western Asia); Australia, Hong Kong (China), Japan, New Zealand, the Republic of Korea, and Singapore (South East Asia, East Asia, and Oceania).

Among the 10 highest-ranked upper-middle-income economies, nine remain from 2017: China (17th this year), Malaysia (35th), Bulgaria (37th), Thailand (44th), the Russian Federation (46th), Romania (49th), Turkey (50th), Montenegro (52nd), and Costa Rica (54th). The newcomer to this group of the 10 best upper-middle-income performers is Croatia (41st), which displaces South Africa (58th this year).

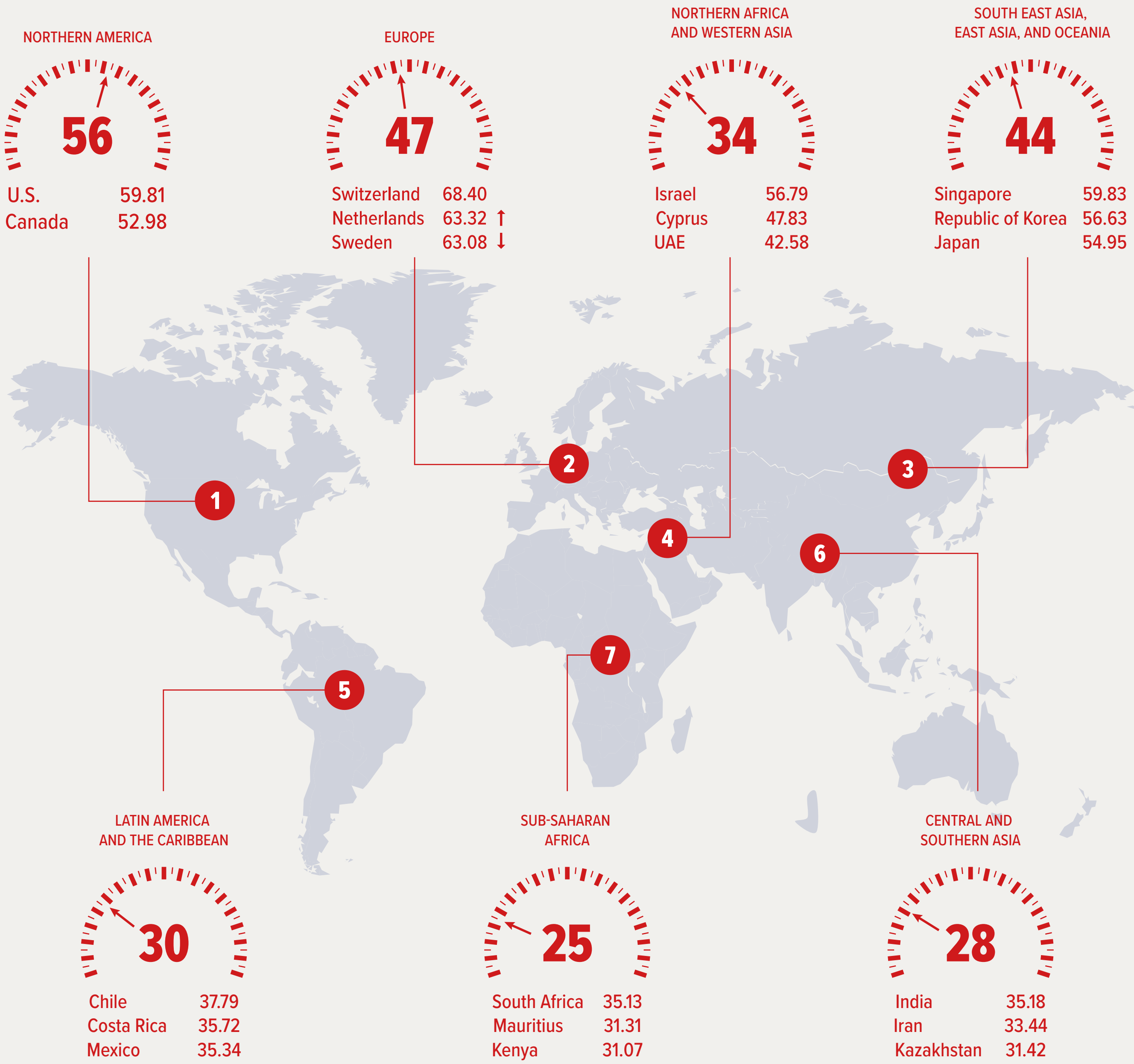
China, Malaysia, Bulgaria, Croatia, Thailand, Romania, and Montenegro are among the group's 10 best-ranked upper-middle-income economies across all three main indices and in the Innovation Efficiency Ratio.

The same analysis for lower-middle-income countries shows that nine of the top 10 countries from 2017 remain in the top 10 this

Figure 7.
Global leaders in innovation in 2018

Every year, the Global Innovation Index ranks the innovation performance of nearly 130 economies around the world.

Top innovation regions by GII score



Innovation leaders by income group

HIGH INCOME (ABOVE $12,236)
- Switzerland.......68.40
- Netherlands......63.32 ↑
- Sweden............63.08 ↓

UPPER-MIDDLE INCOME ($3,956–12,235)
- China.................53.06
- Malaysia.............43.16 ↑
- Bulgaria.............42.65 ↓

LOWER-MIDDLE INCOME ($1,006–3,955)
- Ukraine ....38.52 ↑
- Viet Nam .... 37.94 ↓
- Moldova............ 37.63 ★

LOW INCOME (UNDER $1,005)
- Tanzania............ 28.07
- Rwanda.............26.54
- Senegal.............26.53

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Notes: Position movements are indicated by arrows (↑↓), new entrants by stars (★). Regional averages appear in the centre of the dial. Economies are classified according to the World Bank Income Group Classification (July 2017). Year-on-year GII rank changes are influenced by performance and methodological considerations; some data are incomplete. See Annex 2.

Table 1: Ten best-ranked economies by income group (rank)

	Global Innovation Index	Innovation Input Sub-index	Innovation Output Sub-index	Innovation Efficiency Ratio
High-income economies (47 in total)				
1	**Switzerland (1)**	Singapore (1)	**Switzerland (1)**	**Switzerland (1)**
2	**Netherlands (2)**	**Switzerland (2)**	**Netherlands (2)**	Luxembourg (2)
3	**Sweden (3)**	**Sweden (3)**	**Sweden (3)**	**Netherlands (4)**
4	United Kingdom (4)	United Kingdom (4)	Luxembourg (4)	Malta (7)
5	Singapore (5)	Finland (5)	Germany (5)	Hungary (8)
6	United States of America (6)	United States of America (6)	United Kingdom (6)	Germany (9)
7	Finland (7)	Denmark (7)	United States of America (7)	**Sweden (10)**
8	Denmark (8)	Hong Kong (China) (8)	Finland (8)	Estonia (12)
9	Germany (9)	**Netherlands (9)**	Ireland (9)	Ireland (13)
10	Ireland (10)	Canada (10)	Israel (11)	Israel (14)
Upper-middle-income economies (34 in total)				
1	**China (17)**	**China (27)**	**China (10)**	**China (3)**
2	**Malaysia (35)**	**Malaysia (34)**	**Bulgaria (34)**	Iran, Islamic Rep. (11)
3	**Bulgaria (37)**	**Croatia (42)**	**Malaysia (39)**	**Bulgaria (19)**
4	**Croatia (41)**	Russian Federation (43)	**Croatia (42)**	Turkey (25)
5	**Thailand (44)**	**Bulgaria (44)**	Turkey (43)	**Thailand (33)**
6	Russian Federation (46)	South Africa (48)	**Thailand (45)**	**Croatia (37)**
7	**Romania (49)**	**Romania (49)**	Iran, Islamic Rep. (46)	Costa Rica (43)
8	Turkey (50)	Colombia (50)	**Romania (48)**	**Romania (47)**
9	**Montenegro (52)**	**Montenegro (51)**	Costa Rica (51)	**Malaysia (48)**
10	Costa Rica (54)	**Thailand (52)**	**Montenegro (55)**	**Montenegro (56)**
Lower-middle-income economies (30 in total)				
1	**Ukraine (43)**	Georgia (53)	**Ukraine (35)**	**Ukraine (5)**
2	**Viet Nam (45)**	**India (63)**	**Moldova, Rep. (37)**	**Moldova, Rep. (6)**
3	**Moldova, Rep. (48)**	**Viet Nam (65)**	**Viet Nam (41)**	Armenia (15)
4	**Mongolia (53)**	**Mongolia (66)**	**Mongolia (47)**	**Viet Nam (16)**
5	**India (57)**	**Ukraine (75)**	Armenia (50)	**Mongolia (30)**
6	Georgia (59)	Tunisia (77)	**India (57)**	Kenya (41)
7	Tunisia (66)	**Moldova, Rep. (79)**	Georgia (62)	Egypt (45)
8	Armenia (68)	Philippines (82)	Tunisia (63)	Pakistan (46)
9	Philippines (73)	Morocco (84)	Kenya (64)	**India (49)**
10	Morocco (76)	Kyrgyzstan (85)	Jordan (67)	Jordan (50)
Low-income economies (15 in total)				
1	**Tanzania, United Rep. (92)**	Rwanda (73)	**Tanzania, United Rep. (71)**	**Tanzania, United Rep. (31)**
2	Rwanda (99)	**Uganda (98)**	Madagascar (85)	Madagascar (40)
3	**Senegal (100)**	**Nepal (101)**	**Senegal (90)**	Zimbabwe (69)
4	**Uganda (103)**	**Senegal (102)**	Zimbabwe (99)	**Senegal (70)**
5	Madagascar (106)	**Tanzania, United Rep. (106)**	Mali (100)	Mali (73)
6	**Nepal (108)**	Benin (110)	**Malawi (108)**	**Mozambique (88)**
7	Mali (112)	**Malawi (111)**	**Mozambique (109)**	**Malawi (89)**
8	Zimbabwe (113)	**Mozambique (112)**	**Uganda (111)**	Guinea (102)
9	**Malawi (114)**	Niger (113)	**Nepal (114)**	**Nepal (107)**
10	**Mozambique (115)**	Burkina Faso (117)	Guinea (118)	**Uganda (108)**

Notes: Economies with top 10 positions in the GII, the Input Sub-Index, the Output Sub-Index, and the Innovation Efficiency Ratio within their income groups are highlighted in bold. Year-on-year GII rank changes are influenced by performance and methodological considerations; some country data are incomplete. See Annex 2.

year. These include Ukraine (43rd), Viet Nam (45th), the Republic of Moldova (48th), Mongolia (53rd), India (57th), Tunisia (66th), Armenia (68th), the Philippines (73rd), and Morocco (76th). New this year to the top 10 lower-middle-income countries is Georgia (59th), which displaces Kenya (78th). Five of the top 10 lower-middle-income countries—Ukraine, Viet Nam, the Republic of Moldova, Mongolia, and India—have rankings in the group's top 10 for each of the three indices and the Innovation Efficiency Ratio.

A strong consistency is also evident among low-income countries, with eight out of 10 economies remaining in the top 10 in this group. The United Republic of Tanzania remains the top-ranked low-income country (92nd), gaining four positions from last year. Following in the ranking of low-income countries are Rwanda (99th); Senegal (100th); Uganda (103rd); Madagascar (106th); Nepal (108th); Mali (112th), which takes the spot left by Ethiopia, which is not included in the GII this year; Zimbabwe (113th), which takes the place of Benin (121st); Malawi (114th); and Mozambique (115th). Ranking well across all main indices of the GII, the United Republic of Tanzania, Senegal, Uganda, Nepal, Malawi, and Mozambique are among the top 10 low-income countries. All economies in the low-income top 10, except Rwanda, are in the low-income top 10 in the Innovation Efficiency Ratio.

Effectively translating innovation inputs to outputs: The notion of innovation efficiency

How does one translate massive investments in education, a high number of qualified researchers, and high R&D expenditures into high-quality innovation outputs?

How do economies with severe budget constraints on the input side nevertheless manage to shine with a surprising number of innovation outputs?

These questions are a source of concern to most science and technology ministers and high-level policy makers. Some high-income countries—despite massive investment in innovation inputs—do not generate a correspondingly high level of innovation outputs. In turn, some low- and middle-income countries manage to generate a comparatively high level of innovation outputs despite a more frugal approach to spending on inputs.

Over the years, the GII has made a number of attempts to determine how economies effectively translate innovation inputs into innovation outputs. One effort is encapsulated in the so-called Innovation Efficiency Ratio—simply calculated as the ratio of the Output Sub-Index score over the Input Sub-Index score. The Innovation Efficiency Ratio constitutes an important contribution to understanding the relationship between inputs and outputs, possibly shedding light on the effectiveness of innovation systems and policies.

The 10 countries with the highest Innovation Efficiency Ratios are countries that combine certain levels of innovation inputs with more robust output results (see Table 1 on the best-ranked economies by income group): Switzerland, Luxembourg, China, the Netherlands, Ukraine, the Republic of Moldova, Malta, Hungary, Germany, and Sweden. New lower- and upper-middle-income economies have joined the top 10 most efficient economies this year: the Republic of Moldova and Ukraine are now part of this group. Although Turkey and Viet Nam exit, Viet Nam continues to be within the top 20. Among upper-middle-income economies, the Islamic Republic of Iran and Bulgaria are in the top 20 in terms of efficiency. Aside from Viet Nam, and from the lower-middle-income group, the top 20 includes Armenia.

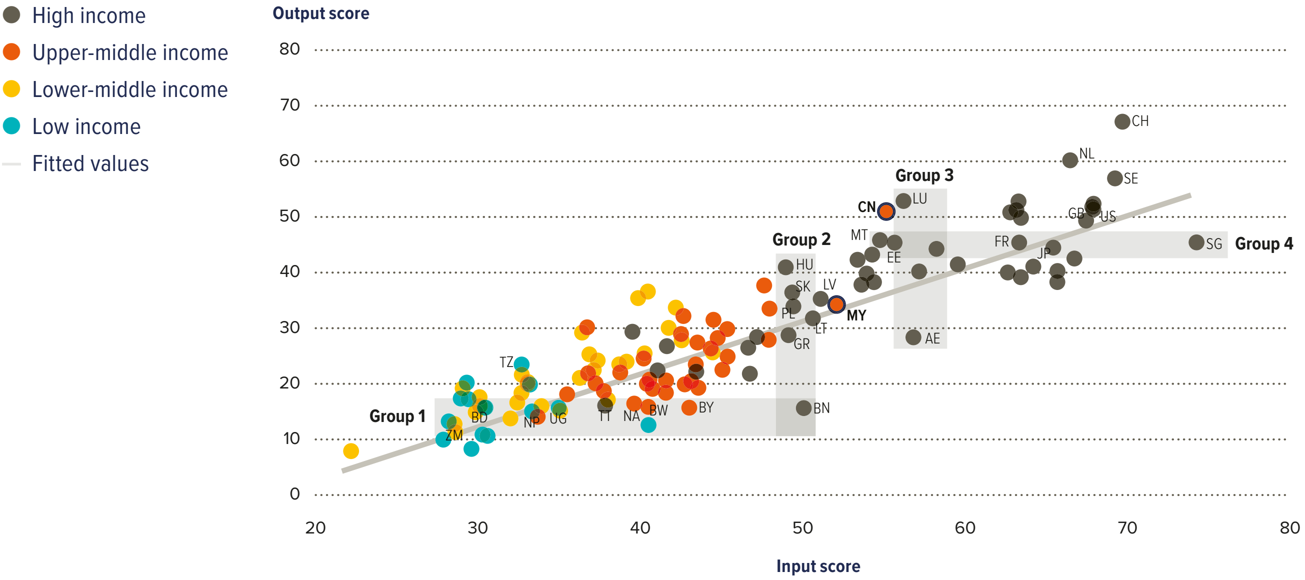
That said, using this ratio to form a cross-country ranking of innovation efficiency has to be taken with a grain of salt.

First, economies might reach a relatively high Innovation Efficiency Ratio as a result of particularly low input scores.[63] As a result, the ratio must be analysed jointly with GII, Innovation Input Sub-Index, and Innovation Output Sub-Index scores, and with the development stages of the economies in mind. Second, this ratio assumes a rather linear relationship between inputs and outputs, which is rarely the case in practice. As evidenced by the many economies that struggle to convert inputs effectively into outputs, sound innovation ecosystems and their successful workings continue to be more like a black box than a function of the ratio of inputs to outputs. Third, from a statistical perspective, taking the ratio of two indices and plugging in the uncertainty bounds for each index (in this case, the input and output sides) results in efficiency ratios that are volatile with high uncertainty bounds that complicate the ability to distinguish the performance between many countries in a relevant way (see the JRC audit in Annex 3).

Another approach, which is more statistically fitting, is to plot the Input-Output performance in a way similar to the way we plot GII scores against the economies' level of development (aka the 'Bubble Chart', see Figure 9; see also Figure 2 in Chapter 1 of the GII 2012 for the same Innovation Output Sub-Index vs. Innovation Input Sub-Index ratio).

Figure 8.

Innovation Output Sub-Index score vs Innovation Input Sub-Index score by income group, 2018



Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Notes: This figure and the related analysis benefited strongly from the comments of our colleagues at the JRC, in particular Michaela Saisana. China and Malaysia (highlighted) are two upper-middle-income economies that manage to move into the high-income group in both innovation input and output. ISO-2 codes are used to identify economies; see page 37 for a list of the codes.

Many of economies covered do indeed sit on the projected line that neatly predicts a linear output-to-input ratio (Figure 8). As expected, high-income economies sit more towards the right, whereas low-income economies sit to the left. But there are important outliers that strongly over- or under-deliver with respect to their efficiency in obtaining outputs for inputs.

First, there are marked differences among high-income countries (ISO-2 codes are provided for countries that are identified in Figure 8). Switzerland (CH), the Netherlands (NL), Sweden (SE), Germany, Ireland, Luxembourg (LU), and also Hungary (HU) stand out for producing many outputs for their given level of inputs. Singapore (SG), Australia, Japan (JP), Hong Kong (China), Canada, New Zealand, and Norway, as well as many resource-rich economies such as the United Arab Emirates (AE), Brunei Darussalam (BN), Saudi Arabia, Qatar, Bahrain, Oman, and Trinidad and Tobago (TT), stand out as high-income economies that—assuming that both inputs and outputs are properly measured—tend to get less 'bang for their buck' (see also Box 3 on country size).

Second, a few upper- and lower-middle economies stand out. Two upper-middle income countries—China (CN) and Malaysia (MY)—manage to move into the group of high-income countries in both innovation input and innovation output, although China strongly overperforms in the said efficiency relationship, whereas Malaysia slightly underperforms. Among lower-middle economies, Ukraine, the Republic of Moldova, and Viet Nam (and other countries such as Armenia, Mongolia, Egypt, and Pakistan) stand out as performing better than would be expected by their income level, whereas Kyrgyzstan, El Salvador, and the Plurinational State of Bolivia underperform.

Third, analysing economies at similar levels of innovation inputs or outputs provides interesting policy insights and comparisons:

- Group 1 countries in Figure 8, for example, have almost identical innovation output scores but rather different innovation input scores. For instance, high-income Trinidad and Tobago (TT) and upper-middle-income countries Namibia (NA), Botswana (BW),

BOX 5

Measuring the quality of innovation

Measuring the quality of innovation-related input and output indicators is essential to understanding their significance. To this end, three indicators were introduced into the GII in 2013: (1) quality of local universities (indicator 2.3.4, QS university ranking, average score of top 3 universities); (2) internationalization of local inventions (indicator 5.2.5, patent families filed in three offices, changed to patent families filed in at least two offices in the GII 2016); and (3) the number of citations that local research documents receive abroad (indicator 6.1.5, citable documents H index). Figure 5.1 shows how the scores of these three indicators add up and captures the top 10 highest performing high- and middle-income economies.

Top 10 high-income group: Japan and Switzerland on top, France in for first time

The top 5 high-income economies in the quality of innovation in 2018 are Japan, Switzerland, the United States of America (U.S.), Germany, and the United Kingdom (U.K.). This year both Japan and Switzerland move ahead of the U.S. in innovation quality. While Japan reclaims the top spot in innovation quality—the position it held in 2016—Switzerland reaches 2nd position for the first time. The Republic of Korea moves up, overtaking Sweden this year, while France enters the top 10 for the first time, with Denmark exiting.

In 2018 Japan gains ground in the quality of its universities with a higher overall score for its three best universities: the University of Tokyo, Kyoto University, and Tokyo Institute of Technology. The country also shows improvement in the quality of its publications. Japan also shares the top score in patent families among high-income economies—it is tied with Switzerland, the Republic of Korea, and Finland.

Since 2017 Switzerland has been among the highest-scoring high-income economies in patent families, and this year it remains one of the world leaders in this indicator. Its scores for the quality of its top three universities—the Swiss Federal Institute of Technology (ETH Zurich), École polytechnique fédérale de Lausanne (EPFL), and the University of Zurich—and the quality of its scientific publications have remained relatively stable over the last five years.

A factor behind the downward movement of the quality of innovation in the U.S. is that the country's score in patent families drops this year—it has been around half of Japan's score for the last two years. The U.S., along with the U.K., has been the top economy in the quality of scientific publications since 2013. For the third year in a row, the U.S. outranks the U.K. in the quality of its universities, taking the 1st place in this indicator globally thanks to top scores for Massachusetts Institute of Technology (MIT), Stanford, and Harvard University.

Germany retains the 4th spot in the quality of innovation, ahead of the U.K. A moderately enhanced quality of universities—led by the Technical University of Munich (TUM), the Ludwig Maximilian University of Munich, and Heidelberg University—along with improved performance in patent families helps Germany remain the 4th economy in the quality of innovation globally. In the latter indicator, Germany scores above the U.S. as well as the U.K., the Netherlands, and France. The U.K. again takes the 5th position in innovation quality: it retains 1st place in the quality of its universities and improves its score in patent families, where the country is 21st among the high-income group for second consecutive year. Its lower absolute scores for its top three universities—Cambridge, Oxford, and University College London—result in a lower overall score in that variable.

The Republic of Korea moves one position above Sweden to 6th, echoing its 2016 quality of innovation ranking. This year not only does this country maintain the highest score in patent families but also improves its performance in the quality of its scientific publications and the quality of its universities, assisted by high scores for Seoul National University, the Korea Advanced Institute of Science and Technology (KAIST), and Pohang University of Science and Technology (Postech). Sweden, on the other hand, improved its score in patent families while also showing a slight reduction in score in the quality of scientific publications and the quality of universities, the result of reduced scores for Lund and Uppsala Universities.

The Netherlands remains 8th for second consecutive year and increasing its scores in all three quality components. The most noticeable improvement for this country comes from patent families, where it ranks 10th globally. The quality of its universities also shows progress, with higher scores for Delft University of Technology, the University of Amsterdam, and Eindhoven University of Technology. This year France enters the high-income top 10 group at 9th place, with scores for patent families above those of the U.K. and for the quality of its scientific publications above those of Switzerland. France also benefits from a high score for the quality of its universities boosted by those for École Normale Supérieure, Paris (ENS); École Polytechnique; and the Pierre and Marie Curie University (UPMC) this year.

Denmark drops out of the high-income top 10 in 2018, standing now at the 13th position globally. In addition to France and Finland's enhanced performance, this is the result of improved scores in patent families and the quality of scientific publications for Canada (11th) and in the quality of universities and patent families for Israel (12th). Finland stays in the top 10 for the second consecutive year with a top score in patent families and an improved score for the quality of scientific publications.

Top 10 middle-income economies: China and India lead with the gap narrowing; Mexico and Malaysia up the most

Among the middle-income group, the top 5 remain steady with China, India, and the Russian Federation at the top, followed by Brazil and Argentina. Mexico and Malaysia are advancing the most in this group.

Although more than half of the countries in the top 10 middle-income group move up in the quality of innovation rankings this year, most of their scores are still significantly below those of the countries in the top 10 high-income group. Without China, the difference in average scores between these two groups is expanding in quality of universities (29.15) and quality of scientific publications (25.59), and more dramatically in patent families (33.13).

China remains the top middle-income economy for sixth consecutive year and is the only country closing the gap with the high-income group, especially in patent families (29th) and quality of scientific publications (14th). In the quality of scientific publications and the quality of its universities, China performs above the high-income group average, and, in the latter indicator, above the score of top-ranked Japan. This reflects the high-quality scores achieved by Tsinghua, Peking, and Fudan Universities this year. Nonetheless, China moves down one position to 17th in the overall quality ranking in 2018, mostly because Austria moves ahead of both Belgium and China.

Although the majority of middle-income group economies depend on the quality of their universities to improve their overall quality of innovation, China is the one middle-income country that shows a more balanced distribution among the three quality components. Other middle-income economies that are beginning to show such balanced distribution this year are South Africa, India, the Russian Federation, Malaysia, and Turkey.

India is 2nd among the middle-income economies for the third consecutive year, with rankings that are edging slightly closer to those of China. This year India remains 2nd in both the quality of its universities and the quality of its scientific publications among middle-income economies. This is possible because of an improved quality of scientific publications and the high quality of university scores for the Indian Institute of Science Bangalore and the Indian Institute of Technology—both Delhi and Bombay. Although India's score for patent families drops slightly in 2018, its overall performance in this indicator still drives it up to the 5th position in the group.

The Russian Federation remains 3rd in the middle-income group, moving up to 27th overall. Although showing a reduction in patent families, the country achieved better performance in the quality of its scientific publications and higher scores for its top three universities: Lomonosov Moscow State University, Saint-Petersburg State University, and Novosibirsk State University.

Brazil is stable as the 4th middle-income economy in the quality of innovation and the 28th overall this year. It is also the highest ranked from Latin America and the Caribbean. Although its score for patent families decreases slightly this year, its improved scores for the University of São Paulo, University of Campinas, and Federal University of Rio de Janeiro, along with a higher quality of scientific publications score, moves it up one position in the overall quality rankings.

Argentina also remains stable in this top 10 group at 5th, moving up one position to 29th in the overall quality rankings. Mexico follows as the 3rd middle-income country in Latin America and the Caribbean, reaching the 6th position. This is the only movement among the top 10 middle-income economies in 2018. Behind this movement are a higher Mexican score for patent families, an improved quality of scientific publications, and better scores for its National Autonomous University of Mexico (UNAM) and the Monterrey Institute of Technology and Higher Education (ITESM).

Although not in the top 10 in either group, Chile and Colombia are the closest other Latin American countries, respectively at 35th and 44th position globally. While all countries in Latin America and the Caribbean in the top 10 perform relatively well in the quality of their universities, they are relatively weak in patent families.

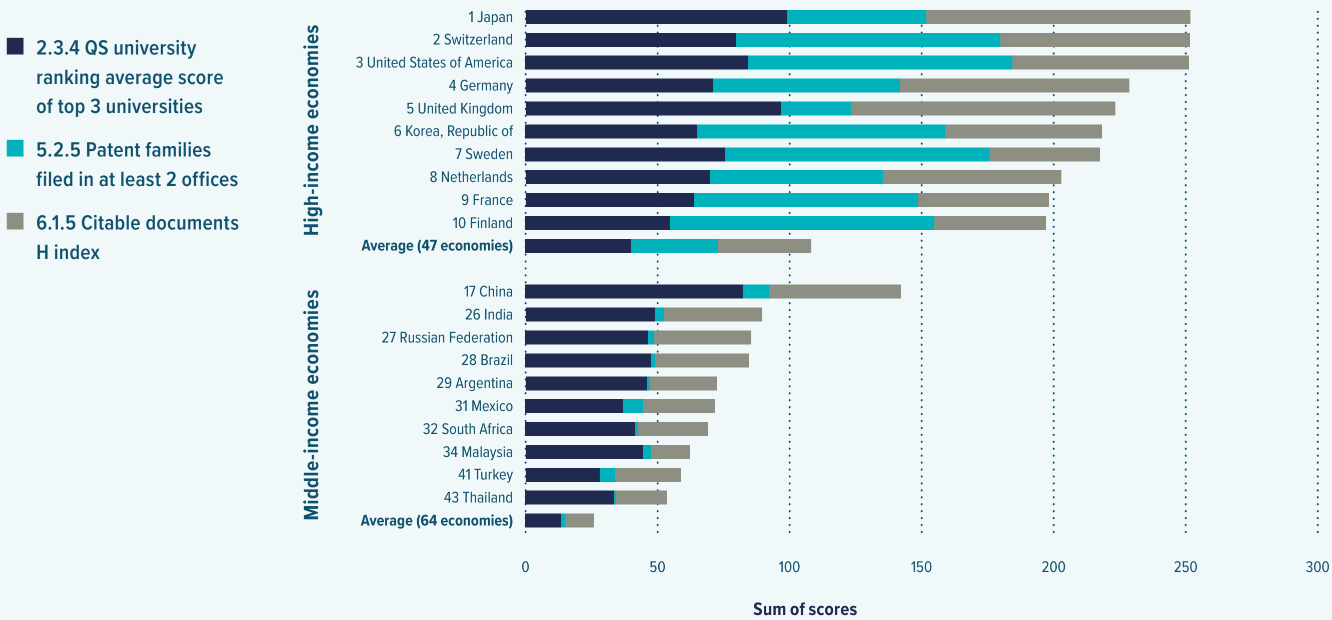
This year South Africa, 7th among middle-income economies, shows a reduced score for patent families, although it displays improvement in both the quality of its universities (with better scores for the University of Cape Town, the University of Witwatersrand, and Stellenbosch University) and a higher quality of scientific publications. Malaysia (34th) shows improvement in its quality of universities with higher scores for both Malaya University (UM) and Putra Malaysia University (UPM); it also has a higher quality of scientific publications score.

In future editions of the GII, and taking note of the fact that many advanced countries want to move beyond quantity to quality, this set of indicators will be refined.

Figure 5.1: Metrics for quality of innovation: Top 10 high- and top 10 middle-income economies

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Note: Numbers to the left of the economy name are the innovation quality rank. Economies are classified by income according to the World Bank Income Group Classification (July 2017). Upper- and lower-middle income categories are grouped together as middle-income economies.



and Belarus (BY) all show innovation outputs at a level similar to that of low-income countries such as Uganda (UG) and Nepal (NP). Furthermore, Tanzania (TZ), a low-income country, is particularly noteworthy for achieving high innovation output scores relative to its input scores.

- Groups 2 and 3 harbour high-income countries with almost identical innovation inputs but with very different levels of innovation output. In group 2, Brunei Darussalam (BN) is the only high-income country with an innovation input score equivalent to that of Hungary (HU) (which is an outlier among the outperformers) and an innovation output score similar to that of Bangladesh (BD) (which performs relatively better for its level of innovation input). Other high-income economies in this group that relatively underperform in their innovation output are Greece (GR) and Lithuania (LT); those that relatively overperform are Latvia (LV), Poland (PL), and Slovakia (SK). Similarly, for group 3, the United Arab Emirates (AE) is the outlier in underperformance and Luxembourg (LU) is the outlier in overperformance.
- Group 4 consists of countries with the same income level (high) and the same level of output but very different levels of input. In this group, a noteworthy example is Estonia (EE), which, with lower levels of input, produces an innovation output score that is the equivalent of some top 20–ranked high-income countries such as France (FR) and Japan (JP).

A total of 20 economies compose the group of innovation achievers—three more than last year.

Even this analysis has to be used with caution. The fact of the matter is that we are still considerably better at measuring innovation inputs (and increasingly also their quality) than we are at measuring innovation outputs. This is not a problem of the GII per se. It is a problem of all existing innovation metrics, which often resort to intermediate innovation outputs such as patents or high-tech production or trade items to proxy the more complex phenomenon of innovation. A key challenge is to find metrics that capture innovation as it occurs in the world today. Direct official measures that quantify innovation outputs remain extremely scarce. For example, there are no official statistics on the amount of innovative activity—defined as the number of new products, processes, or other innovations—for any given innovation actor, let alone for any given country. Most measures also struggle to appropriately capture the innovation outputs of a wider spectrum of innovation actors, such as the services sector, public entities, and so on.

Clustering innovation over- and underachievers relative to GDP: The GII bubble chart

The GII helps to identify economy-specific performance in innovation relative to its level of GDP. Figure 9 on pages 36–37 presents the GII scores plotted against GDP per capita in PPP$ (in natural logs), following a slight methodological improvement over that of previous years.[64] Identical to previous years, the economies that appear close to the trend line show results that are in accordance with what is expected based on their level of development. The further up and above the trend line a country appears, the better its innovation performance is when compared with that of its peers at the same stage of development. Yellow-coloured bubbles in the figure correspond to the innovation leaders, orange correspond to the innovation achievers (innovation leaders and innovation achievers all appear above the trend line), brown represents countries performing as expected for their level of development (some appear above the trend line, some at the line, and some below it), and red represents countries performing below expected for their level of development.

In the group of innovation leaders we find the same top 25 economies as in 2017, with two exceptions: Belgium is moving back into this group while the Czech Republic is moving out. All of these innovation leaders are high-income economies, with the sole exception of China, which belongs to the upper-middle-income group. These economies show mature innovation systems with solid institutions and high levels of market and business sophistication, allowing investment in human capital and infrastructure to translate into quality innovation outputs.

Economies that perform at least 10% above their peers for their level of GDP are called 'innovation achievers.' These are shown in Table 2, listed by income group, region, and years as an innovation achiever. These economies show better results in innovation because they continuously improve their innovation systems, have more structured institutional frameworks, develop linkages that allow knowledge absorption and the flow of highly skilled human capital, and foster a higher integration with international markets. Although these traits translate into proper resource allocation for education, higher levels of economic growth, and income for workers, they are not homogenous among these economies.

Table 2: Innovation achievers: Income group, region, and years as an innovation achiever

Economy	Income group	Region	Years as an innovation achiever (total)
Moldova, Rep.	Lower-middle income	Europe	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Viet Nam	Lower-middle income	South East Asia, East Asia, and Oceania	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
India	Lower-middle income	Central and Southern Asia	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Kenya	Lower-middle income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2013, 2012, 2011 (8)
Armenia	Lower-middle income	Northern Africa and Western Asia	2018, 2017, 2016, 2015, 2014, 2013, 2012 (7)
Ukraine	Lower-middle income	Europe	2018, 2017, 2016, 2015, 2014, 2012 (6)
Mongolia	Lower-middle income	South East Asia, East Asia, and Oceania	2018, 2015, 2014, 2013, 2012, 2011 (6)
Malawi	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Mozambique	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Rwanda	Low income	Sub-Saharan Africa	2018, 2017, 2016, 2015, 2014, 2012 (6)
Georgia	Lower-middle income	Northern Africa and Western Asia	2018, 2014, 2013, 2012 (4)
Thailand	Upper-middle income	South East Asia, East Asia, and Oceania	2018, 2015, 2014, 2011 (4)
Montenegro	Upper-middle income	Europe	2018, 2015, 2013, 2012 (4)
Bulgaria	Upper-middle income	Europe	2018, 2017, 2015 (3)
Madagascar	Low income	Sub-Saharan Africa	2018, 2017, 2016 (3)
Serbia	Upper-middle income	Europe	2018, 2012 (2)
Costa Rica	Upper-middle income	Latin America and the Caribbean	2018, 2013 (2)
South Africa	Upper-middle income	Sub-Saharan Africa	2018 (1)
Tunisia	Lower-middle income	Northern Africa and Western Asia	2018 (1)
Colombia	Upper-middle income	Latin America and the Caribbean	2018 (1)

Note: Income group classification follows the World Bank Income Group Classification (July 2017); regional classification follows the online version of the United Nations publication Standard Country or Area Codes for Statistical Use, originally published as Series M, No. 49, and now commonly referred to as the M49 standard (April 2018).

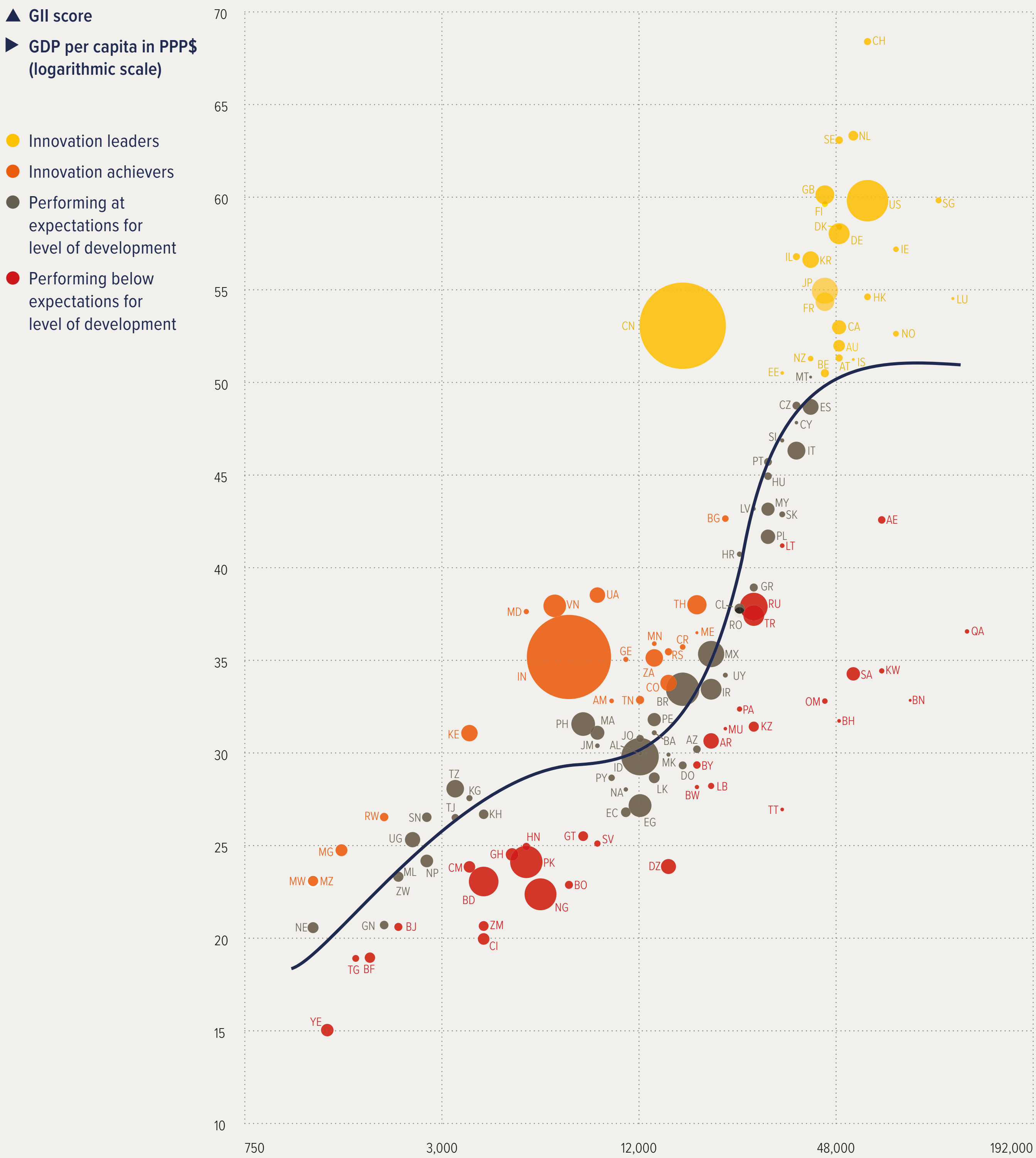
A total of 20 economies compose the group of innovation achievers—three more than last year. Nine countries entered this group this year and six exited.[65] New entrants include Colombia, Tunisia, South Africa, Costa Rica, Serbia, Montenegro, Thailand, Georgia, and Mongolia. Among these, Colombia, Tunisia, and South Africa join this group for the first time. Countries that left this group are Uganda, Senegal, Tajikistan, Malta, Burundi, and the United Republic of Tanzania.

Of these 20 economies—six in total, the most from any region—come from Sub-Saharan Africa. These are followed by five economies in the Eastern region of Europe; three each from the Northern Africa and Western Asia region and the South East Asia, East Asia, and Oceania region; two from Latin America and the Caribbean; and one from Central and Southern Asia region.

Importantly, Kenya, Rwanda, Mozambique, Malawi, and Madagascar stand out for being innovation achievers at least three times in the previous eight years. Kenya, the chief innovation achiever in the region, has been considered as such every year since 2011. For the very first time, South Africa—which boasts a much higher GDP per capita than other countries in the region—also joins this group of achievers from Sub-Saharan Africa. In other regions, this year Mongolia, Thailand, and Montenegro make a comeback after two years, while Georgia, Serbia, and Costa Rica re-enter after three years or more. Most of these economies perform above their peers in terms of having a better business environment, and more accessible investment and financial frameworks. Some are strong in productivity growth, FDI net inflows, and have a strong focus on the use and production of technology and ICT goods or services, as reflected in their high-tech net imports and ICT services exports.

This analysis also allows for the identification of economies that perform at least 10% below their peers for their level of GDP. This cluster includes 34 countries from different regions and income groups: 9 are from the high-income group (6 of these are from the Northern Africa and Western Asia region: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates); 10 are from the upper-middle-income group, including Algeria, Argentina, Lebanon, the Russian Federation, and Turkey; 12 are from the lower-middle-income group, including Bangladesh, Bolivia, Cameroon, and Ghana; and 3 are low-income economies, namely Benin, Burkina Faso, and Togo.

Figure 9.
GII scores and GDP per capita in PPP$ (bubbles sized by population)



Note: The trend line is the cubic spline with five knots determined by Harrell's default percentiles. (R^2 = 0.7064).

ISO-2 Country Codes

Code	Country/Economy
AE	United Arab Emirates
AL	Albania
AM	Armenia
AR	Argentina
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BD	Bangladesh
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BH	Bahrain
BJ	Benin
BN	Brunei Darussalam
BO	Bolivia, Plurinational State of
BR	Brazil
BW	Botswana
BY	Belarus
CA	Canada
CH	Switzerland
CI	Côte d'Ivoire
CL	Chile
CM	Cameroon
CN	China
CO	Colombia
CR	Costa Rica
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
DO	Dominican Republic
DZ	Algeria
EC	Ecuador
EE	Estonia
EG	Egypt
ES	Spain
FI	Finland
FR	France
GB	United Kingdom
GE	Georgia
GH	Ghana

Code	Country/Economy
GN	Guinea
GR	Greece
GT	Guatemala
HK	Hong Kong (China)
HN	Honduras
HR	Croatia
HU	Hungary
ID	Indonesia
IE	Ireland
IL	Israel
IN	India
IR	Iran, Islamic Republic of
IS	Iceland
IT	Italy
JM	Jamaica
JO	Jordan
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KH	Cambodia
KR	Korea, Republic of
KW	Kuwait
KZ	Kazakhstan
LB	Lebanon
LK	Sri Lanka
LT	Lithuania
LU	Luxembourg
LV	Latvia
MA	Morocco
MD	Moldova, Republic of
ME	Montenegro
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MT	Malta
MU	Mauritius
MW	Malawi
MX	Mexico
MY	Malaysia
MZ	Mozambique
NA	Namibia

Code	Country/Economy
NE	Niger
NG	Nigeria
NL	Netherlands
NO	Norway
NP	Nepal
NZ	New Zealand
OM	Oman
PA	Panama
PE	Peru
PH	Philippines
PK	Pakistan
PL	Poland
PT	Portugal
PY	Paraguay
QA	Qatar
RO	Romania
RS	Serbia
RU	Russian Federation
RW	Rwanda
SA	Saudi Arabia
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SV	El Salvador
TG	Togo
TH	Thailand
TJ	Tajikistan
TN	Tunisia
TR	Turkey
TT	Trinidad and Tobago
TZ	Tanzania, United Republic of
UA	Ukraine
UG	Uganda
US	United States of America
UY	Uruguay
VN	Viet Nam
YE	Yemen
ZA	South Africa
ZM	Zambia
ZW	Zimbabwe

Regional rankings

This section discusses regional and sub-regional trends, with snapshots for some of the economies leading in the rankings.

To put the discussion of rankings further into perspective, Figure 10 presents, for each region, bars representing the median pillar scores (second quartile) as well as the range of scores determined by the first and second quartile; regions are presented in decreasing order of their average GII rankings (except for the EU, which is placed at the end).

Northern America (2 economies)

Northern America, the UN-defined region that includes the U.S. and Canada, holds two of the top 25 economies in this year's GII. Both the U.S. and Canada are high-income economies. The U.S. ranks 6th overall this year, down two from 2017, and is in the top 10 economies in both the Innovation Input Sub-Index (6th) and the Innovation Output Sub-Index (7th). Canada keeps the 18th position overall and the 10th in Innovation Input Sub-Index, but loses three positions in the Innovation Output Sub-Index (26th).

Sub-Saharan Africa (24 economies)

For several editions, the GII has noted that Sub-Saharan Africa performs relatively well on innovation. Since 2012 the region has had more countries among the group of innovation achievers than any other region. It will be important for Africa to preserve its current innovation momentum.

As last year, this year South Africa takes the top spot among all economies in the region (58th), followed by Mauritius (75th), Kenya (78th), Botswana (91st), the United Republic of Tanzania (92nd), Namibia (93rd), Rwanda (99th), and Senegal (100th). Among these, Kenya, the United Republic of Tanzania, and Namibia improve their GII ranking compared to 2017, while Rwanda and Senegal remain stable and the other three economies (South Africa, Mauritius, and Botswana) lose positions.

The remaining 16 economies in this region can be found at ranks lower than 100. Nine of them have improved since 2017: Madagascar (106th), Cameroon (111th), Mali (112th), Zimbabwe (113th), Malawi (114th), Nigeria (118th), Guinea (119th), Zambia (120th), and Niger (122nd).

Because of issues with data coverage, Ethiopia and Burundi drop out of the GII this year, while Ghana is added back after having dropped out in 2017 (see Annex 2).

Latin America and the Caribbean (18 economies)

Latin America and the Caribbean includes only upper- and lower-middle-income economies, with three exceptions: Chile, Uruguay, and Trinidad and Tobago, which are all high-income economies. Still leading the region in the GII rankings for another year, Chile (47th) loses one position this year; it is followed by Costa Rica (54th, down one) and Mexico (56th, up two).

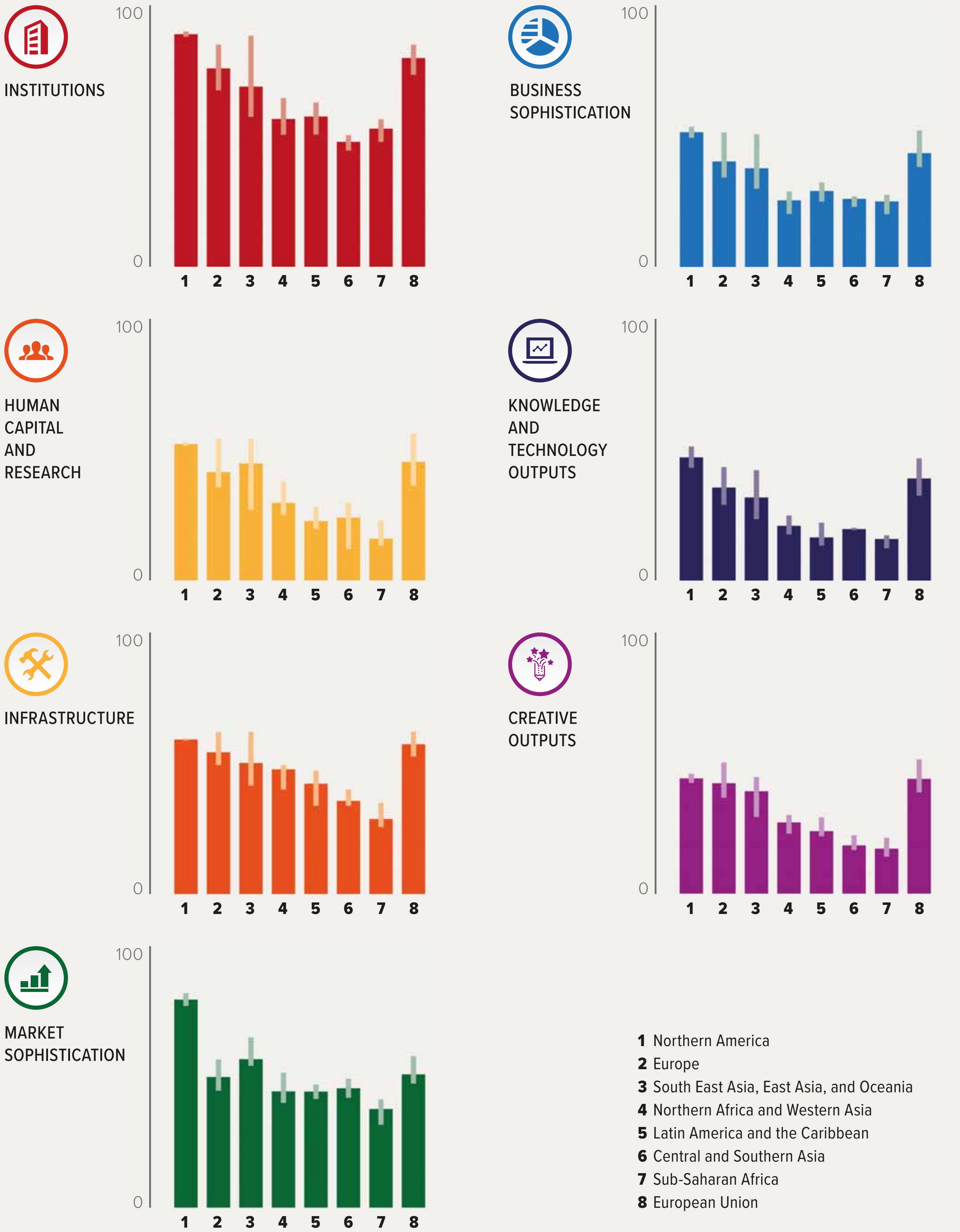
Following these countries, and ranking in the top half of the GII this year, are Uruguay (62nd) and Colombia (63rd). The top 100 economies overall include Brazil (64th), Panama (70th), Peru (71st), Argentina (80th), Jamaica (81st), Dominican Republic (87th), Paraguay (89th), Trinidad and Tobago (96th), and Ecuador (97th). The remaining economies in the region rank below 100 in the GII this year: Guatemala (102nd), El Salvador (104th), Honduras (105th), and the Plurinational State of Bolivia (117th).

Although important regional potential exists, the GII rankings of countries in Latin America relative to other regions have not steadily improved. Until this year, no economies from this region had been identified as innovation achievers. In 2018, thanks to the new approach used to draw the trend line curve of the bubble chart (see Figure 9), two Latin American economies—Costa Rica and Colombia—are identified as innovation achievers.

As last year, and because of the minimum data coverage threshold rule applied in the GII, Nicaragua and the Bolivarian Republic of Venezuela are still unable to be included in the GII 2018 (see Annex 2).

Chile ranks 47th in the GII this year, at the top spot in the region but down one position since 2017. It holds a place in the top 50 economies across three pillars: Institutions (37th), Business sophistication (48th), and Knowledge and technology outputs (48th). Its improvements in 2018 lie in Institutions (37th, up four), and in both output pillars, where it gains one spot in each. In Institutions, Chile improves the most in the sub-pillar Business environment (47th). This

Figure 10.
Median scores by regional group and by pillar



Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Note: The bars show the median scores (second quartiles); the lines show the range for scores between the first and third quartiles. Countries/economies are classified according to the United Nations geographical classification. The European Union overlaps (it includes 27 European countries and Cyprus in Western Asia).

progress is also related to the removal of the variable ease of paying taxes. In Knowledge and technology outputs, the country gains six positions in Knowledge impact (46th), thanks to improvements in productivity growth, computer software spending, and high- and medium-high-tech manufactures. In Creative outputs (58th), Chile improves the most in Creative goods and services (72nd), with a better ranking in printing and other media manufactures. The sub-pillars that lose the most positions are Trade, competition, and market scale, Innovation linkages, and Online creativity and mobile app creation (72nd, a weakness). Chile shows areas of weakness also in Human capital and research in a total of four indicators—government funding per pupil, pupil-teacher ratio, tertiary inbound mobility, and global R&D companies expenditures. Other weak indicators include the state of cluster development, GERD financed by abroad, ICT services exports, and industrial designs by origin.

India has ... outperformed on innovation relative to its GDP per capita for many years in a row.

Brazil is ranked 64th in the GII 2018, moving up five positions since 2017. The country advances the most this year in Knowledge and technology outputs (64th). Institutions (82nd), Business sophistication (38th), and Creative outputs (78th) also gain positions. Brazil's upward movement in Institutions is also due to the removal of the variable ease of paying taxes, where it ranked 124th last year. In Business sophistication, the country gains the most positions in Knowledge workers (43rd), and in particular in GERD financed by business and females employed with advanced degrees, but also in university/industry research collaboration. In Knowledge and technology outputs, Brazil moves up several spots in Knowledge impact (84th), which this year ceases to be a weakness for the country. In this pillar, it improves in important variables such as patents by origin, productivity growth, high-tech exports, and ICT services exports. In Creative outputs, its major gains are in Intangible assets (77th) and Creative goods and services (92nd), and primarily in ICT and business model creation, cultural and creative services exports, and creative goods exports. Despite these improvements, Brazil is relatively weak in the sub-pillars Business environment and Credit and in particular indicators such as ease of starting a business, PISA results, graduates in science and engineering, tertiary inbound mobility, gross capital formation, JV-strategic alliance deals, productivity growth, new businesses, and printing and other media manufactures.

Central and Southern Asia (9 economies)

Economies of the Central and Southern Asia region see further improvements in their GII rankings in 2018, with seven economies improving their rankings and India moving forward into the top half of the GII (Box 6).

India maintains its top place in the region, moving up three spots—from 60th last year to 57th this year. The Islamic Republic of Iran remains 2nd in the region, with a spectacular 10-position jump to the 65th spot (see also Box 4). Kazakhstan moves up four positions, ranking 74th this year. The remaining economies rank in order within the region as follows: Sri Lanka shows a two-position improvement this year (88th); this is followed by Kyrgyzstan (94th), Tajikistan (101st), Nepal (108th), Pakistan (109th), and Bangladesh (116th). Despite the improvements in data coverage in the region, Bhutan does not meet the 66% data coverage threshold (see Annex 2) and is thus excluded from the 2018 GII.

India remains 1st in the region and moves up to the 5th position in the GII rankings among lower-middle-income economies. India has also outperformed on innovation relative to its GDP per capita for many years in a row. This year India ranks 57th in the overall GII, gaining three positions since 2017. The country confirms its rank among the top 50 economies in two pillars—Market sophistication (36th) and Knowledge and technology outputs (43rd)—and is among the top 25 in two sub-pillars—Trade, competition, and market scale (16th) and Knowledge diffusion (25th).

This year India improves in four out of the seven GII pillars: Institutions (80th, up 12 spots), Human capital and research (56th, up 8), Market sophistication (36th, up 3), and Creative outputs (75th, up 10). In Institutions, India gains the most spots in Business environment (106th), mostly thanks to the removal of the variable ease of paying taxes, where it ranked 118th in 2017, and to a much-improved ranking in ease of resolving insolvency. In Human capital and research, Tertiary education (45th) gains several positions, with better rankings in tertiary enrolment and graduates in science and engineering, where it gains the 6th spot globally. Other significant improvements in this pillar are in school life expectancy and researchers. In Market sophistication, it improves both in Credit (70th) and Investment (35th), mostly as a result of gains in ease of getting credit, ease of protecting minority investors, and applied tariff rate. Other gains for India are

BOX 6

Central and Southern Asia: A heterogeneous region with India and Iran most actively pursuing the innovation agenda

Central and Southern Asia is a rather heterogeneous region. Most of its economies belong to the lower-middle-income group, although it does include two upper-middle-income economies, the Islamic Republic of Iran and Kazakhstan, and one low-income country, Nepal.

In terms of the GII rankings, India is the only economy from the region in the top half of the GII, and it has been climbing in the rankings since 2016. The Islamic Republic of Iran (65th), which is moving closer to the top half of the GII this year, has also improved its ranking remarkably since 2014, when it ranked 120th. The other seven economies in this group can be loosely grouped as follows: In the first group are countries whose GII ranks have moved up and down in the last few years. One of them is Kazakhstan, which ranks 74th this year. Sri Lanka has also moved recently, while increasing its ranking since 2017. In the second group are Nepal, Pakistan, and Bangladesh, which have recently boosted their GII rankings, but from low ranks. Finally, Kyrgyzstan has improved its rank considerably in the last few years, and comes in at 94th this year.

Despite the evident differences among them, the economies of this region are achieving good results in a number of important areas, notably Market sophistication and its sub-pillar Investment. Tajikistan, for example, ranks 10th globally. Best-ranked indicators in this pillar include ease of getting credit, microfinance loans, and domestic market scale. Knowledge and technology outputs is another pillar where the region performs relatively well, especially thanks to good rankings in productivity growth. By contrast, Institutions and Creative outputs are the areas where, on average, Central and Southern Asia performs less well.

In sum, some of the economies in Central and Southern Asia are already occupying key leading positions in the global innovation landscape. India and the Islamic Republic of Iran are rapidly improving their GII rankings and gaining top spots in key innovation input and output factors. The other economies in the region can still benefit from realizing untapped potential. Plans for this are underway and need additional support—Bangladesh's strategy to further boost its IT services industry is a good example. The Bangladeshi government plans for this sector aim at training professionals and promoting the use of modern technologies to attract foreign investments, strengthen the export capacity of domestic small and medium-sized enterprises, and increase the value addition of the industry to 1% of the Bangladesh's GDP.[1] First results of these initiatives include the newly opened Samsung R&D centre in Bangladesh, and planned additional investments from global leaders such as International Business Machines Corporation (IBM) and LG in Bangladesh.[2]

Notes

1 BASIS, 2014.
2 ITC News, 2014. See also https://basis.org.bd/resource/About_Industry.pdf.

in Creative outputs, and especially in Online creativity (67th), where it ranks well in the newly introduced indicator, mobile app creation. At the indicator level, India ranks very well in a number of important indicators, including productivity growth and ICT services exports (1st).

Despite the achievements documented so far, India loses ground in Infrastructure (77th), Business sophistication (64th), and Knowledge and technology outputs (43rd). All the Infrastructure sub-pillars move down, with Ecological sustainability (119th) losing the most and becoming one of India's relative weaknesses this year. In Business sophistication, the country drops in all sub-pillars, and especially in Knowledge workers (97th), the result of two newly available indicators—knowledge-intensive employment and females employed with advanced degrees—and Knowledge absorption (66th), where research talent in business enterprises loses several spots from 2017. Despite this fall in Business sophistication, India gains positions in this pillar in a number of important indicators: patent families in two or more offices, IP payments, high-tech imports, ICT services imports, and FDI inflows. In Knowledge and technology outputs (43rd), India loses several positions in Knowledge impact (42nd) while keeping its 55th spot in Knowledge creation and entering the top 25 in Knowledge diffusion (25th). In this pillar, it improves the most in scientific and technical publications, high- and medium-high-tech manufactures, and FDI outflows.

India still has more potential, with the sub-pillar Education and some important indicators marked as relative weaknesses. These include

PISA results, environmental performance, females employed with advanced degrees, new businesses, and entertainment and media market.

Northern Africa and Western Asia (19 economies)

Israel (11th, up by six, the most striking upward move in the region) and Cyprus (29th, up by one) achieve the top two spots in the region for the sixth consecutive year. Third in the region is the United Arab Emirates (38th), which moves down three places from last year.

Seventeen of the 19 economies in the Northern Africa and Western Asia region are in the top 100, including Turkey (50th), Qatar (51st), Georgia (59th), Kuwait (60th), Saudi Arabia (61st), Tunisia (66th), Armenia (68th), Oman (69th), Bahrain (72nd), Morocco (76th), Jordan (79th), Azerbaijan (82nd), Lebanon (90th), and Egypt (95th). Of all the economies in the region, Egypt sees the most improvement in its overall GII ranking, having moved up 10 spots. The other two economies in the region, Algeria and Yemen, rank 110th and 126th respectively.

Israel moves up six places, from 17th to 11th, getting very close to the top 10 and remaining number 1 in the Northern Africa and Western Asia region. Israel is the only economy in the region to rank in the top 10 for any pillar (3rd, Business sophistication; and 7th, Knowledge and technology outputs). This year Israel improves in all pillars, with the most significant gains in Institutions (34th) and Creative outputs (15th). In Creative outputs, Israel improves the rankings of some indicators and comes in 4th in the newly introduced indicator, mobile application creation. At the sub-pillar level, Israel ranks third in Research and development (R&D) and gains the top rank in Innovation linkages. It also ranks 1st in a number of important indicators, including researchers, R&D expenditures, venture capital deals, GERD performed by business, research talent in business enterprise, ICT services exports, and Wikipedia edits. Other top 3 ranks include university/industry research collaboration (3rd) and GERD financed by abroad (2nd). Beyond this, Israel's weaknesses are found mostly in the input side of the GII. These include government funding per pupil, PISA results, tertiary inbound mobility, gross capital formation, firms offering formal training, and GERD financed by business. On the output side, two areas of weakness are found in the pillar Creative outputs: trademarks by origin and printing and other media manufactures.

South East Asia, East Asia, and Oceania (15 economies)

This year all economies within the South East Asia, East Asia, and Oceania region are ranked within the top 100 in the GII. Except for Cambodia and Brunei Darussalam, all other economies in the region are in the top 100 in the Innovation Input Sub-Index, the Innovation Output Sub-Index, and the Innovation Efficiency Ratio.

Seven of these 15 economies rank in the top 25 of the GII: Singapore (5th), the Republic of Korea (12th), Japan (13th), Hong Kong (China) (14th), China (17th), Australia (20th), and New Zealand (22nd). The top four economies in the region also rank in the top 25 overall for both the Innovation Input Sub-Index and the Innovation Output Sub-Index.

Malaysia follows New Zealand, moving up two positions to 35th thanks to increases in most pillars—Institutions (43rd), Human capital and research (31st), Infrastructure (43rd), Business sophistication (39th), and Knowledge and technology outputs (33rd). Malaysia is also among the middle-income economies that move closer to the top 25 this year (see Box 4 on the innovation divide).

Thailand makes enormous progress this year, moving up seven positions and reaching the 44th place overall. It gains between 3 and 15 spots in all pillars except for Infrastructure, where it loses one, and Knowledge and technology outputs, stable at the 40th position (see also Box 4). Viet Nam gains another two positions, ranking 45th this year (see Box 4). Mongolia (53rd) follows Viet Nam, ranking in the top half of the GII this year as well. Brunei Darussalam, the Philippines, Indonesia, and Cambodia rank 67th, 73rd, 85th, and 98th, respectively.

As noted last year (see Box 6 in GII 2017), ASEAN economies are making great progress in innovation and socioeconomic development indicators. In 2018 again, most of the ASEAN economies included in the GII improve their GII rankings. Figure 11 shows the scores of these economies in selected innovation input and output indicators. As noted last year, a certain stability exists at the top of the ASEAN rankings. Singapore has the highest scores among ASEAN members in many of the selected indicators, excluding expenditure on education (topped again by Viet Nam), tertiary enrolment (where data are not available for Singapore, and Thailand leads the ASEAN countries),

Figure 11.
ASEAN scores in selected input and output indicators

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.

Note: No data are available for Lao People's Democratic Republic or Myanmar, which are also omitted from the GII 2018.

gross capital formation (topped again by Brunei Darussalam), ICT service exports (topped again by the Philippines), and trademarks by origin (topped by Viet Nam this year). As noted last year, Cambodia is relatively new in the global innovation landscape. Within the ASEAN group, the economy is second after Singapore in FDI inflows and scores relatively well in the state of cluster development. Despite this, Cambodia is still lagging behind in most of the input indicators selected here. In output indicators, the weakest indicator among those selected is patent applications by origin.

Japan has risen in the GII rankings each year for the last six years, taking the 13th place in 2018.

As for the other economies in the group, Viet Nam shows the best score of the group in expenditure on education and trademarks by origin. It is also performing well in gross capital formation and FDI inflows; at the same time, it has some of the lowest scores in tertiary enrolment, university/industry research collaboration, and knowledge-intensive employment. In the output indicators selected here, Viet Nam has the lowest score of the group in ICT services exports, but ranks well also in scientific and technical publications. This year Thailand is the strongest in the ASEAN group for tertiary enrolment and the second strongest in quality of scientific publications and trademarks by origin. Malaysia ranks 2nd in half of the input indicators selected here—expenditure on education, tertiary enrolment, state of cluster development, and university/industry research collaborations. It also scores well in ICT use and knowledge-intensive employment. In output indicators, Malaysia has the second highest score in the group in patent applications by origin and scientific and technical publications. It also scores well in the quality of its scientific publications and ICT services exports, where, however, its distance from the number 1 in the group, the Philippines, is the greatest among output indicators. Indeed, as we noted last year, the distance between top performers and the other economies is larger in output than in input indicators.

As happens in various countries, the Vietnamese government has assigned responsibilities to ministries, agencies, and local governments to undertake actions to improve Viet Nam's innovation performance guided by the GII and to address missing and outdated data, in collaboration with WIPO. With the knowledge gained, Viet Nam's Ministry of Science and Technology has published a handbook on the GII including detailed guidance on definitions, data sources, and indications of how to access original data. A series of workshops has also been organized to introduce the GII framework to ministries and local governments and to support them in designing action plans to address their assigned mission of improving specific aspects of the Vietnamese innovation system. In a short period of time, GII has been considered to be an important element in the agenda of both central and local governments.

The Republic of Korea (Korea) moves down one position from 2017, ranking 12th this year. It loses three positions in the Innovation Output Sub-Index, dropping from 9th to 12th place, but gains two spots in the Innovation Input Sub-Index, from 16th to 14th. On the input side, Korea improves in Institutions (26th, up nine) and loses positions in Business sophistication (20th), while the other three input pillars remain stable. The country keeps its 2nd spot in Human capital and research and its 1st rank in the sub-pillar Research and development, as well as its 2nd position in the indicator R&D expenditures. On the output side, Korea loses positions in both pillars, with three of the six output sub-pillars moving downward: Knowledge creation, Knowledge diffusion, and Creative goods and services. While the country drops three spots in Knowledge and technology outputs (9th), it maintains its top rankings in patents applications by origin and PCT patent applications and gains it in high-tech exports. In Creative outputs (17th, down by two), Korea also keeps its 1st spot in industrial designs by origin and ranks 8th in the newly introduced indicator, mobile app creation. The country's areas of relative weakness include ICT services exports and printing and other media manufactures on the side of outputs; and tertiary inbound mobility, GDP per unit of energy use, venture capital deals, GERD financed by abroad, ICT services imports, and FDI inflows on the inputs side.

Japan has risen in the GII rankings each year for the last six years, taking the 13th place in 2018. Japan ranks 12th (down by one) in the Innovation Input Sub-Index and 18th in the Innovation Output Sub-Index (up by two). This year it improves its rank in Institutions (8th, up by five), Market sophistication (10th, up two), and Creative outputs (31st, up five). In Institutions, it improves the most in Business environment. In Market sophistication, Japan keeps its 3rd rank in Trade, market scale, and competition, while gaining one spot in Credit (11th). In Creative outputs the country advances in all sub-pillars, especially thanks to major improvements in trademarks by origin and a good rank in the newly introduced indicator, mobile app creation. Japan ranks in the top 10 economies for six sub-pillars: Political environment and Business environment (both 7th), Research and development (5th), Information and communication technologies

(5th), Trade, competition, and market scale (3rd), and Knowledge absorption (8th). Japan ranks 1st in a number of input and output indicators, including GERD financed by business, patent families in two or more offices, patents by origin, PCT patent applications, and IP receipts. Despite these achievements, Japan moves down two spots in Human capital and research (16th), losing positions in Education (49th) and Research and development (R&D, 5th) and the indicators expenditure on education, school life expectancy, tertiary inbound mobility, researchers, and R&D expenditures. Opportunities for further improvement are found in various areas, including in ease of starting a business, ease of getting credit, FDI inflows, productivity growth, new businesses, ICT services exports, and cultural and creative services exports.

Europe (39 economies)

As last year, in this year's edition of the GII, 15 of the top 25 economies come from Europe. This region is home to the top 3 economies of the GII 2018: Switzerland (1st), the Netherlands (2nd), and Sweden (3rd). Following these regional leaders among this group of top 25 are the U.K. (4th), Finland (7th), Denmark (8th), Germany (9th), Ireland (10th), Luxembourg (15th), France (16th), Norway (19th), Austria (21st), Iceland (23rd), Estonia (24th), and Belgium (25th). It should be noted that most of the economies in this region have the fewest missing values, leading them to display the most accurate GII rankings (see Annex 2). This includes the following economies with 100% data coverage in the Innovation Input Sub-Index, the Innovation Output Sub-Index, or both: Denmark, Finland, Germany, France, Austria, the Czech Republic, Italy, Portugal, Hungary, Poland, Romania, and the Russian Federation.

Eighteen economies follow among the top 50 and have maintained relatively stable rankings since 2014: Malta (26th), the Czech Republic (27th), Spain (28th), Slovenia (30th), Italy (31st), Portugal (32nd), Hungary (33rd), Latvia (34th), Slovakia (36th), Bulgaria (37th), Poland (39th), Lithuania (40th), Croatia (41st), Greece (42nd), Ukraine (43rd), the Russian Federation (46th), the Republic of Moldova (48th), and Romania (49th).

The remaining European economies remain among the top 100 economies overall (see Box 7). The region's rankings continue as follows: Montenegro (52nd), Serbia (55th), Bosnia and Herzegovina (77th), Albania (83rd), The former Yugoslav Republic of Macedonia (84th), and Belarus (86th).

France moves down one spot this year, from 15th to 16th. It ranks 16th in both the Innovation Input Sub-Index and Output Sub-Index, respectively down one spot and up two. It ranks in the top 25 economies in all pillars, showing improvements in Institutions (21st), Human capital and research (11th), Infrastructure (10th), and Knowledge and technology outputs (19th). In Institutions, France's most-improved sub-pillar is Business environment (22nd). In Human capital and research, various indicators—government funding per pupil, school life expectancy, tertiary enrolment, and graduates in science and technology—move up. In Infrastructure, France gains several positions in Ecological sustainability (27th), where it gains 2nd place in environmental performance. In Knowledge and technology outputs, Knowledge impact (32nd) and Knowledge diffusion (14th) move up four spots each, with computer software spending and FDI outflows improving the most. France presents relatively weak ranks in pupil-teacher ratio, gross capital formation, ease of getting credit, GERD financed by abroad, FDI inflows, utility models by origin, productivity growth, new businesses, and printing and other media manufactures.

Identifying regional top science and technology clusters

Successful innovation clusters, and thus agglomerations of innovation activity, are considered essential for national innovation performance. Recognizing this fact, innovation policy instruments are often designed and applied at the sub-national level. In addition, most ministers in charge of innovation and R&D financing around the world also pursue the ultimate (but challenging) goal of harbouring state-of-the-art top innovation clusters of their own.

To this end, countries have shown particular interest in assessing and monitoring innovation performance in their states, regions, or cities. In this context, various countries have approached the GII publishers with the desire to apply the GII framework to the sub-national level with a view to measuring sub-national performance. In February 2017, the Indian government, for example, decided to benchmark the performance of Indian states in the 'India Innovation Index', using the GII framework while adding India-centric parameters.[66] The idea is to

BOX 7

The European Union's role in shaping national innovation performance

The Global Innovation Index (GII) uses countries or geographic areas—as defined by the United Nations Statistics Division—as units of analysis when assessing the innovation performance of countries. Although efforts are underway to measure innovation clusters within countries, supra-national country groupings are not explicitly the subject of study in the GII.

This is for a good reason. The vast majority of countries design their supply- and demand-side innovation policies primarily on the national level.[1] Almost no country has delegated the funding or steering of innovation policies to the supra-national level.

The European Union (EU), composed of 28 member states, is an exception.[2] At the supra-national level it controls direct and indirect EU-wide innovation policy levers. Direct EU-level actions focus on creating platforms for transnational and transregional partnerships, as well as investing in research and commercializing innovation.[3] The Horizon 2020 research and innovation programme, for example, proposes nearly €80 billion of innovation funding from 2014 to 2020.[4]

Likewise, many EU regulations indirectly impact GII parameters, including framework conditions. Examples are the creation of the European Single Market, support for the mobility of students and researchers, and access to finance, as well as harmonized rules that relate to innovation outputs. Take the case of intellectual property (IP): nowadays regulations on IP rights are mostly devised at the EU level, including efforts to introduce unitary patent protection across Europe, complementing the EU trademark and EU Community design, which are valid in all EU countries.

At the same time, many aspects of innovation policy and regulation (in particular in the area of education but also in the field of IP), and the brunt of R&D budgets, are still shouldered on the national or often also the sub-national level. The EU R&D funding thus accounts for about 10% of total public investment in research and innovation in the EU (see note 3).

With this in mind, a natural question to ask is: How do the EU countries fare as a group in terms of innovation?

The European Innovation Scoreboard (EIS) 2017 finds that the EU is catching up with the United States of America (U.S.), yet it is losing ground vis-à-vis the Republic of Korea and Japan and it is trailing the innovation performance of Australia and Canada too.[5] The EU's performance lead over Brazil, India, the Russian Federation, and South Africa is significant; its lead over China is decreasing.

For various technical reasons, computing a GII ranking for the EU as a whole regional bloc is not possible. The main reasons are the lack of EU-level key indicators comparable to GII indicators on government effectiveness, environmental performance, or the intensity of local competition, since these are indices or data that exist only at the specific country level. Still, the GII shows that the EU hosts many of the GII's key innovation players. Among the GII rankings, countries such as Sweden, the Netherlands, the United Kingdom, Finland, Denmark, Ireland, and more recently Germany are regularly in the top 10—thus seven out of the 10 top innovating countries are in the EU. The EU as a whole is clearly an important force for innovation, in particular if one considers the EU-wide efforts on education, the R&D expenditure of the region, and the combined IP filings or its output in the area of total high-tech manufacturing.

The GII also documents some longstanding innovation policy concerns of the EU: First, it showcases the persistent differences in innovation performance within the EU region.[6] While the above-mentioned EU countries are in the top 10, others such as Italy, Portugal, Latvia, Hungary, Bulgaria, Slovakia, Poland, and Lithuania are between the top 30 and 40, while Croatia, Greece, and Romania are in the top 50. Second, the GII also shows the important strengths that the EU harbours on the side of innovation input—including academic components such as scientific publications—versus lower performance on firm innovation components such as business R&D or innovation outputs. This has been classically referred to as the 'EU paradox' since the mid-1990s: With excellent EU higher education systems and good research infrastructure and scientific research results, some struggle to translate these assets into marketable innovations.[7] Third, the GII also attests that entrepreneurial activity is sometimes more constrained than would be ideal. Over the last decades, EU policy makers have deplored that the European start-up scene has been less dynamic than the U.S. one. Recent years, however, have witnessed a renewed start-up spurt in many EU capitals—a trend that is worth amplifying in the next months.

How then do EU innovation policies succeed in going beyond and enriching national policy frameworks? What is the 'EU value-added' in the field of innovation?

Putting exact figures to this EU value-added is challenging. The evaluations of past and current EU innovation policy packages reveal important insights, though. They confirm that scientific excellence and the competitiveness of industry's capacity to innovate have been improved by EU policies.[8] Current EU innovation policies are found to produce benefits—and value-added—in terms of scale, speed and scope, notably through the creation of cross border, multidisciplinary networks, the pooling of resources, stronger human resources via better mobility of researchers and doctoral training, and due to their critical mass required to tackle global challenges.[9] Put simply, a majority of EU projects would not have gone ahead without Horizon 2020, for example. To better address the above challenges, EU innovation policy has readjusted its priorities while shifting from supply- or technology-oriented policies to more solution-specific, demand side–oriented policies. Its priorities now include the creation of partnerships involving small firms and a greater focus on spurring actual innovation commercialization.

In turn, administrative procedures and related bureaucracies around EU innovation policies were deemed worthy of improvement, as were the synergies with other research and innovation funding schemes. A current weakness is that the EU programmes are not yet effectively supporting young, fast-growing companies. A number of factors hamper innovation uptake in the marketplace: technological and regulatory obstacles, lack of standards and access to finance, and lack of customer acceptance of new solutions. Looking ahead, the recent *Report of the Independent High Level Group on Maximising the Impact of EU Research & Innovation Programmes* suggests making the EU innovation polices ever more mission-oriented and impact-focused, reducing red tape in R&D funding, and better aligning programmes with national funding.[10]

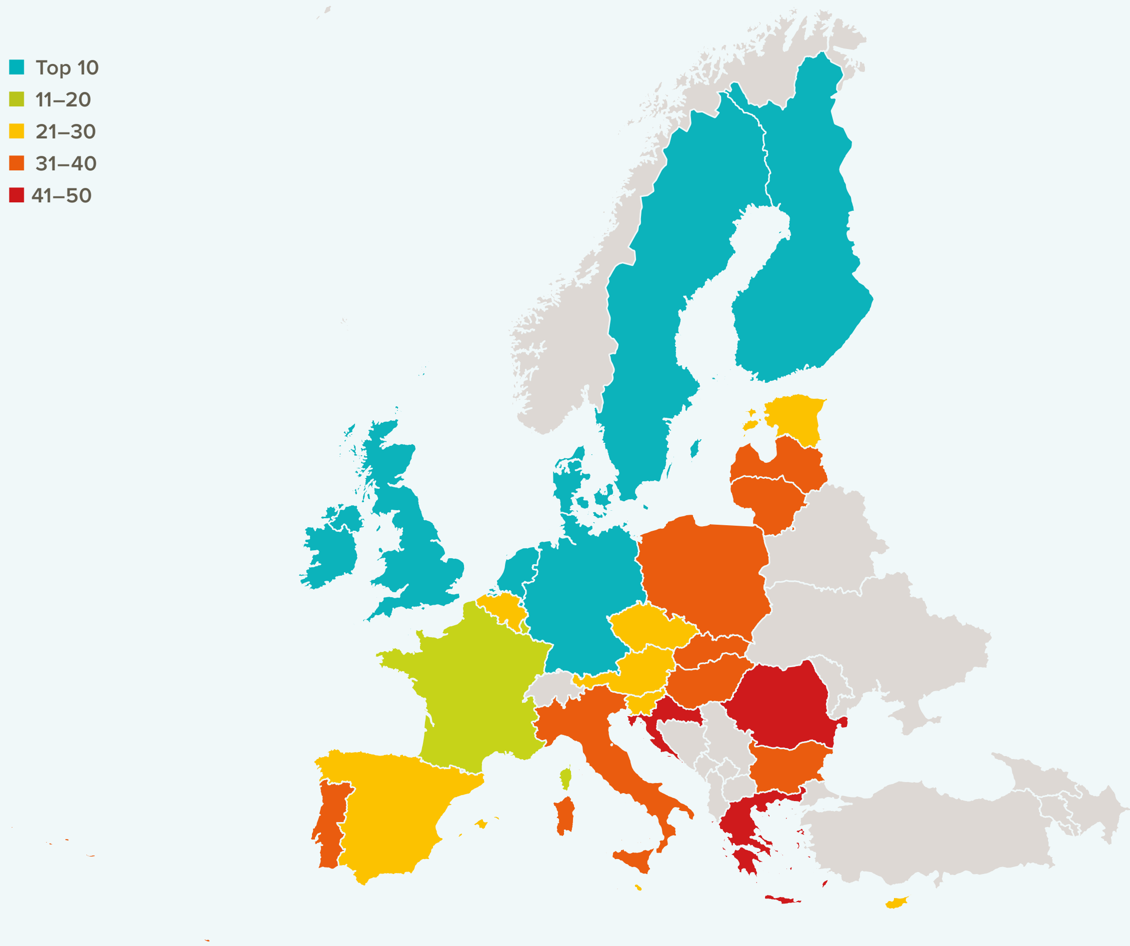
In sum, however, considering the track record of the EU, and not withstanding conceivable enhancements, other world regions might well benefit from emulating similar supra-national innovation policy pooling or coordination.

Notes

Notes for this box appear at the end of the chapter.

Figure 7.1: GII 2018 rankings of EU countries

Source: Global Innovation Index Database, Cornell, INSEAD, and WIPO.



monitor progress of innovation indicators at the state level on real-time basis.

To better capture this important local dimension of innovation systems, measuring inventive, technological, or entrepreneurial performance at the more local level is of crucial importance. The challenge is that official data on the existence and performance of clusters of innovation at the international level are hard to come by. Only a few GII indicators are readily available at the regional or city level for a large set of countries. Thus far, efforts to include an official data point on innovation clusters in the GII from recognized statistical agencies have failed.

To take a step towards improving this data shortage, last year the GII included a Special Section on Clusters in a first attempt at identifying the top sub-national innovation clusters. Its authors Bergquist, Fink, and Raffo proposed a novel approach—drawing on big data (see also Annex 1 Box 1)—to assess inventive cluster capacity. By means of geocoding inventor addresses, the authors identified the largest inventive clusters as measured by WIPO's Patent Cooperation Treaty (PCT) patenting activity, to a very high level of accuracy, thanks to advanced mapping techniques.

The Special Section on Clusters included in this year's GII 2018 is based on a further development of this initial approach. This year the identification of top science and technology clusters rests on international patent filings as last year, with the addition of metrics for scientific publishing activity. In other words, the addresses of authors of scientific publications are used to enrich the existing geocoding exercise (see the Special Section for more details and results). Some of the results are as follows:

- Nine of last year's top 10 clusters are still among the top 10 this year, despite the revised methodology described above.
- Again, Tokyo–Yokohama tops the overall innovation cluster ranking, followed by Shenzhen–Hong Kong.
- The U.S., with 26 clusters, accounts for the highest number, followed by China (16), Germany (8), the U.K. (4), and Canada (4).
- In addition to China, there are clusters from five middle-income countries—Brazil, India, the Islamic Republic of Iran, the Russian Federation, and Turkey—in the top 100.

To highlight the top cluster emanating from this research per country or economy, Table 3 presents the number 1 cluster per economy(ies) that result from this analysis.

In the coming years, attempts to foster the collection of data on local innovation clusters will receive increased attention within the GII as well as other innovation measurement efforts. The discussions triggered by such novel measurement techniques that move beyond official data specific to established city or regional codes—for example, to also include cross-country innovation clusters—will help fine-tune related measurement efforts.

Conclusions

The theme for this year's GII is 'Energizing the World with Innovation'.

This chapter has provided an overview of how innovation can contribute to and address the energy equation while providing a sustainable solution. The global energy transition requires a change in innovation systems to one where the production of knowledge and technology for the energy sector is encouraged by means of technological linkages between large companies and their suppliers. The report also finds that one of the biggest challenges with respect to energy innovation seems to be on the side of diffusion and adoption, which are slow and missing incentives. Complementary social and organizational innovations are needed.

This chapter has also presented the main GII 2018 results, distilling main messages and noting some important evolutions that have taken place since last year (see the Key Findings for more details). The aim of the GII team is to continuously improve the report methodology in concert with its application and related analysis based on the audit, external feedback, changing data availability, and shifting policy priorities. The GII has also undergone a fundamental re-design this year, making some aspects of the report, in particular the Country/Economy Profiles, more accessible, while also innovating on the report analytics—for example, the indication of strengths and weaknesses relative to a country's income group, and an assessment of the relevance of country size or industry structure as determinants of innovation performance (Box 3).

With each new edition, the GII seeks to improve the understanding of the innovation ecosystem with a view to facilitating evidence-based policy making. In this light, the GII team also continues to experiment with the use of novel innovation metrics, as reflected in the inclusion of the mobile app creation indicator 7.3.4 introduced this year.

The majority of our indicator work, however, is invisible to the reader. Every year several dozen new innovation metrics are analysed and tested for inclusion, often to replace existing and currently inadequate data points, on topics such as entrepreneurship, innovation linkages, open innovation, and new metrics for innovation outcomes at the local and national level.

Over the last years, the GII has established itself as a leading reference on innovation, becoming a 'tool for action' for decision makers wishing to improve their countries' innovation performance. In 2017 and 2018, numerous GII workshops in different countries—including Argentina, Belgium, Brazil, Costa Rica, China, Egypt, France, Germany, India, Indonesia, the Islamic Republic of Iran, Kazakhstan, Malaysia, Mexico, Namibia, Sri Lanka, Uganda, the United Arab Emirates, Switzerland, the U.S., Viet Nam, and Zimbabwe, among others—took place, often with the presence of the key concerned ministers and with the direct attention of presidents and prime ministers.

The mission of this work is to apply the insights gleaned from the GII on the ground. In a first step, statisticians and decision makers are brought together to help improve innovation data availability. This work helps to shape the innovation measurement agenda at WIPO and at other international and domestic statistical organizations. In a second step, the challenge is to use the GII metrics and experiences in other countries to leveraging domestic innovation opportunities while overcoming country-specific weaknesses.

Often these activities are an exercise in careful coordination and orchestration among different public and private innovation actors, as well as between government entities at local, regional, and national levels. The GII then becomes a tool for such coordination because the country is united in its common objective: to foster enhanced domestic innovation performance. At best, this coordination leads to policy goals and targets that are regularly revisited and evaluated. For it is those countries that have persevered in their innovation agenda, with consistent focus and set of priorities over time, that have been most successful in achieving the status of innovation leader or achiever relative to their level development.

These exchanges on the ground also generate feedback that, in turn, improves the GII and assists the journey towards improved innovation measurement and policy.

Table 3: Top cluster of economies or cross-border regions within the top 50

Rank	Cluster name	Economies
1	Tokyo–Yokohama	JP
2	Shenzhen–Hong Kong	CN/HK
3	Seoul	KR
4	San Jose–San Francisco, CA	US
5	Beijing	CN
9	Paris	FR
15	London	GB
17	Amsterdam–Rotterdam	NL
20	Cologne	DE
22	Tel Aviv–Jerusalem	IL
28	Singapore	SG
29	Eindhoven	BE/NL
30	Moscow	RU
31	Stockholm	SE
33	Melbourne	AU
37	Toronto, ON	CA
38	Madrid	ES
44	Tehran	IR
45	Milan	IT
48	Zurich	CH/DE

Source: See Table 2 in the Special Section Annex.
Note: Codes refer to the ISO-2 codes; see page 37 for a full list.

Notes for Box 2

1 For a discussion of the 2030 Agenda, see Box 2 in Chapter 1 in Cornell et al., 2017. For details about the Paris Agreement, see http://unfccc.int/paris_agreement/items/9485.php.

2 UN General Assembly Resolution A/RES/72/L224: Ensuring access to affordable, reliable, sustainable and modern energy for all can be found at http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/72/224. This resolution, encourages the development, dissemination, diffusion, and transfer of environmentally sound technologies.

3 Specifically, Goal 9 refers to 'Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation'.

4 Details about the HLPF 2018 Forum are available at https://sustainabledevelopment.un.org/hlpf/2018.

5 Information about WIPO GREEN is available at https://www3.wipo.int/wipogreen/en/.

Notes for Box 3

1 Weller (2016) notes that tiny economies lead the innovation rankings. How different structural, geographic, and historical circumstances of an EU member state affects innovation performance has also been studied in the context of the European Innovation Scoreboard (EIS). A closed expert workshop on the contextualization of innovation performance data was organized in Brussels in February 2018 with the participation of GII researchers; see http://ec.europa.eu/growth/industry/innovation/facts-figures/scoreboards_en. For the EIS, a slight positive correlation between GDP and innovation performance is found.

2 These are Sweden, Finland, and Denmark, in order of their 2018 GII ranking.

3 The ICT Development Index 2017 is available at http://www.itu.int/net4/ITU-D/idi/2017/-.

4 The GII 2018 scales 22 variables by GDP and 8 variables by population.

5 See www.globalinnovationindex.org.

6 Any correlation analysis and its related statistical tests should take into account development effects. This means using the part of the GII score that can be explained by country characteristics while controlling for the different levels of economic development, proxied in this case by (log) GDP per capita.

7 There can be multiple reasons that rich countries score better on the GII. An interesting one could be that many small high-income economies such as Luxembourg or Hong Kong (China) are very much service-based economies, and that innovation in the services sector, including in areas such financial innovation, is harder to capture via classic innovation metrics such as scientific publications or patents than innovation in other sectors.

8 These small natural resource–endowed countries are Bahrain, Botswana, Brunei Darussalam, Croatia, Kuwait, Latvia, Lithuania, Mongolia, Oman, Qatar, Trinidad and Tobago, and Uruguay.

9 For details see the paper on uncovering the effects of country-specific characteristics on innovation performance on the GII website. We use as a proxy of product concentration the Hirschman-Herfindahl Index (HHI) for the domestic industry from the UNIDO INDSTAT database, developed by the EQuIP project of UNIDO. The HHI is a measure of concentration and can help to determine the extent to which a country's industrial system is diversified across different industrial sub-sectors (or, conversely, concentrated in a few industrial sub-sectors). See UNIDO, 2015, for details about the EQuIP project.

10 We test for trade concentration by using the HHI for export product diversification sourced from the UN Comtrade database, available at https://comtrade.un.org/, and also derived from UNIDO's EQuIP project. The HHI for export product diversification shows the extent to which a country's industrial exports are diversified across different industrial sub-sectors or products.

Notes for Box 7

1 Dutta et al., 2016.

2 The 28 EU member states are Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

3 See https://ec.europa.eu/growth/industry/innovation/policy_en. Input to this box was kindly provided in form of an unpublished Background Note by Daniel W. Bloemers, European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, and his colleagues at the European Commission.

4 See https://ec.europa.eu/programmes/horizon2020/. Also the European Structural and Investment Funds, with a focus on sub-national regions, dedicate around €110 billion to innovation. Additional funding opportunities for innovators and entrepreneurs are provided by the European Fund for Strategic Investments (EFSI) and a recently established Venture Capital Fund-of-Funds.

5 European Commission, 2017a.

6 See also OECD, 2016.

7 European Commission, 1995.

8 High Level Expert Group, 2015.

9 Results of the interim evaluation of Horizon 2020 input studies and evaluation methods can be found https://ec.europa.eu/research/evaluations/index.cfm?pg=h2020evaluation.

10 LAB – FAB – APP, 2017.

Notes for Chapter 1

* Consultant.

1 Conference Board, 2018a; IMF, 2018; OECD, 2018a; World Bank, 2018. For 2018 and 2019, the OECD (2018a) and the IMF (2018) forecast a growth rate of 3.9%, with the OECD revising the two rates slightly upward in November 2017. The World Bank (2018), instead, forecasts a growth rate of 3.1% for 2018 and 3.0% for 2019, with 0.2 and 0.1 upward revisions respectively from June 2017. The Conference Board (2018a) also predicts a slower rate of economic growth at 3.3% for 2018.

2 WTO, 2018.

3 IMF, 2018. According to the Conference Board (2018a) and World Bank (2018), growth rates for emerging and developing economies are forecast to be around 4–4.7% in 2018 and 2019.

4 Conference Board, 2018a; IMF, 2018; OECD, 2018a; World Bank, 2018.

5 The members of ASEAN are Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Viet Nam. On the innovation achievements of ASEAN countries, see Box 6 in Dutta et al., 2017.

6 Based on IMF World Economic Outlook Dataset (April 2018).

7 IMF, 2018.

8 IMF, 2018; OECD, 2018a.

9 OECD, 2018a; Dutta et al., 2016, 2017.

10 IMF, 2018; OECD, 2018a; World Bank, 2018.

11 Conference Board, 2018b.

12 Conference Board, 2018b; Dutta et al., 2017.

13 See WIPO, 2015a and Box 1.4 in IMF, 2018.

14 UNCTAD, 2018.

15 WIPO, 2015a.

16 IMF, 2018; World Bank, 2018.

17 OECD, 2009; Dutta et al., 2017.

18 See WIPO, 2017a, for examples in coffee, photovoltaic cells, and smartphones.

19 See the historical cases of airplanes and semiconductors in WIPO, 2015b.

20 National Science Board, 2018 and various prior editions, as well as WIPO, 2011 and OECD, 2017.

21 WIPO, 2017c, 2018a.

22 WIPO, 2017b.

23 UNESCO UIS estimates.

24 OECD, 2018b. GPD is the denominator in the R&D intensity equation; slower growth translates, *ceteris paribus,* to increased R&D intensity.

25 WIPO, 2017b.

26 OECD, 2009; Dutta et al., 2017.

27 OECD, 2009.

28 Authors' estimates based on UNESCO-UIS, 2018.

29 OECD, 2018b.

30 Authors' estimates based on UNESCO-UIS data.

31 Authors' estimates based on UNESCO-UIS data.

32 OECD, 2018c.

33 OECD, 2018b.

34 Strategy&, 2017; European Commission, 2017b. The top 2,500 data are a good proxy for up to 90% of the world's business-funded R&D. According to these private sources, the top companies' R&D investment increased by 3.2% between 2016 and 2017 as estimated for the top 1,000 by Strategy& (2017) and by 5.8% as estimated for the top 2,500 by the European Commission (2017b).

35 Strategy&, 2017. According to the European Commission (2017b), the world's top 2,500 companies in terms of investment into R&D increased by 5.8% over 2016, companies with headquarters in the EU did so by 7%.

36 Strategy&, 2017.

37 Strategy&, 2017. Over half of companies expect a moderate to significant impact to their R&D and innovation efforts caused by the economic nationalism.

38 See for more background and a summary of the literature, see Keisner et al., 2016 and WIPO, 2015a and the many news items on this topic.

39 IEA, 2017. The largest contribution to energy demand growth—almost 30%—comes from India, whose share of global energy use is expected to rise to 11% by 2040. Overall, developing countries in Asia account for two-thirds of global energy growth; the rest comes mainly from the Northern Africa and Western Asia, Sub-Saharan Africa, and Latin America and the Caribbean.

40 Sustainability is not limited to greenhouse gas (GHG) emissions. It also encompasses the use of limited energy resources (e.g., fossil fuels); the impact of the exploitation of energy resources; the impact of air pollution, especially in cities; and so on.

41 The current energy transformation is driven by climate change and by addressing energy independence and security, energy resilience, and energy competitiveness, among others (Chapter 3).

42 IRENA, 2018b.

43 IRENA, 2018b.

44 ILO, 2018. Global renewable energy employment reached 10.3 million jobs in 2017, increasing 5.3% over the previous year. China alone accounts for 43% of all renewable energy jobs. See also IRENA, 2018a.

45 See WIPO, 2017a, Chapter 3 'Photovoltaics: Technological Catch-Up and Competition in the Global Value Chain'.

46 See Cornell University, INSEAD and WIPO, 2017, Chapter 11 'Enhancing Innovation in the Ugandan Agri-Food Sector: Progress, Constraints, and Possibilities' for a comparable approach to innovation in agriculture value chains. See also Chapter 5 (Wilson and Kim) in this report for a discussion on how technology-specific assessments and cross-technology comparisons are complementary to innovation system processes and how these are needed for supporting specific energy technologies.

47 For more on the 'flexibility options' to support the integration of variable renewable energy, see IRENA, 2015.

48 Other aspects should also be accounted for. As renewable energies become mature, one can expect that the number of inventions and innovations deaccelerates. Also, innovation might be moving towards technologies that enable more renewable energies, such as electric vehicles or batteries. See also Figure 3, where an increase in energy conservation published patent families is observed.

49 Frankfurt School-UNEP Centre, 2018. Investment data are based on the output of the database of Bloomberg New Energy Finance (BNEF), a database of investors, projects, and transactions in clean energy. It includes projects, investments, and transactions from start-ups, corporate entities, venture capital and private equity providers, banks, and other investors. The following renewable energy projects are included: wind, solar, biomass and waste, biofuels, geothermal and marine projects, and small hydro-electric damns of less than 500 MW. The aggregate renewable energy investment figure of US$2.9 trillion over the period 2004–17 excludes large hydro-electric projects of more than 500 MW. More details on the methodology and definitions used in the BNEF database for the estimation of investments in green energy sources are available in Frankfurt School-UNEP Centre, 2018.

50 CAGR was equal to –0.5% in this period. However, it is important to note that renewable energies deployment keeps growing while the costs of renewable energies keep decreasing.

51 IRENA and CPI, 2018. "Investment" is a financial commitment represented by a firm obligation, for example by means of a Board (or equivalent body) decision, backed by the necessary funds, to provide specified financing through debt, equity or other financial instruments. More information on the methodology is available in IRENA and CPI, 2018. See also Chapter 3 for IRENA's contribution to the GII 2018, 'Innovation Driving the Energy Transition'.

52 WIPO, 2017b.

53 Saha and Muro, 2017.

54 See also WIPO, 2018b, for details on the methodology. A 'patent family' is a set of interrelated patent applications filed in one or more countries or jurisdictions to protect the same invention.

55 'Internationally oriented patent families' are defined as patent families filed by residents in at least two different countries.

56 In photovoltaics (PV), the shift in global value chain production—combined with the steep fall in prices—put many traditional PV manufacturers in the U.S., Europe, and elsewhere under competitive pressure, resulting in bankruptcies and acquisitions. This partly explains the decline in PV patent filings worldwide after 2011. However, the complete picture is more nuanced. With a saturated solar PV market and low prices that result in tight profit margins, surviving firms have stepped up their investments in R&D to develop new cost-competitive PV technology. A closer look at the patent data reveals that patent applications per applicant have continued to grow in the countries where most filings are observed (e.g., China, Japan, U.S.) since 2011, suggesting an increase in patenting among surviving firms. See WIPO, 2017a. On declining prices see IRENA and CPI, 2018.

57 A distinction between central (national) governments on one hand and local (typically municipal) authorities on the other is worth making here. Recent efforts to build 'smart cities' have devoted significant attention (and investment) to smart energy grids, leading to impressive savings and changes in consumers' habits. See for example Singh and Yassine, 2017.

58 Foxon, 2018.

59 See also www.wipo.int/green.

60 Economies are grouped according to the World Bank classification (July 2017) gross national income (GNI) per capita, calculated using the World Bank Atlas method. The groups are: low income, US$1,005 or less; lower-middle income, US$1,006 to US$3,955; upper-middle income, US$3,956 to US$2,235; and high income, US$12,235 or more; see https://blogs.worldbank.org/opendata/new-country-classifications-income-level-2017-2018..

61 Since 2012, the regional groups have been based on the United Nations Classification: EUR = Europe; NAC = Northern America; LCN = Latin America and the Caribbean; CSA = Central and Southern Asia; SEAO = South East Asia, East Asia, and Oceania; NAWA = Northern Africa and Western Asia; and SSF = Sub-Saharan Africa.

62 Note that any assessment of how the U.K.'s planned withdrawal from the European Union affects the country's GII rank would still be speculative, at best. First, most of the data still predate or coincide with the year of the actual related referendum. Only 35% of the U.K.'s indicators are from 2017; the remaining 65% reflect 2016 and earlier years. Second, as noted last year as well, the causal relations between plans or the actual withdrawal from the EU and the GII indicators are complex and uncertain in size and direction.

63 See GII 2012, Chapter 1, which notes on page 22 that 'the over-representation of the efficiency ratio in the media in 2011 out of the proper context—namely GII scores—was unfortunate, with analysts jumping to the conclusion that countries with high efficiency ratios were to be commended when in effect these high ratios often reflected blatant deficiencies in the input side and a performance in the GII well below that of countries with similar GDP per capita'.

64 The GII bubble chart plots GDP per capita against the GII scores and includes a trend line that is extrapolated from available data. It was introduced in the GII 2012. Since then, the following trend line curves were used: (1) polynomial of degree 4 with no intercept was used in 2012 and (2) polynomial of degree 3 with intercept was used from 2013 until the GII 2017. This new choice, while preserving an adequate coefficient of determination (R^2), also allowed the trend line to behave more in accordance with what would be expected from the relationship of both variables plotted. More recently, Advisory Board members to the GII, notably Sibusiso Sibisi, suggested that a piece-wise curve fitting approach using a fit cubic spline could be more appropriate for the GII. The idea was that this could better fit several local curves that are joined together at the boundaries in a suitably smooth manner (i.e., matching boundary values and their derivatives). Moreover, one additional question is whether a spline trend line would favour middle-income countries, resulting in more innovation achievers from this income group. In the run-up to the 2018 GII edition, STATA was used to predict the GII 2018 scores using a restricted cubic spline. Harrell (2001) recommends placing knots at equally spaced percentiles of the original variable's marginal distribution. Five knots determined by Harrell's default percentiles were defined on the bubble chart's x axis, or along the log of GDP per capita in PPP$, for each country included in the GII 2018. The spline construction estimates for each country a variable (and coefficient) for each of the distribution segments resulting in each of Harrell's knots. The prediction is then based on a model with four variables corresponding to the placement of each of the knots, plus the intercept. It was concluded that the empirically and methodologically the cubic spline performs better (i.e., the fitness of the model is higher than the polynomial degree 3 and degree 4 constructions). It was decided to adopt the cubic spline construction, using Harrell's percentile knots for the predictions.

65 See endnote 64, which sets out methodological changes having possibly contributed to this shift as well.

66 NITI Aayog, 2017.

References and sources

BASIS. 2014. 'One Bangladesh: Next Five Years Vision of Bangladesh Software & IT Services Industry Launched'. BASIS Media Room Press Release, 16 February 2014. Available at https://www.basis.org.bd/index.php/media/news_detail/230.

Conference Board. 2018a. *Global Economic Outlook 2018,* February 2018.

——. 2018b. 2018 Productivity Brief, Total Economy Database: Key Findings. March 2018 release. Available at https://www.conference-board.org/data/economydatabase/index.cfm?id=25667.

Cornell University, INSEAD, and WIPO. 2017. *The Global Innovation Index 2017: Innovation Feeding the World,* eds. S. Dutta, B. Lanvin, and S. Wunsch-Vincent. Ithaca, Fontainebleau, and Geneva: Cornell, INSEAD, and WIPO.

Dutta, S, Escalona Reynoso, R., Litner, J., Lanvin, B., Wunsch Vincent S. and F. Guadagno. 2017. 'The Global Innovation Index 2017: Innovation Feeding the World'. In *The Global Innovation Index 2017: Innovation Feeding the World,* eds. S. Dutta, B. Lanvin, and S. Wunsch-Vincent. Ithaca, Fontainebleau, and Geneva: Cornell, INSEAD, and WIPO. Chapter 1.

Dutta, S, Escalona Reynoso, R., Litner, J., Lanvin, B., Wunsch Vincent S. and K. Saxena. 2016. 'The Global Innovation Index 2016: Winning with Global Innovation'. In *The Global Innovation Index 2016: Winning with Global Innovation,* eds. S. Dutta, B. Lanvin, and S. Wunsch-Vincent. Ithaca, Fontainebleau, and Geneva: Cornell, INSEAD, and WIPO. Chapter 1.

EPO (European Patent Office). 2013. *Finding Sustainable Technologies in Patents.* Munich: European Patent Office.

European Commission. 1995, *Green Paper on Innovation.* Available at http://europa.eu/documents/comm/green_papers/pdf/com95_688_en.pdf.

———. 2017a. *European Innovation Scoreboard 2017.* EU Publications Office. Available at http://ec.europa.eu/DocsRoom/documents/24829.

———. 2017b. 'The 2017 EU Industrial R&D Investment Scoreboard'. Authors Héctor Hernández, Nicola Grassano, Alexander Tübke, Lesley Potters, Sara Amoroso, Mafini Dosso, Petros Gkotsis and Antonio Vezzani. Seville: European Commission, Joint Research Centre. Available at http://iri.jrc.ec.europa.eu/scoreboard17.html.

Foxon, T. 2018. *Energy and Economic Growth.*London: Routledge.

Frankfurt School-UNEP Centre/BNEF. 2018. *Global Trends in Renewable Energy Investment 2018.* Available at http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-report-2018.

Harrell, F. E., Jr. 2001. *Regression Modelling Strategies: With Applications to Linear Models, Logistic Regression, and Survival Analysis.* New York: Springer.

High Level Expert Group. 2015. *Commitment and Coherence: Ex-Post-Evaluation of the 7th EU Framework Programme (2007–2013).* Available at https://ec.europa.eu/research/evaluations/pdf/fp7_final_evaluation_expert_group_report.pdf.

IEA (International Energy Agency). 2017. *World Energy Outlook 2017.* Paris: OECD Publishing. Available at http://dx.doi.org/10.1787/weo-2017-en.

ILO (International Labour Organization). 2018. *World Employment and Social Outlook 2018: Greening with Jobs.* Geneva: ILO. Available at http://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_628654.pdf.

IMF (International Monetary Fund). 2018. 'World Economic Outlook: Global Prospects and Policies. In *World Economic Outlook (WEO): Cyclical Upswing, Structural Change,* April 2018. Washington, DC: IMF. Chapter 1.

INSEAD and WIPO (Word Intellectual Property Organization). 2012. *The Global Innovation Index 2012: Stronger Innovation Linkages for Global Growth,* ed. S. Dutta. Fontainebleau and Geneva: INSEAD and WIPO.

IRENA (International Renewable Energy Agency). 2015. *The Age of Renewable Power: Designing National Roadmaps for a Successful Transformation.* Abu Dhabi: IRENA. Available at http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_PST_Age_of_Renewable_Power_2015.pdf.

———. 2018a. *Renewable Energy and Jobs: Annual Review 2018.* Abu Dhabi: IRENA. Available at http://irena.org/-/media/Files/IRENA/Agency/Publication/2018/May/IRENA_RE_Jobs_Annual_Review_2018.pdf.

———. 2018b. *Renewable Power Generation Costs in 2017.* Abu Dhabi: IRENA. Available at http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.

IRENA and CPI. 2018. *Global Landscape of Renewable Energy Finance 2018.* Abu Dhabi: IRENA. Available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Global_landscape_RE_finance_2018.pdf.

ITC News. 2014. 'Dhaka Seminar Explores How to Boost Competitiveness of Bangladesh ICT Sector'. ITC News, 9 December 2014. Available at http://www.intracen.org/news/Dhaka-Seminar-Explores-how-to-Boost-Competitiveness-of-Bangladesh-ICT-Sector/.

Keisner A., J. Raffo, and S. Wunsch-Vincent. 2016. 'Robotics: Breakthrough Technologies, Innovation, Intellectual Property'. *Foresight and STI Governance* 10 (2): 7–27. Available at https://foresight-journal.hse.ru/data/2016/07/01/1115773433/1-Robotics-7-27.pdf.

LAB – FAB – APP. 2017. *Investing in the European Future We Want: Report of the Independent High Level Group on Maximising the Impact of EU Research & Innovation Programmes.* Brussels: European Commission. Available at http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/hlg_2017_report.pdf.

National Science Board. 2018. *Science and Engineering Indicators 2018.* NSB-2018-1. Alexandria, VA: National Science Foundation. Available at https://www.nsf.gov/statistics/indicators/.https://www.nsf.gov/statistics/2018/nsb20181/.

NITI Aayog. 2017. 'Amitabh Kant Launches India Innovation Index: A Joint Initiative of NITI Aayog, DIPP and CII: States Will Be Ranked on Innovations from 2017'. Press Release, Press Information Bureau, Government of India, NITI Aayog. 2 February 2017. Available at http://pib.nic.in/newsite/PrintRelease.aspx?relid=157941

OECD (Organisation for Economic Co-operation and Development). 2009. *Policy Responses to the Economic Crisis: Investing in Innovation for Long-Term Growth,* eds. D. Guellec and S. Wunsch-Vincent. Paris: OECD Publishing. Available at https://www.oecd.org/sti/42983414.pdf.

———. 2016. 'Assessing STI Performance: European Union'. Online only. In *OECD Science, Technology and Innovation Outlook 2016.* Paris: OECD Publishing. Available at http://dx.doi.org/10.1787/sti_in_outlook-2016-en.

———. 2017. *Science, Technology and Industry Scoreboard 2017: The Digital Transformation.* Paris: OECD Publishing.

———. 2018a. *OECD Interim Economic Outlook.* 13 March 2018. Paris: OECD Publishing. Available at http://www.oecd.org/eco/outlook/Getting-stronger-but-tensions-are-rising-press-handout-oecd-interim-economic-outlook-march-2018.pdf.

———. 2018b. Main Science and Technology Indicators (MSTI). Last update: MSTI 2017/2 (March 2018). Paris: OECD Publishing.

———. 2018c. Release of Main Science and Technology Indicators: Latest Estimates of R&D investment in OECD and Major Economies. Paris: OECD Publishing. Available at http://www.oecd.org/sti/DataBrief_MSTI_2018.pdf.

Saha D. and M. Muro. 2017. *Patenting Invention: Clean Energy Innovation Trends and Priorities for the Trump Administration and Congress.* Washington, DC: Metropolitan Policy Program at Brookings. Available at https://www.brookings.edu/wp-content/uploads/2018/02/final_cleantech.pdf.

Singh, S. and A. Yassine. 2017. 'Mining Energy Consumption Behavior Patterns for Households in Smart Grid'. *IEEE Transactions on Emerging Topics in Computing.* Available at https://ieeexplore.ieee.org/document/7894203.

Strategy&. 2017. '2017 Global Innovation 1000: Will Stronger Borders Weaken Innovation? Fact Pack'. October 2016. PwC. Available at https://www.strategyand.pwc.com/media/file/2017-Global-Innovation-1000-Fact-Pack.pdf.

UNCTAD (United Nation Conference on Trade and Development). 2018. *Global Investment Trends Monitor No. 28.* January 2018. Geneva and New York: UNCTAD.

UNESCO-UIS (UNESCO Institute for Statistics). 2018. UNESCO-UIS Science & Technology Data Center, March 2018.

UNIDO (United Nations Industrial Development Organization). 2015. 'EQuIP Tool 4: Diversification – Domestic and Export Dimensions'. In *EQuIP: Enhancing the Quality of Industrial Policies.* Vienna and Bonn: UNIDO and GMBH. Available at http://www.equip-project.org/wp-content/uploads/2015/08/EQuIP_Tool-4_V150821.pdf.

Weller, C. 2016. 'The 15 Most Innovative Countries in the World'. *Business Insider France,* 29 August 2016. Available at http://www.businessinsider.fr/us/most-innovative-countries-in-the-world-2016-8.

WIPO (World Intellectual Property Organization). 2011. 'The Changing Nature of Innovation and Intellectual Property'. In *World Intellectual Property Report: The Changing Face of Innovation.* Geneva: WIPO. Chapter 1.

———. 2015a. 'A Look inside the Economic Growth Engine'. In *World Intellectual Property Report: Breakthrough Innovation and Economic Growth.* Geneva: WIPO. Chapter 1.

———. 2015b. *World Intellectual Property Report: Breakthrough Innovation and Economic Growth.* Geneva: WIPO.

———. 2017a. *World Intellectual Property Report: Intangible Assets and Global Value Chains.* Geneva: WIPO.

———. 2017b. *World Intellectual Property Indicators 2017.* Geneva: WIPO.

———. 2017c. 'China Tops Patent, Trademark, Design Filings in 2016'. 6 December 2017, Press Release PR/2017/814. Geneva: WIPO.

———. 2018a. 'China Drives International Patent Applications to Record Heights; Demand Rising for Trademark and Industrial Design Protection'. 21 March 2018, Press Release PR/2018/816, Geneva: WIPO.

———. 2018b. 'Measuring Innovation in Energy Technologies: Green Patents as Captured by WIPO's IPC Green Inventory'. *Economic Research Working Paper* No. 44.Geneva: WIPO.

World Bank. 2018. *Global Economic Prospects: Broad-Based Upturn, but for How Long?* Washington, DC: World Bank. Available at https://openknowledge.worldbank.org/bitstream/handle/10986/28932/9781464811630.pdf.

WTO (World Trade Organization) 2018. 'Strong Trade Growth in 2018 Rests on Policy Choices'. World Trade Organization Press Release. PRESS/820. 12 April 2018. Geneva: WTO.

ANNEX 1

THE GLOBAL INNOVATION INDEX (GII) CONCEPTUAL FRAMEWORK

The rationale for the Global Innovation Index

The Global Innovation Index (GII) project was launched by Professor Dutta at INSEAD in 2007 with the simple goal of determining how to find metrics and approaches that better capture the richness of innovation in society and go beyond such traditional measures of innovation as the number of research articles and the level of research and development (R&D) expenditures.[1]

There were several motivations for setting this goal. First, innovation is important for driving economic progress and competitiveness—both for developed and developing economies. Many governments are putting innovation at the centre of their growth strategies. Second, the definition of innovation has broadened—it is no longer restricted to R&D laboratories and to published scientific papers. Innovation could be and is more general and horizontal in nature, and includes social innovations and business model innovations as well as technical ones. Last but not least, recognizing and celebrating innovation in emerging markets is seen as critical for inspiring people—especially the next generation of entrepreneurs and innovators.

Now in its 11th edition, the GII helps to create an environment in which innovation factors are under continual evaluation, and it provides a key tool for decision makers and a rich database of detailed metrics for refining innovation policies.

The GII is not meant to be the ultimate and definitive ranking of economies with respect to innovation. Measuring innovation outputs and impacts remains difficult, hence great emphasis is placed on measuring the climate and infrastructure for innovation and on assessing related outcomes.

Although the end results take the shape of several rankings, the GII is more concerned with improving the 'journey' to better measure and understand innovation and with identifying targeted policies, good practices, and other levers that foster innovation. The rich metrics can be used—on the level of the index, the sub-indices, or the actual raw data of individual indicators—to monitor performance over time and to benchmark developments against countries in the same region or income classification.

Drawing on the expertise of the GII's Knowledge Partners and its prominent Advisory Board, the GII model is continually updated to reflect the improved availability of statistics and our understanding of innovation. This year the model continues to evolve, although its mature state now requires only minor updates (refer to Annex 2).

An inclusive perspective on innovation

The GII adopts a broad notion of innovation, originally elaborated in the *Oslo Manual* developed by the European

Communities and the Organisation for Economic Co-operation and Development (OECD):[2]

> An innovation is the implementation of a new or significantly improved product (good or service), a new process, a new marketing method, or a new organizational method in business practices, workplace organization, or external relations.

This definition reflects the evolution of the way innovation has been perceived and understood over the last two decades.[3]

Economists and policy makers used to focus on R&D-based technological product innovation, largely produced in-house and mostly in manufacturing industries. This type of innovation was performed by a highly educated labour force in R&D-intensive companies. The process leading to such innovation was conceptualized as closed, internal, and localized. Technological breakthroughs were necessarily 'radical' and took place at the 'global knowledge frontier'. This characterization implied the existence of leading and lagging countries, with low- or middle-income economies only catching up.

Today innovation capability is seen more as the ability to exploit new technological combinations; it embraces the notion of incremental innovation and 'innovation without research'. Non-R&D innovative expenditure is an important component of reaping the rewards of technological innovation. Interest in understanding how innovation takes place in low- and middle-income countries is increasing, along with an awareness that incremental forms of innovation can impact development. Furthermore, the process of innovation itself has changed significantly. Investment in innovation-related activity has consistently intensified at the firm, country, and global levels, adding both new innovation actors from outside high-income economies and nonprofit actors. The structure of knowledge production activity is more complex and geographically dispersed than ever.

A key challenge is to find metrics that capture innovation as it actually happens in the world today.[4] Direct official measures that quantify innovation outputs remain extremely scarce.[5] For example, there are no official statistics on the amount of innovative activity—defined as the number of new products, processes, or other innovations—for any given innovation actor, let alone for any given country (see Box 1, Annex 1 of Chapter 1 in the GII 2013). Most measures also struggle to appropriately capture the innovation outputs of a wider spectrum of innovation actors, such as the services sector or public entities. These measures include innovation surveys that have contributed greatly to the measurement of innovation activities, but that fail to provide a good and reliable sense of cross-country innovation output performance and that are often not applicable to developing countries where innovation is often informal.[6]

The GII aims to move beyond the mere measurement of simple innovation metrics. To do so requires the integration of new variables, with a trade-off between the quality of the variable on the one hand and achieving good country coverage on the other hand. A key priority is to improve the measurement of innovation in the field of knowledge-intensive services, end-user and public-sector innovation, innovation linkages (in particular international ones), and innovation outputs and impacts more generally.[7]

The timeliest possible indicators are used for the GII: this year, 31.8% of data obtained are from 2017, 38.3% are from 2016, 10.6% are from 2015, 4.3% from 2014, and the small remainder 4.8% from earlier years.[8]

The GII conceptual framework

The GII is an evolving project that builds on its previous editions while incorporating newly available data and that is inspired by the latest research on the measurement of innovation. This year the GII model includes 126 countries/economies, which represent 90.8% of the world's population and 96.3% of the world's GDP (bn PPP $). The GII relies on two sub-indices—the Innovation Input Sub-Index and the Innovation Output Sub-Index—each built around pillars. Four measures are calculated (see Figure 1):

1. **Innovation Input Sub-Index:** Five input pillars capture elements of the national economy that enable innovative activities.
2. **Innovation Output Sub-Index:** Innovation outputs are the results of innovative activities within the economy. Although the Output Sub-Index includes only two pillars, it has the same weight in calculating the overall GII scores as the Input Sub-Index.
3. **The overall GII score** is the simple average of the Input and Output Sub-Indices.

Figure 1.
Framework of the Global Innovation Index 2018

4. **The Innovation Efficiency Ratio** is the ratio of the Output Sub-Index to the Input Sub-Index. It shows how much innovation output a given country is getting for its inputs.

Each pillar is divided into three sub-pillars, each of which is composed of individual indicators, for a total of 80 indicators this year. The GII pays special attention to presenting a scoreboard for each economy that includes strengths and weaknesses (Appendix I Country/Economy Profiles), making accessible the data series (Appendix II Data Tables, available online at http://globalinnovationindex.org), and providing data sources and definitions (Appendix III) and detailed technical notes (Appendix IV). Adjustments to the GII framework, including a detailed analysis of the factors influencing year-on-year changes, are detailed in Annex 2. In addition, since 2011 the GII has been submitted to an independent statistical audit performed by the Joint Research Centre of the European Union (results are detailed in Annex 3).

The Innovation Input Sub-Index

The first sub-index of the GII, the Innovation Input Sub-Index, has five enabler pillars: Institutions, Human capital and research, Infrastructure, Market sophistication, and Business sophistication. Enabler pillars define aspects of the environment conducive to innovation within an economy.

Pillar 1: Institutions

Nurturing an institutional framework that attracts business and fosters growth by providing good governance and the correct levels of protection and incentives is essential to innovation. The Institutions pillar captures the institutional framework of a country.

The Political environment sub-pillar includes two indices: one that reflects perceptions of the likelihood that a government might be destabilized; and one that reflects the quality of public and civil services, policy formulation, and implementation.

The Regulatory environment sub-pillar draws on two indices aimed at capturing perceptions of the ability of the government to formulate and implement cohesive policies that promote the development of the private sector and at evaluating the extent to which the rule of law prevails (in aspects such as contract enforcement, property rights, the police, and the courts). The third indicator evaluates the cost of redundancy dismissal as the sum, in salary weeks, of the cost of advance notice requirements added to severance payments due when terminating a redundant worker.

The Business environment sub-pillar expands on two aspects that directly affect private entrepreneurial endeavours by using the World Bank indices on the ease of starting a business and the ease of resolving insolvency (based on the recovery rate recorded as the cents on the dollar recouped by creditors through reorganization, liquidation, or debt enforcement/foreclosure proceedings). This year the model drops the indicator measuring ease of paying taxes (see Annex 2 for details).

Pillar 2: Human capital and research

The level and standard of education and research activity in a country are prime determinants of the innovation capacity of a nation. This pillar tries to gauge the human capital of countries.

The first sub-pillar includes a mix of indicators aimed at capturing achievements at the elementary and secondary education levels. Education expenditure and school life expectancy are good proxies for coverage. Government funding per pupil, secondary gives a sense of the level of priority given to secondary education by the state (excluding funding from abroad). The quality of education is measured through the results to the OECD Programme for International Student Assessment (PISA), which examines 15-year-old students' performances in reading, mathematics, and science, as well as the pupil-teacher ratio.

Higher education is crucial for economies to move up the value chain beyond simple production processes and products. The sub-pillar on tertiary education aims at capturing coverage (tertiary enrolment); priority is given to the sectors traditionally associated with innovation (with a series on the percentage of tertiary graduates in science, engineering, manufacturing, and construction); and the inbound and mobility of tertiary students, which plays a crucial role in the exchange of ideas and skills necessary for innovation.

The last sub-pillar, on R&D, measures the level and quality of R&D activities, with indicators on researchers (full-time equivalent), gross expenditure, the R&D expenditures of top global R&D spenders, and the quality of scientific and research institutions as measured by the average score of the top three universities in the QS World University Ranking of 2017. The R&D expenditures of the top three firms in a given country looks at the average expenditure of these three firms that are part of the top 2,500 R&D spenders worldwide. The QS university rankings indicator gives the average scores of the country's top three universities that belong to the top 700 universities worldwide. These indicators are not aimed at assessing the average level of all institutions within a particular economy.

Pillar 3: Infrastructure

The third pillar includes three sub-pillars: Information and communication technologies (ICTs), General infrastructure, and Ecological sustainability.

Good and ecologically friendly communication, transport, and energy infrastructures facilitate the production and exchange of ideas, services, and goods and feed into the innovation system through increased productivity and efficiency, lower transaction costs, better access to markets, and sustainable growth.

The ICTs sub-pillar includes four indices developed by international organizations on ICT access, ICT use, online service by governments, and online participation of citizens.

The sub-pillar on general infrastructure includes the average of electricity output in kWh per capita; a composite indicator on logistics performance; and gross capital formation, which consists of outlays on additions to the fixed assets and net inventories of the economy, including land improvements (fences, ditches, drains); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings.

The sub-pillar on ecological sustainability includes three indicators: GDP per unit of energy use (a measure of efficiency in the use of energy), the Environmental Performance Index of Yale and Columbia Universities, and the number of certificates of conformity with standard ISO 14001 on environmental management systems issued.

Pillar 4: Market sophistication

The availability of credit and an environment that supports investment, access to the international market, competition, and market scale are all critical for businesses to prosper and for innovation to occur. The Market sophistication pillar has three sub-pillars structured around market conditions and the total level of transactions.

The Credit sub-pillar includes a measure on the ease of getting credit aimed at measuring the degree to which collateral and bankruptcy laws facilitate lending by protecting the rights of borrowers and lenders, as well as the rules and practices affecting the coverage, scope, and accessibility of credit information. Transactions are given by the total value of domestic credit and, in an attempt to make the model more applicable to emerging markets, by the gross loan portfolio of microfinance institutions.

The Investment sub-pillar includes the ease of protecting minority investors index as well as two indicators on the level of transactions. These two indicators look at whether market size is matched by market dynamism and provide a hard data metric on venture capital deals.

The last sub-pillar tackles trade, competition, and market scale. The market conditions for trade are given in the first indicator measuring the average tariff rate weighted by import shares. The second indicator is a survey question that reflects the intensity of competition in local markets. Efforts made at finding hard data on competition so far remain unsuccessful. Domestic market scale, as measured by an economy's GDP, was incorporated in 2016, so the last sub-pillar takes into consideration the impact that the size of an economy has on its capacity to introduce and test innovations in the market place.

Pillar 5: Business sophistication

The last enabler pillar tries to capture the level of business sophistication to assess how conducive firms are to innovation activity. The Human capital and research pillar (pillar 2) made the case that the accumulation of human capital through education, particularly higher education and the prioritization of R&D activities, is an indispensable condition for innovation to take place. That logic is taken one step further here with the assertion that businesses foster their productivity, competitiveness, and innovation potential with the employment of highly qualified professionals and technicians.

The first sub-pillar includes four quantitative indicators on knowledge workers: employment in knowledge-intensive services; the availability of formal training at the firm level; R&D performed by business enterprise (GERD) as a percentage of GDP (i.e., GERD over GDP); and the percentage of total gross expenditure of R&D that is financed by business enterprise. In addition, the sub-pillar includes an indicator related to the percentage of females employed with advanced degrees. This indicator, in addition to providing a glimpse into the gender labour distributions of nations, offers more information about the degree of sophistication of the local human capital currently employed.

Innovation linkages and public/private/academic partnerships are essential to innovation. In emerging markets, pockets of wealth have developed around industrial or technological clusters and networks, in sharp contrast to the poverty that may prevail in the rest of the territory. The Innovation linkages sub-pillar draws on both qualitative and quantitative data regarding business/university collaboration on R&D, the prevalence of well-developed and deep clusters, the level of gross R&D expenditure financed by abroad, and the number of deals on joint ventures and strategic alliances. In addition, the total number of Patent Cooperation Treaty (PCT) and national office published patent family applications filed by residents in at least two offices proxies for international linkages. The GII team has been evaluating various hard data–based indicators to measure innovation linkages in an economy. Measuring innovation linkages adequately remains challenging, if not impossible, based on existing innovation metrics.

New measures based on big data may provide better measurement indicators in the future (see Box 1).

In broad terms, pillar 4 on market sophistication makes the case that well-functioning markets contribute to the innovation environment through competitive pressure, efficiency gains, and economies of transaction and by allowing supply to meet demand. Markets that are open to foreign trade and investment have the additional effect of exposing domestic firms to best practices around the globe, which is critical to innovation through knowledge absorption and diffusion, which are considered in pillars 5 and 6. The rationale behind sub-pillars 5.3 on knowledge absorption (an enabler) and 6.3 on knowledge diffusion (a result)—two sub-pillars designed to be mirror images of each other—is precisely that together they will reveal how good economies are at absorbing and diffusing knowledge.

Sub-pillar 5.3 includes five metrics that are linked to sectors with high-tech content or are key to innovation: intellectual property payments as a percentage of total trade; high-tech net imports as a percentage of total imports; imports of communication, computer and information services as a percentage of total trade; and net inflows of foreign direct investment (FDI) as a percentage of GDP (three-year average). To strengthen the sub-pillar, the percentage of research talent in business was added in 2016 to provide a measurement of professionals engaged in the conception or creation of new knowledge, products, processes, and methods and systems, including business management.

The Innovation Output Sub-Index

Innovation outputs are the results of innovative activities within the economy. Although the Output Sub-Index includes only two pillars, it has the same weight in calculating the overall GII scores as the Input Sub-Index. There are two output pillars: Knowledge and technology outputs and Creative outputs.

Pillar 6: Knowledge and technology outputs

This pillar covers all those variables that are traditionally thought to be the fruits of inventions and/or innovations. The first sub-pillar refers to the creation of knowledge. It includes five indicators that are the result of inventive and innovative activities: patent applications filed by residents both at the national patent office and at the international level through the PCT; utility model applications filed by residents at the national office; scientific and technical published articles in peer-reviewed journals; and an economy's number of articles (H) that have received at least H citations.

The second sub-pillar, on knowledge impact, includes statistics representing the impact of innovation activities at the micro- and macroeconomic level or related proxies: increases in labour productivity, the entry density of new firms, spending on computer software, the number of certificates of

BOX 1

Big data for innovation policy

We are witnessing a rapid expansion in data sources and improvements in analytics that together offer unprecedented possibilities for measuring and mapping the innovation ecosystem. Data from unconventional sources such as business websites and social media, as well as novel proprietary databases (such as online job datasets), have become the loci of various projects and studies using techniques such as text mining and machine learning to examine questions of interest for innovation policy. These possibilities—and their associated practical, conceptual, and ethical considerations—are increasingly finding their way into the mainstream discourse of governments and their evidence advisory systems. Against a backdrop of increasingly complex global issues and grand challenges, the question of how to leverage the opportunities offered by big data while ensuring the utility and legitimacy of the findings derived from them has become increasingly urgent to address.

What promises are offered by big data to understand innovation performance?

Traditional data sources such as patents and innovation surveys have been essential to broadening and deepening our understanding of key dimensions of the innovation ecosystem. However, these data capture only certain types and facets of innovation, tend to be presented in a static and highly aggregated form, and can be months or years out of date by the time they are published. As our world is increasingly digitalized and new data sources become available, opportunities abound for fresh, timely, and granular insight into both existing and previously unexplored questions that are difficult or impossible to capture with traditional metrics.

Exciting examples of the use of big data for innovation questions are beginning to emerge. For instance, web data have been used to capture the emergence of industries that do not appear in established industrial classifications and to measure innovation in industries that are less reliant on patents and publications for their innovation activities (such as the creative industries).[1] Data from the crowdsourcing website/app Yelp have been used to 'nowcast' local economic activity in the United States of America (U.S.),[2] and new online interfaces have helped us visualize tech networking trends in Wales,[3] enabling active exploration of granular innovation data by empowered users.

New analytics and data combinations also allow us to assess existing data in a different light, providing needed insight on deep and pervasive trends in the innovation landscape. In one such case, researchers linked U.S. tax records and patent data to show how socioeconomic class, gender, ethnicity, and early exposure to inventors influences becoming an inventor later in life.[4] This is an important development at a time when a growing chorus of voices are demanding fairer, more inclusive and equitable innovation outcomes.

Traditional innovation indicators are stewarded by national and international bodies that oversee their quality, representativeness, and comparability across countries and over time. By comparison, innovation metrics produced using new data sources have largely been confined to regional or national pilots or research studies, which reduces comparability and raises concerns about representativeness. Scaling up successful pilots to 'full' production is slowed by challenges such as insufficient data science capacity, inadequate technological infrastructure, and institutional or procedural rigidity. In some cases, important ethical, privacy, and data access questions also remain.

One promising domain where big data are starting to gain widespread traction is labour statistics, with successful pilots using online job vacancies having been carried out in various countries and regions globally including the U.S., China, India, and Europe (including the United Kingdom).

Another promising example is the use of inventor's or scientist's addresses associated with science and technology outputs such as patent and scientific publications and the ability to geocode them on maps to identify scientific or inventive activity—see, for example, the Special Section on Clusters in this Global Innovation Index (GII) report, which uses big data on international patent filings and scientific publishing to identify sub-national clusters of science and technology activity.

Whether big data are—broadly speaking—'ready' for inclusion in official reports must be considered within the broader goals of the publication, its intended audience, and the trade-offs between key dimensions such as novelty and geographic coverage. For instance, we may be able to add significant nuance to an existing innovation dimension or shed light on a previously unexplored question but only in a subset of countries where data coverage is adequate. These questions and trade-offs must be balanced against the relative strengths and shortcomings of existing indicators.

Going forward, more experimentation and experience with big data and new measurement approaches will be required to better assess the opportunities and challenges, to identify their optimal use in research and innovation policy making, and their potential use as input or output indicators to assess innovation performance in the GII.

Source

1 This box is based on the contribution of Juan Mateos-Garcia and Chantale Tippett of Nesta, U.K.

Notes

2 Bakhshi and Mateos-Garcia, 2016.
3 Glaeser, 2017.
4 Arloesiadur, a collaboration between Nesta and the Welsh government to map innovation in Wales, is an example of such an online interface. Information about Arloesiadur is available at https://arloesiadur.org/about.
5 Bell et al., 2017.

conformity with standard ISO 9001 on quality management systems issued, and the measure of high- and medium-high-tech industrial output over total manufactures output.

The third sub-pillar, on knowledge diffusion, is the mirror image of the knowledge absorption sub-pillar of pillar 5, with the exception of indicator 5.3.5. It includes four statistics all linked to sectors with high-tech content or that are key to innovation: intellectual property receipts as a percentage of total trade; high-tech net exports as a percentage of total exports; exports of ICT services as a percentage of total trade; and net outflows of FDI as a percentage of GDP (three-year average).

Pillar 7: Creative outputs

The role of creativity for innovation is still largely underappreciated in innovation measurement and policy debates. Since its inception, the GII has always emphasized measuring creativity as part of its Innovation Output Sub-Index. The last pillar, on creative outputs, has three sub-pillars.

The first sub-pillar on intangible assets includes statistics on trademark applications by residents at the national office; industrial designs included in applications at a regional or national office, and two survey questions regarding the use of ICTs in business and organizational models, new areas that are increasingly linked to process innovations in the literature.

The second sub-pillar on creative goods and services includes proxies to get at creativity and the creative outputs of an economy. In 2014, in an attempt to include broader sectoral coverage, a global entertainment and media output composite was added. In addition, in 2017 the indicator on audio-visual and related services exports was renamed 'Cultural and creative services exports' and expanded to include information services, advertising, market research and public opinion polling, and other, personal, cultural and recreational services (as a percentage of total trade). These two indicators complement the remainder of the sub-pillar, which measures national feature films produced in a given country (per capita count) and printing and recorded media output (as a percentage of total manufactures output), which underwent methodological change to precisely capture printing and media outputs and exclude paper industry outputs (see Annex 2 for details). Finally, the sub-pillar also measures creative goods exports (as a percentage of total trade), all which are aimed at providing an overall sense of the international reach of creative activities in the country.

The third sub-pillar on online creativity includes four indicators: generic and country-code top level domains and average yearly edits to Wikipedia, all scaled by population aged 15 through 69 years old, and mobile app creation, which is scaled by GDP (bn PPP $). This year the indicator on mobile app creation replaces the indicator video uploads on YouTube. Mobile apps represent the global commerce in digital goods, and therefore provide insight into how innovation, production and trade of digitalized creative products and services are evolving in an innovation-based economy.

Notes

1 For a fuller introduction to the Global Innovation Index, see the GII 2011.

2 Eurostat and OECD, 2005.

3 OECD, 2010; INSEAD, 2011; and WIPO, 2011.

4 INSEAD, 2011; OECD, 2013; WIPO, 2011.

5 INSEAD, 2011; OECD, 2011; WIPO, 2011.

6 See Elahi and De Beer, 2013; Charmes et al., 2016.

7 OECD, 2016.

8 For completeness, 1.7% of data points are from 2013, 0.7% from 2012, 0.7% from 2011, 0.7% from 20, 0.4% from 2009, 0.4% from 200, and 0.1% from 200. In addition, the GII is calculated on the basis of 9,042 data points (compared to 10,080 with complete series), implying that 10.3% of data points are missing. The Data Tables (Appendix II, available online at http://globalinnovationindex.org) include the reference year for each data point and mark missing data as not available (n/a).

References

Bakhshi, H. and J. Mateos-Garcia. 2016. 'New Data for Innovation Policy'. Draft Paper. Available at https://www.oecd.org/sti/106%20-%20Bakhshi%20and%20Mateos-Garcia%202016%20-%20New%20Data%20for%20Innovation%20Policy.pdf.

Bell, A., R. Chetty, X. Jaravel, N. Petkova, and J. Van Reenen. 2017, 'Who Becomes an Inventor in America? The Importance of Exposure to Innovation'. *NBER Working Paper* 24062. Cambridge. MA: National Bureau of Economic Research. Available at http://www.equality-of-opportunity.org/assets/documents/inventors_paper.pdf.

Charmes, J., F. Gault, and S. Wunsch-Vincent. 2016. 'Formulating an Agenda for the Measurement of Innovation in the Informal Economy'. In *The Informal Economy in Developing Nations: Hidden Engine of Innovation,* eds. E. Kraemer-Mbula and S. Wunsch-Vincent. Cambridge: Cambridge University Press. 336–66. Available at doi:10.1017/CBO9781316662076.

Cornell University, INSEAD, and WIPO (World Intellectual Property Organization). 2013. *The Global Innovation Index 2013: The Local Dynamics of Innovation*, eds. S. Dutta and B. Lanvin. Geneva, Ithaca, and Fontainebleau: Cornell, INSEAD, and WIPO.

Elahi, S., and J. De Beer. 2013. Knowledge and innovation in Africa: Scenarios for the future (with D. Kawooya, C. Oguamanam, and N. Rizk). Cape Town: Open AIR.

Eurostat and OECD (Organisation for Economic Co-operation and Development). 2005. *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data,* 3rd edition. Paris: OECD.

Glaeser, E. L., H. Kim, and M. Luca. 2017. 'Nowcasting the Local Economy: Using Yelp Data to Measure Economic Activity'. Harvard Business School Working Paper 18-022. Available at http://www.hbs.edu/faculty/Publication%20Files/18-022_b618d193-9486-4de3-abc4-232e1baecbeb.pdf.

INSEAD. 2011. *The Global Innovation Index 2011: Accelerating Growth and Development,* ed. S. Dutta. Fontainebleau: INSEAD.

OECD (Organisation for Economic Co-operation and Development). 2010. *The OECD Innovation Strategy: Getting a Head Start on Tomorrow.* Paris: OECD.

———. 2011. *OECD Science, Technology and Industry Scoreboard 2011.* Paris: OECD.

———. 2013. *OECD Science, Technology and Industry Scoreboard 2013.* Paris: OECD.

———. 2016. OECD Blue Sky Forum on Science and Innovation Indicators, 19–21 September 2016, Ghent, Belgium. Available at http://www.oecd.org/innovation/blue-sky.htm.

WIPO (World Intellectual Property Organization), 2011. 'The Changing Nature of Innovation and Intellectual Property'. In *World Intellectual Property Report 2011: The Changing Face of Innovation,* Chapter 1. Geneva: WIPO. Available at http://www.wipo.int/edocs/pubdocs/en/intproperty/944/wipo_pub_944_2011.pdf.

ANNEX 2

ADJUSTMENTS TO THE GLOBAL INNOVATION INDEX FRAMEWORK AND YEAR-ON-YEAR COMPARABILITY OF RESULTS

The Global Innovation Index (GII) is a cross-country performance assessment, compiled on an annual basis, which continuously seeks to update and improve the way innovation is measured. The GII report pays special attention to making accessible the statistics used in the Country/Economy Profiles and Data Tables, providing data sources and definitions, and detailing the computation methodology (Appendices I, II, III, and IV, respectively). This annex summarizes the changes made this year and provides an assessment of the impact of these changes on the comparability of rankings.

Adjustments to the Global Innovation Index framework

The GII model is revised every year in a transparent exercise. This year no change was made at either the pillar or the sub-pillar level.

Beyond the use of World Intellectual Property Organization (WIPO) data, we collaborate with both public international bodies such as the International Energy Agency; the United Nations Educational, Scientific and Cultural Organization (UNESCO); the United Nations Industrial Development Organization (UNIDO); the International Telecommunication Union (ITU); and the Joint Research Centre of the European Commission (JRC); as well as with private organizations such as the International Organization for Standardization (ISO), IHS Global Insight, QS Quacquarelli Symonds Ltd, Bureau van Dijk (BvD), ZookNIC Inc, Wikimedia Foundation, and AppAnnie to obtain the best globally available data on innovation measurement.

Table 1 provides a summary of adjustments to the GII 2018 framework for quick reference. A total of 12 indicators were modified this year: one indicator was removed, one indicator was replaced, and 10 indicators underwent methodological and/or name changes. Indicators that retained the same name as last year but are derived from a source that changed its methodology are not identified in Table 1.

The statistical audit performed by the JRC (see Annex 3) provides a confidence interval for each ranking following a robustness and uncertainty analysis of the modelling assumptions.

Sources of changes in the rankings

The GII compares the performance of national innovation systems across economies, and it also presents changes in economy rankings over time.

Importantly, scores and rankings from one year to the next are not directly comparable (see Annex 2 of the GII 2013 for a full explanation). Making inferences about absolute or relative performance on the basis of year-on-year

Table 1: Changes to the Global Innovation Index framework

GII 2017		Adjustment	GII 2018	
1.3.3	Ease of paying taxes	Removed		
2.1.2	Gov't expenditure/pupil, secondary, % GDP/cap	Indicator changed at source	2.1.2	Government funding/pupil, secondary, % GDP/cap
4.2.2	Market capitalization, % GDP	Methodology changed	4.2.2	Market capitalization, % GDP (3 year avg.)
5.1.1	Knowledge-intensive employment, %	Methodology changed	5.1.1	Knowledge-intensive employment, %
5.1.5	Females employed w/advanced degrees, % total	Name changed	5.1.5	Females employed w/advanced degrees, %
5.3.2	High-tech imports less re-imports, % total trade	Name changed	5.3.2	High-tech net imports, % total trade
6.1.2	PCT patent applications/bn PPP$ GDP	Name changed	6.1.2	PCT patents by origin/bn PPP$ GDP
6.2.5	High- & medium-high-tech manufactures, %	Methodology changed	6.2.5	High- & medium-high-tech manufactures, %
6.3.2	High-tech exports less re-exports, % total trade	Name changed	6.3.2	High-tech net exports, % total trade.
7.2.3	Global ent. & media market/th pop. 15–69.	Name changed	7.2.3	Entertainment & Media market/th pop. 15–69
7.2.4	Printing & publishing manufactures, %	Name and methodology changed	7.2.4	Printing publications & other media, % manufacturing
7.3.4	Video uploads on YouTube/pop. 15–69	Replaced	7.3.4	Mobile app creation/bn PPP$ GDP

Note: Refer to Annex 1 and Appendix III for detailed explanations of terminologies and acronyms. Indicators whose name did not change but methodology at the source did are not part of this list. Refer to Appendix III for detailed explanations of methodological changes at the source.

differences in rankings can be misleading. Each ranking reflects the relative positioning of that particular country/economy on the basis of the conceptual framework, the data coverage, and the sample of economies in the given year, also reflecting changes in the underlying indicators at the source and data availability.

A few particular factors influence the year-on-year ranking of a country/economy:

- the actual performance of the economy in question;
- adjustments made to the GII framework;
- data updates, the treatment of outliers, and missing values; and
- the inclusion or exclusion of countries/economies in the sample.

Additionally, the following characteristics complicate the time-series analysis based on simple GII scores or rankings:

- **Missing values.** The GII produces relative index scores, which means that a missing value for one economy affects the index score of other economies. Because the number of missing values decreases every year, this problem is reduced over time.
- **Reference year.** The data underlying the GII do not refer to a single year but to several years, depending on the latest available year for any given variable. In addition, the reference years for different variables are not the same for each economy. The motivation for this approach is that it widens the set of data points for cross-economy comparability.
- **Normalization factor.** Most GII variables are normalized using either GDP or population. This approach is also intended to enable cross-economy comparability. Yet, again, year-on-year changes in individual variables may be driven either by the variable's numerator or by its denominator.
- **Consistent data collection.** Finally, measuring year-on-year performance changes relies on the consistent collection of data over time. Changes in the definition of variables or in the data collection process could create movements in the rankings that are unrelated to true performance.

A detailed economy study based on the GII database and the country/economy profile over time, coupled with analytical work on grounds that include innovation actors and decision makers, yields the best results in terms of grasping an economy's innovation performance over time as well as possible avenues for improvement.

Methodology and data

The revision of the computation methodology for certain individual indicators is detailed below.

Indicator 1.3.3, which measured ease of paying taxes from the World Bank's Ease of Doing Business survey, has undergone several revisions in the past year that caused significant year-on-year fluctuations and certain criticism from surveyed countries. The indicator is currently under review,[1] hence it was removed from GII 2018 model.

Indicator 2.1.2, which measured government expenditure per pupil at the secondary school level as a percentage of GDP per capita, will no longer be produced by UNESCO and has been replaced by initial government funding per secondary student as a percentage of GDP per capita. The difference between the two is that the new indicator no longer accounts for international transfers. This indicator has been renamed accordingly.

The methodology underpinning indicator 4.2.2 was updated to measure the average of the most recent three years in order to produce a more stable reflection of this indicator.

The names of indicators 5.1.5, 5.3.2, 6.1.2, 6.3.2, and 7.2.3 were changed to be concise and better reflect what these indicators measure. This is a cosmetic change without change to the underlying measurement approach.

For indicator 5.1.1 on knowledge-intensive employment, the methodology was refined to capture a country's labour force engaged in knowledge-related activities more accurately. This indicator now uses only International Standard Classification of Occupations (ISCO)-88 (Legislators, senior officials and managers, Professionals, Technicians and associate professionals) and ISCO-08 (Managers, Professionals, and Technicians and associate professionals). The process now takes data from ISCO-08 when available and from ISCO-88 when not.

The underlying methodology for 6.2.5 has changed; it now captures a wider range of manufactured goods by assuring that when three-digit values for particular product families are absent, it is calculated using the four-digit values composing these product families. For each year, and only the same-year data are used in these calculations.

Indicator 7.2.4 now only measures a country's production of printing and recorded media outputs as classified by the International Standard Classification of All Economic Activities (ISIC Rev. 4 Division 18, group 181 with class 1811 and 1812 and group 182 with class 1820) and no longer captures the paper industry output or publishing activity. It would be desirable to continue capturing the latter creative activity. Yet in current classifications this component has been moved to services industry classifications (ISIC Rev. 4 Division 58, groups 581 and 582), which most countries—in particular non-OECD countries—do not yet report on.

Table 2: Top 15 GII economies in mobile app creation

Economy	GII score	GII rank
Cyprus	100.00	1
Finland	66.11	2
Lithuania	63.35	3
Israel	59.41	4
Estonia	52.44	5
Sweden	50.17	6
Denmark	49.65	7
Korea, Republic of	48.88	8
Moldova, Republic of	45.90	10
Hong Kong (China)	44.50	10
Lebanon	44.09	11
Slovenia	42.84	12
Switzerland	41.96	13
United States of America	41.79	14
Serbia	39.48	15

Indicator 7.3.4 previously measured video uploads on YouTube in a country. Despite its imperfections—for example, diverse uptake of this video portal across countries, lack of clear assessment of what is being uploaded, and so on—this indicator was an important marker within the GII to proxy online user creativity in the last years (see Box 2, Annex 1 of the GII 2012). A new indicator that measures the number of mobile apps created in a country replaced the indicator measuring video uploads this year (see Table 2 for the top 15 economies in this new indicator). These changes target a measurement of the innovative creative outputs produced in a country. Apps represent global commerce in completely digital goods, and therefore provide insight into how innovation, production, and trade of digitized products and services are evolving in an increasingly globalized digital economy.

Missing values

Since its inception, the GII has had a positive influence on data availability, increasing awareness of the importance of submitting timely data. The number of data points submitted by economies to international data

Table 3: GII economies with the most missing values

Economy	Number of missing values	Economy	Number of missing values
Trinidad and Tobago	26	Kuwait	20
Côte d'Ivoire	23	Jamaica	20
Togo	23	Nepal	20
Guinea	21	Benin	20

Table 4: GII economies with the fewest missing values

Economy	Number of missing values	Economy	Number of missing values
Romania	0	Estonia	3
Mexico	0	Belgium	3
Colombia	0	Spain	3
Czech Republic	1	Slovakia	3
Hungary	1	Croatia	3
Malaysia	1	Costa Rica	3
Poland	1	Serbia	3
Thailand	1	India	3
Russian Federation	1	South Africa	3
Chile	1	Kazakhstan	3
Turkey	1	Indonesia	3
Korea, Republic of	2	Switzerland	4
France	2	Netherlands	4
Austria	2	Luxembourg	4
Slovenia	2	Australia	4
Italy	2	Malta	4
Portugal	2	Cyprus	4
Bulgaria	2	Latvia	4
Ukraine	2	Lithuania	4
Brazil	2	Morocco	4
Sweden	3	Argentina	4
United Kingdom	3	Ireland	5
Finland	3	Greece	5
Denmark	3	Moldova, Republic of	5
Germany	3	Tunisia	5
Israel	3	Panama	5
Japan	3	Philippines	5
Norway	3	Egypt	5
New Zealand	3		

When it comes to country coverage, the objective is to include as many economies as possible.

agencies has substantially increased in recent years. In the GII 2018, coverage remains at a level similar to last year's, with 10.3% of data points missing.

When it comes to country coverage, the objective is to include as many economies as possible. However, it is also important to maintain a good level of data coverage within each of these economies. Because the GII results are linked to data availability (see the JRC Statistical Audit presented in Annex 3 for more details), which affects the overall GII ranks, in 2016 and 2017 the threshold rule for countries with missing data and the minimum coverage necessary per sub-pillar were progressively tightened. To be included in the GII 2018, an economy must have a minimum symmetric data coverage of 35 indicators in the Innovation Input Sub-Index (66%) and 18 indicators in the Innovation Output Sub-Index (66%), and it must have scores for at least two sub-pillars per pillar. Missing values are indicated with 'n/a' and are not considered in the sub-pillar score. This has led to the exclusion of countries that fail to meet the desired minimum coverage for indicators in any sub-pillar (see Appendix I for more details).

This adjustment derives from a sensitivity that is the result of the data availability, which is less satisfactory in the case of the Output Sub-Index: two countries that were part of the GII 2017 have data coverage below the 66% threshold in the 27 variables in the Output Sub-Index. In contrast, data coverage is satisfactory in all of these cases in the Input Sub-Index (all of these economies have indicator coverage of more than 66% over the 53 input variables). As a result, Burundi and Ethiopia, which were included in the GII 2017, dropped out this year.[2]

Despite requiring minimum levels of coverage, for several economies the number of missing data points remains very high. Table 3 lists the countries that have the highest number of missing data points (20 or more), ranking them according to how many data points are missing.

Conversely, Table 4 lists those economies with the best data coverage, ranking them according to the least number of missed data points. These economies are missing at most only five data points; some are missing none at all.

Notes

1 See http://www.worldbank.org/en/news/statement/2018/01/13/world-bank-group-statement-on-doing-business-index for the World Bank Group's Statement on the Doing Business Index, issued on 13 January 2018.

2 Conversely, Ghana—which was not included in the GII 2017—enters the GII this year with the required coverage in both sub-indices and sufficient data availability per pillar.

ANNEX 3

JOINT RESEARCH CENTRE STATISTICAL AUDIT OF THE 2018 GLOBAL INNOVATION INDEX

Michaela Saisana, Marcos Domínguez-Torreiro, and **Daniel Vértesy,** European Commission, Joint Research Centre (JRC), Ispra, Italy

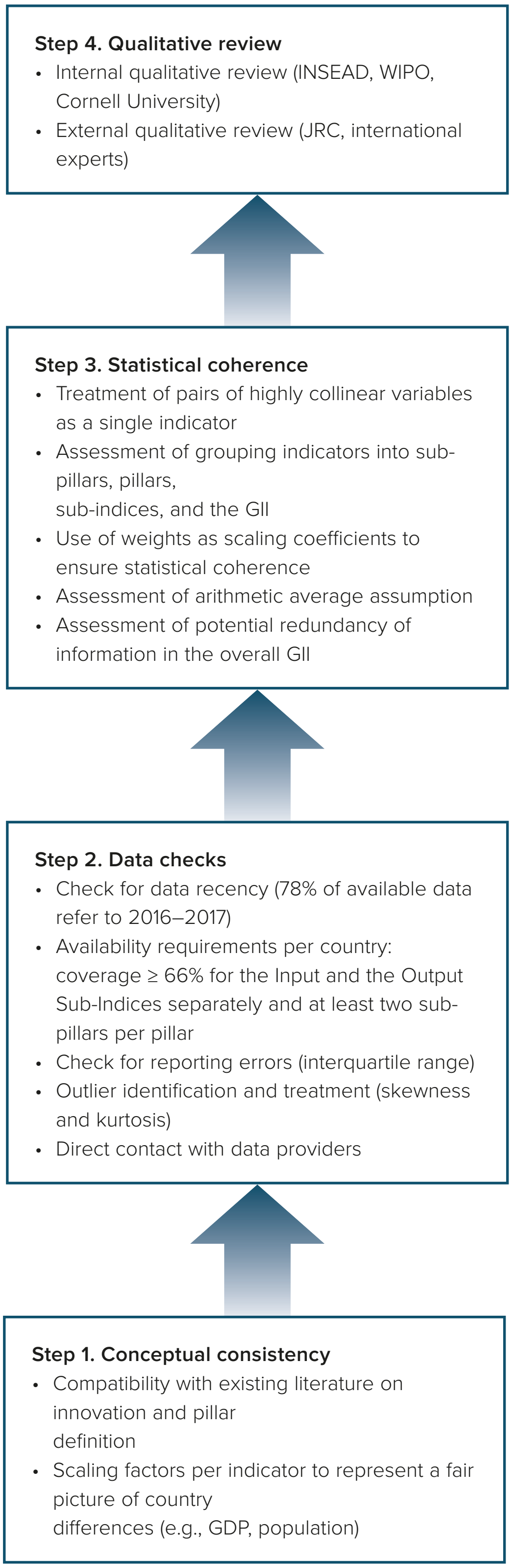
Conceptual and practical challenges are inevitable when trying to understand and model the fundamentals of innovation at the national level worldwide. In its 11th edition, the 2018 Global Innovation Index (GII) considers these conceptual challenges in Chapter 1 and deals with practical challenges—related to data quality and methodological choices—by grouping country-level data over 126 countries and across 80 indicators into 21 sub-pillars, 7 pillars, 2 sub-indices, and, finally, an overall index. This annex offers detailed insights into the practical issues related to the construction of the GII, analysing in depth the statistical soundness of the calculations and assumptions made to arrive at the final index rankings. Statistical soundness should be regarded as a necessary but not sufficient condition for a sound GII, since the correlations underpinning the majority of the statistical analyses carried out herein 'need not necessarily represent the real influence of the individual indicators on the phenomenon being measured'.[1] Consequently, the development of the GII must be nurtured by a dynamic iterative dialogue between the principles of statistical and conceptual soundness or, to put it another way, between the theoretical understanding of innovation and the empirical observations of the data underlying the variables.

The European Commission's Competence Centre on Composite Indicators and Scoreboards at the Joint Research Centre (JRC) in Ispra has been invited for the eighth consecutive year to audit the GII. As in previous editions, the present JRC audit focuses on the statistical soundness of the multi-level structure of the index as well as on the impact of key modelling assumptions on the results.[2] The independent statistical assessment of the GII provided by the JRC guarantees the transparency and reliability of the index for both policy makers and other stakeholders, thus facilitating more accurate priority setting and policy formulation in this particular field.

As in past GII reports, the JRC analysis complements the country rankings with confidence intervals for the GII, the Innovation Input Sub-Index, and the Innovation Output Sub-Index in order to better appreciate the robustness of these ranks to the computation methodology. This year a discussion of the Innovation Efficiency Ratio and the caution that needs to be attached to it is added. Finally, the JRC analysis includes an assessment of the added value of the GII and a measure of the distance to the efficient frontier of innovation by using data envelopment analysis.

Figure 1.

Conceptual and statistical coherence in the GII 2018 framework



Source: European Commission, Joint Research Centre, 2018.

Conceptual and statistical coherence in the GII framework

An earlier version of the GII model was assessed by the JRC in April–May 2018. Fine-tuning suggestions were taken into account in the final computation of the rankings in an iterative process with the JRC aimed at setting the foundation for a balanced index. The entire process followed four steps (see Figure 1).

Step 1: Conceptual consistency

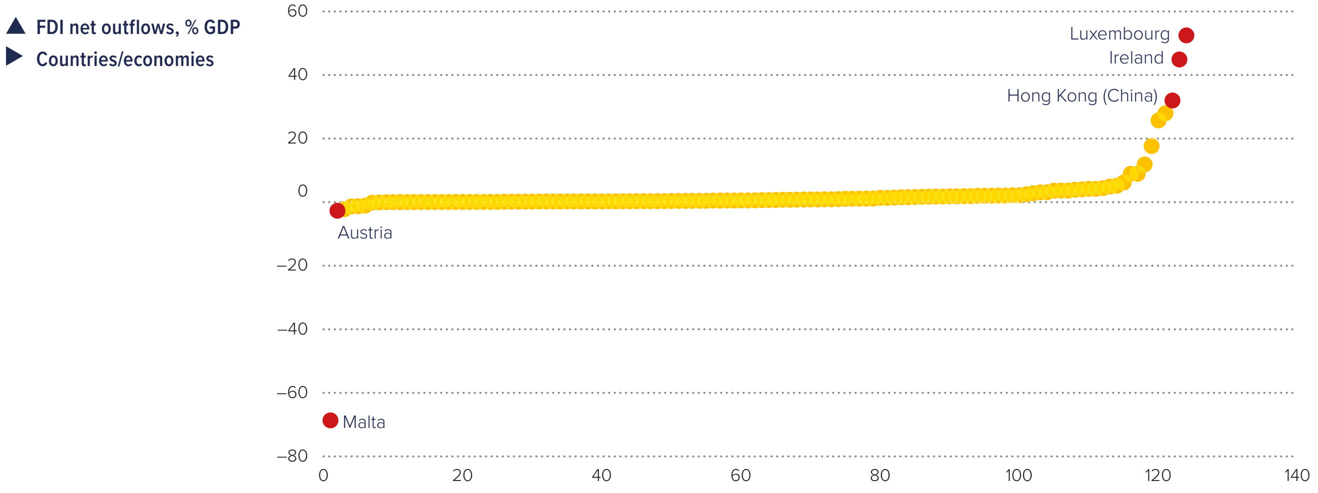
Eighty indicators were selected for their relevance to a specific innovation pillar on the basis of the literature review, expert opinion, country coverage, and timeliness. To represent a fair picture of country differences, indicators were scaled either at the source or by the GII team as appropriate and where needed. For example, expenditure on education is expressed as a percentage of GDP (indicator 2.1.1), while government funding per pupil, secondary, is expressed as a percentage of GDP per capita (indicator 2.1.2).

Step 2: Data checks

The most recently released data within the period 2007–17 were used for each economy: 78% of the available data refer to 2016 or more recent years. In past editions, until 2015, countries were included if data availability was at least 60% across all variables in the GII framework. A more stringent criterion was adopted in 2016, following the JRC recommendation of past GII audits. That is, countries were included if data availability was at least 66% within each of the two sub-indices (i.e., 35 out of 53 variables within the Input Sub-Index and 18 out of the 27 variables in the Output Sub-Index) and at least two of the three sub-pillars in each pillar could be computed. This more stringent criterion for a country’s inclusion in the GII was introduced in 2016 in order to ensure that country scores for the GII and for the two Input and Output Sub-Indices are not particularly sensitive to the missing values (as was the case for the Output Sub-Index scores of several countries in past editions). In practice, data availability for all countries included in the GII 2018 is very good: 80% of data are available for 87% (110 out of 126) of the countries in the sample. Potentially problematic indicators that could bias the overall results were identified on the

Figure 2.

Malta's outlier performance in FDI net outflows



Source: European Commission, Joint Research Centre, 2018.

Notes: Economies with the highest and lowest FDI outflow scores are highlighted. Skewness = –0.75; kurtosis = 28.16.

basis of two measures related to the shape of the distributions: skewness and kurtosis. In past editions, since 2011, values were treated if the indicators had absolute skewness greater than 2.0 and kurtosis greater than 3.5.[3] These criteria were decided jointly with the JRC back in 2011. In 2017, and after having analysed data in GII 2011–GII 2017, a less stringent criterion was adopted: an indicator was treated if the absolute skewness was greater than 2.25 and kurtosis greater than 3.5. These indicators were treated either by winsorization or by taking the natural logarithm (in case of more than five outliers; see Appendix IV Technical Notes in this report for details). In 2018, exceptional behaviour for the FDI net outflows (indicator 6.3.4) indicator was observed: Malta's outlier performance (see Figure 2) was not captured by the skewness and kurtosis criterion because of the symmetric behaviour of this indicator, whereby country values ranged between 68% and 52%. For this reason, and from this year on, it is recommended that the GII rule for the treatment of outliers be adjusted as follows:

- for indicators with absolute skewness greater than 2.25 and kurtosis greater than 3.5: use either winsorization or take the natural logarithm (in case of more than five outliers); and
- for indicators with absolute skewness less than 2.25 and kurtosis greater than 10.0: produce plots similar to the one presented in Figure 2 in order to identify potentially problematic values that need to be considered as outliers and treated accordingly.

Step 3: Statistical Coherence

Weights as scaling coefficients
Weights of 0.5 or 1.0 were jointly decided between the JRC and the GII team in 2012 to be scaling coefficients and not importance coefficients, with the aim of arriving at sub-pillar and pillar scores that were balanced in their underlying components (i.e., that indicators

Table 1: Statistical coherence in the GII: Correlations between sub-pillars and pillars

	Sub-pillar	Institutions	Human capital and research	Infrastructure	Market sophistication	Business sophistication	Knowledge & technology outputs	Creative outputs
INNOVATION INPUT SUB-INDEX	1.1. Political environment	0.95	0.79	0.86	0.71	0.79	0.70	0.79
	1.2. Regulatory environment	0.92	0.71	0.72	0.62	0.74	0.66	0.72
	1.3. Business environment	0.85	0.67	0.70	0.62	0.66	0.64	0.63
	2.1. Education	0.57	0.77	0.55	0.38	0.52	0.50	0.52
	2.2. Tertiary education	0.63	0.81	0.67	0.50	0.51	0.53	0.56
	2.3. Research and development (R&D)	0.75	0.88	0.77	0.73	0.87	0.86	0.74
	3.1. Information and communication technologies (ICTs)	0.80	0.82	0.93	0.72	0.74	0.72	0.79
	3.2. General infrastructure	0.57	0.55	0.68	0.50	0.53	0.52	0.51
	3.3. Ecological sustainability	0.63	0.53	0.75	0.44	0.58	0.55	0.66
	4.1. Credit	0.63	0.53	0.55	0.86	0.57	0.50	0.58
	4.2. Investment	0.46	0.38	0.36	0.68	0.43	0.36	0.34
	4.3. Trade, competition, and market scale	0.52	0.65	0.72	0.70	0.62	0.63	0.61
	5.1. Knowledge workers	0.77	0.81	0.77	0.68	0.88	0.77	0.73
	5.2. Innovation linkages	0.58	0.50	0.53	0.52	0.77	0.60	0.64
	5.3. Knowledge absorption	0.64	0.64	0.63	0.56	0.84	0.79	0.64
INNOVATION OUTPUT SUB-INDEX	6.1. Knowledge creation	0.68	0.78	0.66	0.63	0.81	0.90	0.79
	6.2. Knowledge impact	0.54	0.61	0.62	0.47	0.62	0.79	0.62
	6.3. Knowledge diffusion	0.62	0.61	0.62	0.54	0.73	0.81	0.59
	7.1. Intangible assets	0.60	0.60	0.69	0.55	0.64	0.65	0.89
	7.2. Creative goods and services	0.70	0.65	0.72	0.63	0.68	0.70	0.83
	7.3. Online creativity	0.82	0.74	0.76	0.62	0.81	0.77	0.85

Source: European Commission, Joint Research Centre, 2018.

and sub-pillars can explain a similar amount of variance in their respective sub-pillars/pillars). Becker et al. (2017) and Paruolo et al. (2013) show that, in weighted arithmetic averages, the ratio of two nominal weights gives the rate of substitutability between two indicators, and hence can be used to reveal the relative importance of individual indicators. This importance can then be compared with ex-post measures of variables' importance, such as the non-linear Pearson correlation ratio. As a result of this analysis, 36 out of 80 indicators and two sub-pillars—7.2 Creative goods and services and 7.3 Online creativity—were assigned half weight while all other indicators and sub-pillars were assigned a weight of 1.0. In past GII editions, despite this weighting adjustment, a small number of indicators (seven in the GII 2017 edition) were found to be non-influential in the GII framework, implying that they could not explain at least 9% of countries' variation in the respective sub-pillar scores.[4] This year all 80 indicators are found to be sufficiently influential in the GII framework, which is worth highlighting as a very positive feature of this year's GII framework.

Principal components analysis and reliability item analysis

Principal component analysis (PCA) was used to assess the extent to which the conceptual framework is confirmed by statistical approaches. PCA results confirm the presence of a single latent dimension in each of the seven pillars (one component with an eigenvalue greater than 1.0) that captures between close to 60% (pillar 4: Market sophistication) up to 82% (pillar 1: Institutions) of the total variance in the three underlying sub-pillars. Furthermore, results confirm the expectation that the sub-pillars are more correlated with their own pillar than with any other pillar and that all correlation coefficients are close to or greater than 0.70 (see Table 1).

The five input pillars share a single statistical dimension that summarizes 82% of the total variance, and the five loadings (correlation

Table 2: Distribution of differences between pillar and GII rankings

Rank differences (positions)	Institutions	Human capital and research	Infrastructure	Market sophistication	Business sophistication	Knowledge and technology outputs	Creative outputs
More than 30	14.3%	11.9%	5.6%	21.4%	17.5%	8.7%	4.8%
20–29	11.9%	13.5%	17.5%	15.1%	11.9%	10.3%	9.5%
10–19	23.0%	26.2%	26.2%	27.8%	17.5%	25.4%	24.6%
10 or more*	**49.2%**	**51.6%**	**49.2%**	**64.3%**	**46.8%**	**44.4%**	**38.89%**
5–9	26.2%	23.0%	21.4%	16.7%	19.0%	27.8%	24.6%
Less than 5	21.4%	22.2%	22.2%	17.5%	31.0%	23.0%	31.7%
Same rank	3.2%	3.2%	7.1%	1.6%	3.2%	4.8%	4.8%
Total†	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100%**
Pearson correlation coefficient with the GII	0.89	0.89	0.90	0.79	0.92	0.93	0.93

Source: European Commission, Joint Research Centre, 2018.

* This column is the sum of the prior three rows.

† This column is the sum of all white rows.

coefficients) of these pillars are very similar to each other (0.84–0.92). This similarity suggests that the five pillars make roughly equal contributions to the variation of the Innovation Input Sub-Index scores, as envisaged by the developing team. The reliability of the Input Sub-Index, measured by the Cronbach alpha value, is very high at 0.94—well above the 0.70 threshold for a reliable aggregate.[5]

The two output pillars—Knowledge and technology outputs and Creative outputs—are strongly correlated with each other (0.81); they are also both strongly correlated with the Innovation Output Sub-index (0.95).

Finally, an important part of the analysis relates to clarifying the importance of the Input and Output Sub-Indices with respect to the variation of the GII scores. The GII is built as the simple arithmetic average of the five input sub-pillars and the two output sub-pillars, which implies that the input-related pillars have a weight of 5/7 versus a weight of 2/7 for the output-related pillars. Yet this does not imply that the input aspect is more important than the output aspect in determining the variation of the GII scores. In fact, the Pearson correlation coefficient of either the Input or the Output Sub-Index with the overall GII is 0.97 (and the two sub-indices have a correlation of 0.90), which suggests that the sub-indices are effectively placed on equal footing.

Overall, the tests so far show that the grouping of variables into sub-pillars, pillars, and an overall index is statistically coherent in the GII 2018 framework, and that the GII has a balanced structure at each aggregation level. Furthermore, this year all 80 indicators are found to be sufficiently influential in the GII framework—that is, each indicator explains at least 9% of countries' variation in the respective sub-pillar scores,[6] which is again worth highlighting as a very positive feature of this year's GII framework.

Added value of the GII

As already discussed, the Input and Output Sub-Indices correlate strongly with each other and with the overall GII. Furthermore, the five pillars in the Input Sub-Index have a very high statistical reliability. These results—the strong correlation between Input and Output Sub-Indices and the high statistical reliability of the five input pillars—may be interpreted by some as a sign of redundancy of information in the GII. The tests conducted by the JRC confirm that this is not the case. In fact, for more than 38% (up to 64%) of the 126 economies included in the GII 2018, the GII ranking and any of the seven pillar rankings differ by 10 positions or more (see Table 2). This is a desired outcome because it demonstrates the added value of the GII ranking, which helps to highlight other aspects of innovation that do not emerge directly by looking into the seven pillars separately. At the same time, this result points to the value of duly taking into account the GII pillars, sub-pillars, and individual indicators on their own merit. By doing so, country-specific strengths and bottlenecks on innovation can be identified and serve as an input for evidence-based policy making.

Step 4: Qualitative Review

Finally, the GII results—including overall country classifications and relative performances in terms of the Innovation Input or Output Sub-Indices—were evaluated to verify that the overall results are, to a great extent, consistent with current evidence, existing research, and prevailing theory. Notwithstanding these statistical tests and the positive outcomes on the statistical coherence of the GII structure, the GII model is and has to remain open for future improvements as better data, more comprehensive surveys and assessments, and new relevant research studies become available.

The impact of modelling assumptions on the GII results

An important part of the GII statistical audit is to check the effect of varying assumptions inside plausible ranges. Modelling assumptions with a direct impact on the GII scores and rankings relate to:

- setting up an underlying structure for the index based on a battery of pillars,
- choosing the individual variables to be used as indicators,
- deciding whether (and how) or not to impute missing data,
- deciding whether (and how) or not to treat outliers,
- selecting the normalization approach to be applied,
- choosing the weights to be assigned, and
- deciding on the aggregation rule to be implemented.

The rationale for these choices is manifold. For instance, expert opinion coupled with statistical analysis is behind the selection of the individual indicators, common practice and ease of interpretation suggests the use of a min-max normalization approach in the [0–100] range, the treatment of outliers is driven by statistical analysis, and simplicity and parsimony criteria seem to advocate for not imputing missing data. The unavoidable uncertainty stemming from the above-mentioned modelling choices is accounted for in the robustness assessment carried out by the JRC. More precisely, the methodology applied herein allows for the joint and simultaneous analysis of the impact of such choices on the aggregate scores, resulting in error estimates and confidence intervals calculated for the GII 2018 individual country rankings.

As suggested in the relevant literature on composite indicators,[7] the robustness assessment was based on Monte Carlo simulation and multi-modelling approaches, applied to 'error-free' data where potential outliers and eventual errors and typos have already been corrected in a preliminary stage. In particular, the three key modelling issues considered in the assessment of the GII were the treatment of missing data, the pillar weights, and the aggregation formula used at the pillar level.

Monte Carlo simulation comprised 1,000 runs of different sets of weights for the seven pillars in the GII. The weights were assigned to the pillars based on uniform continuous distributions centred in the reference values. The ranges of simulated weights were defined by taking into account both the need for a wide enough interval to allow for meaningful robustness checks and the need to respect the underlying principle of the GII that the Input and the Output Sub-Indices should be placed on an equal footing. As a result of these considerations, the limit values of uncertainty for the five input pillars are 10%–30%; the limit values for the two output pillars are 40%–60% (see Table 3).

The GII developing team, for transparency and replicability, has always opted not to estimate missing data. The 'no imputation' choice, which is common in similar contexts, might encourage economies not to report low data values. Yet this is not the case for the GII. After 11 editions of the GII, the index-developing team has not encountered any intentional no-reporting strategy. The consequence of the 'no imputation' choice in an arithmetic average is that it is equivalent to replacing an indicator's missing value for a given country with the respective sub-pillar score. Hence the available data (indicators) in the incomplete pillar may dominate, sometimes biasing the ranks up or down. To test the impact of the 'no imputation' choice, the JRC estimated missing data using the Expectation Maximization (EM) algorithm that was applied within each GII pillar.[8]

Regarding the aggregation formula, decision-theory practitioners challenge the use of simple arithmetic averages because of their fully compensatory nature, in which a comparative high advantage on a few indicators can compensate for a comparative disadvantage on many indicators.[9] To assess the impact of this compensability issue, the JRC relaxed the strong perfect substitutability assumption

Table 3: Uncertainty parameters: Missing values, aggregation, and weights

		Reference	Alternative
I. Uncertainty in the treatment of missing values		No estimation of missing data	Expectation Maximization (EM)
II. Uncertainty in the aggregation formula at pillar level		Arithmetic average	Geometric average
III. Uncertainty intervals for the GII pillar weights			
GII Sub-Index	Pillar	Reference value for the weight	Distribution assigned for robustness analysis
Innovation Input	Institutions	0.2	U[0.1, 0.3]
	Human capital and research	0.2	U[0.1, 0.3]
	Infrastructure	0.2	U[0.1, 0.3]
	Market sophistication	0.2	U[0.1, 0.3]
	Business sophistication	0.2	U[0.1, 0.3]
Innovation Output	Knowledge and technology outputs	0.5	U[0.4, 0.6]
	Creative outputs	0.5	U[0.4, 0.6]

Source: European Commission, Joint Research Centre, 2018.

inherent in the arithmetic average and considered instead the geometric average, which is a partially compensatory approach that rewards economies with balanced profiles and motivates economies to improve in the GII pillars in which they perform poorly, and not just in *any* GII pillar.[10]

Four models were tested based on the combination of no imputation versus EM imputation, and arithmetic versus geometric average, combined with 1,000 simulations per model (random weights versus fixed weights), for a total of 4,000 simulations for the GII and each of the two sub-indices (see Table 3 for a summary of the uncertainties considered).

Uncertainty analysis results

The main results of the robustness analysis are shown with median ranks and 90% confidence intervals computed across the 4,000 Monte Carlo simulations for the GII and the two sub-indices (Figure 3 on page 78), and, for the first time this year, for the Efficiency Ratio (Figure 4 on page 79). The figures order economies from best to worst according to their reference rank (black line), the dot being the median rank over the simulations.

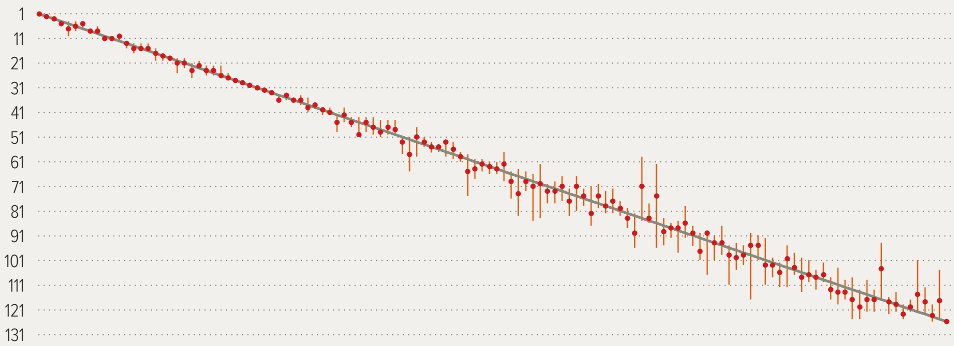
All published GII 2018 ranks lay within the simulated 90% confidence intervals, and for most economies these intervals are narrow enough for meaningful inferences to be drawn: there is a shift of fewer than 10 positions for 92 of the 126 economies. However, it is also true that only a small number of country ranks vary significantly with changes in weights and aggregation formula and because of the estimation of missing data. These six countries—Panama, The former Yugoslav Republic of Macedonia, Belarus, Rwanda, the Plurinational State of Bolivia, and Niger—have 90% confidence interval widths of more than 20 positions (up to 34 positions in the case of Belarus). Consequently, their GII ranks—between the 70th (Panama) and 122nd position (Niger) in the GII classification—should be interpreted cautiously and certainly not taken at face value. This is a remarkable improvement compared to GII versions until 2016, where more than 40 countries had confidence interval widths of more than 20 positions. This improvement in the confidence one can attach to the GII 2018 ranks is the direct result of the developers' choice since 2016 to adopt a more stringent criterion for an economy's inclusion, which requires at least 66% data availability within each of the two sub-indices. Some caution is also warranted in the Input Sub-Index for four economies—Bosnia and Herzegovina, Albania, Ukraine, and Panama—that have 90% confidence interval widths over 20 (up to 25 for Bosnia and Herzegovina). The Output Sub-Index is slightly more sensitive to the methodological choices: 14 countries—Panama, the United Republic of Tanzania, Oman, Paraguay, Mauritius, The former Yugoslav Republic of Macedonia, Ecuador, Zimbabwe, Namibia, Belarus, the Plurinational State of Bolivia, Guinea, Niger, and Togo—have 90% confidence interval widths over 20 (up

Figure 3.
Robustness analysis of the GII and Input and Output Sub-Indices

▲ GII 2018 ranks and interval of simulated ranks
▶ Countries/economies

● Median rank
— GII 2018 rank

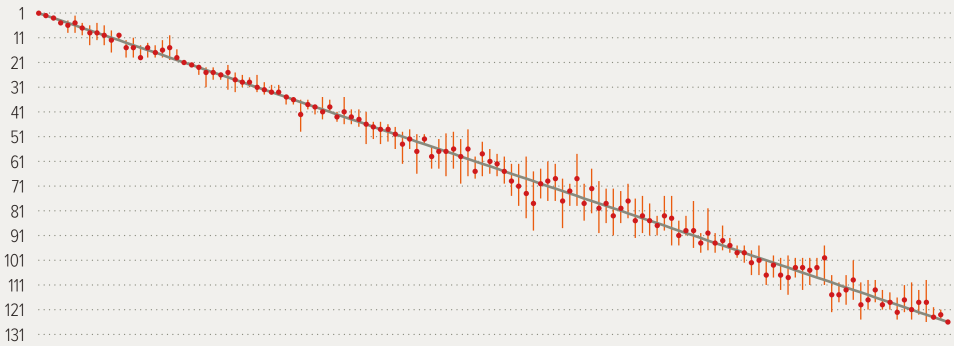
GII rank vs. median rank, 90% confidence intervals



▲ GII 2018 Input ranks and interval of simulated ranks
▶ Countries/economies

● Median rank
— GII 2018 Input rank

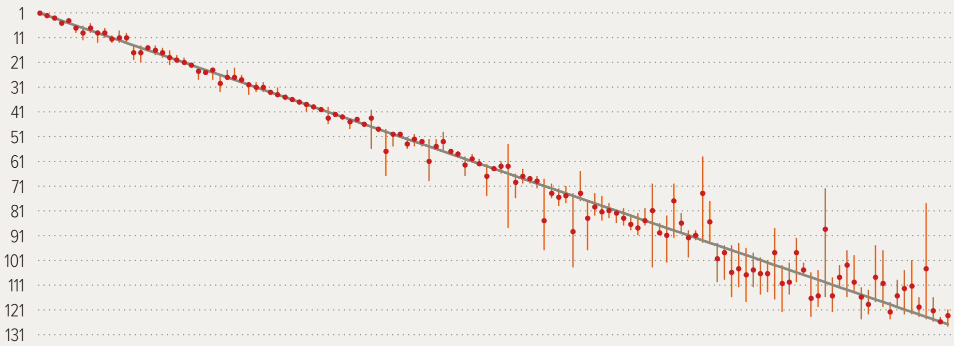
Input rank vs. median rank, 90% confidence intervals



▲ GII 2018 Output ranks and interval of simulated ranks
▶ Countries/economies

● Median rank
— GII 2018 Output rank

Output rank vs. median rank, 90% confidence intervals

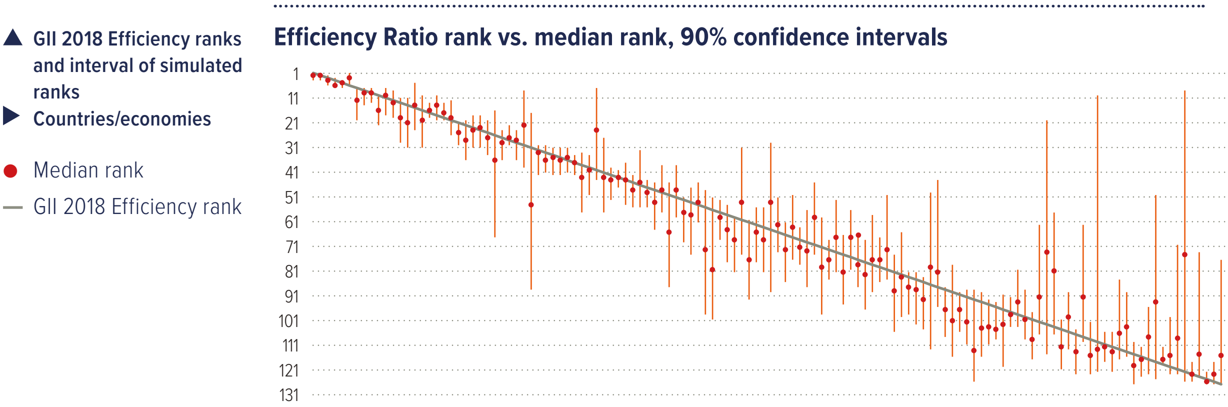


Source: European Commission, Joint Research Centre, 2018.

Notes: Median ranks and intervals are calculated over 4,000 simulated scenarios combining simulated weights, imputed versus missing values, and geometric versus arithmetic average at the pillar level. The Spearman rank correlation between the median rank and the GII 2018 rank is 0.996; between the median rank and the Innovation Input 2018 rank it is 0.997; and between the median rank and the Innovation Output 2018 rank it is 0.990.

Figure 4.

Robustness analysis of the Efficiency Ratio



Source: European Commission, Joint Research Centre, 2018.

Note: Median ranks and intervals are calculated over 4,000 simulated scenarios combining simulated weights, imputation versus no imputation of missing values, and geometric versus arithmetic average within the Input and Output Sub-Indices. The Spearman rank correlation between the median rank and the Innovation Efficiency Ratio 2018 rank is 0.969

to 47 for Togo). This sensitivity is mostly the consequence of the estimation of missing data and the fact that there are only two pillars: this means that changes to the imputation method, weights, or aggregation formula have a more notable impact on the country ranks in the Innovation Output Sub-Index.

Although a few economy ranks, in the GII 2018 overall or in the two sub-indices, appear to be sensitive to the methodological choices, the published rankings for the vast majority can be considered representative of the plurality of scenarios simulated herein. Taking the median rank as the yardstick for an economy's expected rank in the realm of the GII's unavoidable methodological uncertainties, 75% of the economies are found to shift fewer than three positions with respect to the median rank in the GII, or in the Input and Output Sub-Indices.

For full transparency and information, Table 4 reports the GII 2018 Index and Input and Output Sub-Indices economy ranks together with the simulated 90% confidence intervals in order to better appreciate the robustness of the results to the choice of weights, of the aggregation formula, and the impact of estimating missing data (where applicable).

Emphasizing the identification of and relation between innovation input and output indicators seems irresistible from a policy perspective since doing so may possibly shed light on the effectiveness of innovation systems and policies. Yet this statistical audit shows that Innovation Efficiency Ratios, calculated as ratios of indices, have to be approached with care. Upon the request of the GII developing team, this year's JRC audit addresses the following question: How much confidence can one attach to the GII innovation efficiency scores and ranks for the countries worldwide? The Innovation Efficiency Ratio is calculated as the ratio of the Innovation Output Sub-Index score over the Innovation Input Sub-Index score. It shows how much innovation output a given country is getting for its inputs. Figure 4 shows the median ranks and 90% confidence intervals computed across the 4,000 Monte Carlo simulations for the Innovation Efficiency Ratio.

All published GII 2018 Innovation Efficiency ranks lay within the simulated 90% confidence intervals, but for most economies these intervals are too wide for meaningful inferences to be drawn: there is a shift of more than 20 positions for 60 of the 126 economies. Hence, while propagating the uncertainty in the two GII sub-indices to their sum—the GII—has a modest impact on the GII ranks (merely six countries shift more than 20 positions), this same

Table 4: GII 2018 and Input/Output Sub-Indices: Ranks and 90% confidence intervals

	GII 2018		Input Sub-Index		Output Sub-Index	
Country/Economy	Rank	Interval	Rank	Interval	Rank	Interval
Switzerland	1	[1, 1]	2	[2, 3]	1	[1, 1]
Netherlands	2	[2, 3]	9	[5, 12]	2	[2, 2]
Sweden	3	[2, 3]	3	[2, 4]	3	[3, 3]
United Kingdom	4	[4, 6]	4	[4, 6]	6	[6, 9]
Singapore	5	[4, 10]	1	[1, 1]	15	[14, 21]
United States of America	6	[4, 8]	6	[2, 9]	7	[6, 12]
Finland	7	[4, 7]	5	[4, 9]	8	[5, 9]
Denmark	8	[7, 9]	7	[5, 10]	13	[9, 13]
Germany	9	[6, 9]	17	[14, 19]	5	[4, 5]
Ireland	10	[10, 12]	18	[12, 19]	9	[8, 13]
Israel	11	[10, 12]	19	[10, 20]	11	[10, 13]
Korea, Republic of	12	[9, 12]	14	[11, 19]	12	[8, 13]
Japan	13	[13, 15]	12	[9, 12]	18	[15, 19]
Hong Kong (China)	14	[13, 17]	8	[6, 14]	21	[19, 22]
Luxembourg	15	[13, 16]	25	[23, 28]	4	[4, 6]
France	16	[13, 16]	16	[13, 19]	16	[14, 16]
China	17	[15, 20]	27	[22, 32]	10	[7, 11]
Canada	18	[17, 20]	10	[6, 14]	26	[26, 33]
Norway	19	[18, 19]	13	[12, 19]	24	[24, 26]
Australia	20	[19, 25]	11	[8, 17]	31	[29, 33]
Austria	21	[19, 23]	20	[16, 20]	28	[23, 28]
New Zealand	22	[21, 27]	15	[14, 20]	30	[29, 34]
Iceland	23	[20, 23]	22	[22, 23]	19	[16, 22]
Estonia	24	[22, 26]	26	[25, 28]	17	[14, 18]
Belgium	25	[22, 26]	21	[21, 21]	23	[23, 28]
Malta	26	[22, 27]	28	[25, 33]	14	[14, 20]
Czech Republic	27	[25, 28]	30	[27, 31]	20	[18, 21]
Spain	28	[27, 28]	23	[22, 26]	27	[24, 28]
Cyprus	29	[29, 30]	33	[30, 34]	22	[21, 22]
Slovenia	30	[29, 31]	31	[26, 33]	29	[26, 29]
Italy	31	[30, 31]	29	[26, 31]	32	[29, 33]
Portugal	32	[32, 33]	32	[29, 34]	33	[32, 34]
Hungary	33	[32, 33]	41	[36, 41]	25	[23, 28]
Latvia	34	[34, 37]	35	[35, 38]	38	[37, 41]
Malaysia	35	[34, 36]	34	[30, 34]	39	[38, 39]
Slovakia	36	[35, 37]	39	[38, 42]	36	[35, 36]
Bulgaria	37	[34, 38]	44	[40, 46]	34	[31, 34]
United Arab Emirates	38	[35, 41]	24	[23, 31]	54	[52, 55]
Poland	39	[38, 39]	38	[36, 40]	40	[40, 41]
Lithuania	40	[40, 42]	36	[35, 38]	44	[44, 48]
Croatia	41	[39, 41]	42	[41, 45]	42	[41, 42]
Greece	42	[42, 49]	40	[35, 44]	52	[51, 56]
Ukraine	43	[39, 45]	75	[58, 79]	35	[35, 36]
Thailand	44	[43, 47]	52	[48, 56]	45	[43, 45]
Viet Nam	45	[43, 51]	65	[59, 70]	41	[39, 46]
Russian Federation	46	[43, 49]	43	[35, 46]	56	[52, 56]
Chile	47	[43, 50]	45	[40, 47]	53	[50, 55]
Moldova, Republic of	48	[44, 51]	79	[72, 86]	37	[37, 38]
Romania	49	[44, 50]	49	[46, 53]	48	[47, 48]
Turkey	50	[44, 50]	62	[53, 67]	43	[43, 44]
Qatar	51	[51, 58]	47	[45, 52]	60	[59, 67]
Montenegro	52	[51, 65]	51	[49, 62]	55	[52, 69]
Mongolia	53	[47, 59]	66	[62, 75]	47	[40, 56]
Costa Rica	54	[51, 55]	64	[58, 67]	51	[49, 51]
Serbia	55	[53, 57]	56	[52, 64]	58	[56, 58]
Mexico	56	[54, 57]	54	[50, 54]	61	[58, 61]
India	57	[52, 59]	63	[56, 66]	57	[49, 57]
South Africa	58	[53, 60]	48	[45, 54]	65	[61, 66]
Georgia	59	[57, 61]	53	[50, 66]	62	[60, 63]
Kuwait	60	[58, 75]	81	[73, 86]	49	[48, 67]
Saudi Arabia	61	[60, 68]	46	[41, 54]	78	[74, 83]
Uruguay	62	[60, 65]	67	[62, 79]	59	[57, 59]
Colombia	63	[61, 66]	50	[47, 56]	72	[70, 76]

Country/Economy	GII 2018 Rank	GII 2018 Interval	Input Sub-Index Rank	Input Sub-Index Interval	Output Sub-Index Rank	Output Sub-Index Interval
Brazil	64	[61, 66]	58	[49, 64]	70	[67, 72]
Iran, Islamic Republic of	65	[57, 69]	93	[80, 97]	46	[45, 47]
Tunisia	66	[65, 76]	77	[64, 82]	63	[62, 75]
Brunei Darussalam	67	[64, 83]	37	[36, 49]	112	[103, 112]
Armenia	68	[65, 73]	94	[90, 98]	50	[49, 55]
Oman	69	[66, 85]	57	[50, 67]	75	[74, 104]
Panama	70	[62, 84]	78	[69, 90]	66	[54, 88]
Peru	71	[70, 78]	59	[52, 70]	83	[83, 89]
Bahrain	72	[69, 78]	70	[64, 76]	74	[71, 78]
Philippines	73	[67, 77]	82	[70, 84]	68	[64, 70]
Kazakhstan	74	[72, 83]	55	[55, 64]	91	[89, 100]
Mauritius	75	[67, 81]	61	[59, 68]	89	[70, 92]
Morocco	76	[72, 79]	84	[75, 90]	69	[67, 70]
Bosnia and Herzegovina	77	[71, 87]	68	[59, 84]	82	[80, 87]
Kenya	78	[70, 80]	91	[77, 96]	64	[63, 65]
Jordan	79	[73, 82]	88	[75, 95]	67	[66, 76]
Argentina	80	[72, 82]	72	[62, 77]	81	[81, 86]
Jamaica	81	[77, 83]	83	[76, 92]	76	[65, 77]
Azerbaijan	82	[80, 88]	76	[70, 85]	87	[86, 91]
Albania	83	[82, 96]	69	[65, 89]	95	[94, 110]
The former Yugoslav Republic of Macedonia	84	[59, 85]	71	[61, 77]	93	[59, 94]
Indonesia	85	[78, 86]	90	[83, 91]	73	[72, 79]
Belarus	86	[62, 96]	60	[48, 67]	110	[72, 116]
Dominican Republic	87	[84, 95]	92	[90, 98]	77	[77, 97]
Sri Lanka	88	[86, 92]	95	[87, 97]	80	[78, 84]
Paraguay	89	[85, 98]	89	[85, 95]	86	[70, 104]
Lebanon	90	[79, 92]	87	[75, 89]	94	[77, 94]
Botswana	91	[87, 95]	74	[70, 79]	107	[102, 107]
Tanzania, United Republic of	92	[90, 101]	106	[100, 113]	71	[68, 97]
Namibia	93	[89, 107]	80	[72, 91]	103	[88, 117]
Kyrgyzstan	94	[91, 101]	85	[78, 91]	101	[100, 115]
Egypt	95	[87, 99]	105	[100, 108]	79	[75, 85]
Trinidad and Tobago	96	[95, 111]	86	[83, 91]	104	[103, 122]
Ecuador	97	[94, 105]	96	[92, 98]	97	[95, 116]
Cambodia	98	[95, 103]	103	[100, 113]	84	[82, 91]
Rwanda	99	[90, 117]	73	[68, 88]	120	[109, 120]
Senegal	100	[91, 101]	102	[99, 108]	90	[82, 90]
Tajikistan	101	[92, 111]	104	[99, 115]	88	[83, 102]
Guatemala	102	[100, 108]	107	[100, 111]	96	[95, 109]
Uganda	103	[102, 112]	98	[95, 102]	111	[108, 122]
El Salvador	104	[95, 112]	97	[95, 100]	113	[97, 116]
Honduras	105	[98, 107]	99	[97, 107]	106	[92, 110]
Madagascar	106	[100, 114]	119	[116, 125]	85	[80, 87]
Ghana	107	[101, 110]	108	[100, 108]	102	[101, 114]
Nepal	108	[105, 113]	101	[101, 111]	114	[99, 114]
Pakistan	109	[102, 110]	120	[111, 122]	92	[89, 93]
Algeria	110	[108, 117]	100	[95, 107]	116	[113, 123]
Cameroon	111	[104, 119]	115	[109, 121]	98	[94, 112]
Mali	112	[109, 117]	118	[114, 121]	100	[98, 112]
Zimbabwe	113	[108, 125]	121	[110, 125]	99	[96, 118]
Malawi	114	[113, 125]	111	[110, 118]	108	[106, 124]
Mozambique	115	[109, 122]	112	[107, 119]	109	[105, 120]
Bangladesh	116	[113, 122]	114	[110, 125]	105	[102, 115]
Bolivia, Plurinational State of	117	[94, 117]	109	[95, 111]	117	[95, 118]
Nigeria	118	[116, 123]	116	[109, 118]	115	[112, 125]
Guinea	119	[114, 122]	124	[120, 125]	118	[97, 120]
Zambia	120	[119, 125]	123	[109, 126]	119	[118, 125]
Benin	121	[117, 122]	110	[107, 122]	123	[116, 124]
Niger	122	[101, 122]	113	[101, 117]	122	[101, 123]
Côte d'Ivoire	123	[112, 123]	122	[113, 123]	127	[121, 128]
Burkina Faso	124	[119, 126]	117	[113, 121]	121	[105, 123]
Togo	125	[105, 125]	125	[121, 125]	125	[116, 126]
Yemen	126	[125, 126]	126	[125, 126]	124	[78, 125]

Source: European Commission, Joint Research Centre, 2018.

Table 5: Sensitivity analysis: Impact of modelling choices on countries with most sensitive ranks

			Number of countries that *improve*		Number of countries that *deteriorate*	
Index or Sub-Index	Uncertainty tested (pillar level only)	Spearman rank correlation	by 20 or more positions	between 10 and 19 positions	by 20 or more positions	between 10 and 19 positions
GII	Geometric vs. arithmetic average	0.994	0	0	0	4
	EM imputation vs. no imputation of missing data	0.989	2[1]	4	0	3
	Geometric average and EM imputation vs. arithmetic average and missing values	0.984	4[2]	2	0	7
Input Sub-Index	Geometric vs. arithmetic average	0.996	0	0	0	1
	EM imputation vs. no imputation of missing data	0.994	0	2	0	2
	Geometric average and EM imputation vs. arithmetic average and missing values	0.992	0	4	0	2
Output Sub-Index	Geometric vs. arithmetic average	0.997	0	0	0	3
	EM imputation vs. no imputation of missing data	0.962	4[2]	12[3]	2[4]	15[5]
	Geometric average and EM imputation vs. arithmetic average and missing values	0.961	4[2]	9	2[4]	14

Source: European Commission, Joint Research Centre, 2018.

Notes:

1 The former Yugoslav Republic of Macedonia, the Plurinational State of Bolivia.

2 The former Yugoslav Republic of Macedonia, Belarus, the Plurinational State of Bolivia, Togo.

3 Panama, Mauritius, Paraguay, Lebanon, Namibia, Rwanda, El Salvador, Honduras, Nepal, Guinea, Niger, Côte d'Ivoire.

4 Oman, the United Republic of Tanzania.

5 Kuwait, Tunisia, Albania, Dominican Republic, Kyrgyzstan, Trinidad and Tobago, Ecuador, Tajikistan, Uganda, Ghana, Cameroon, Zimbabwe, Malawi, Mozambique, Bangladesh.

uncertainty propagation to their ratio has a very high impact on the country ranks. This is not a challenge specific to the GII framework per se but a statistical property that comes with ratios of composite indicators. Hence developers and users of indices alike need to take efficiency ratios of this nature with great caution. The JRC recommendation to the GII team would be to draw policy inference from the Input-Output performance in way similar to the way they plot GII scores against the economies' level of economic development and to comment on those pairs/groups of economies that have similar Innovation Input levels but very different Innovation Output levels. Economies that are at the same Output level but have very different Input levels should be treated the same way. Additional plots of the Innovation Efficiency Ratios against either the GII scores or economies' GDP per capita levels would offer additional insights in this respect.

Sensitivity analysis results

Complementary to the uncertainty analysis, sensitivity analysis has been used to identify which of the modelling assumptions have the highest impact on certain country ranks.

Table 5 summarizes the impact of changes of the EM imputation method and/or the geometric aggregation formula, with fixed weights at their reference values (as in the original GII). Similar to last year's results, this year neither the GII nor the Input or Output Sub-Index are found to be heavily influenced by the imputation of missing data, or the aggregation formula. Depending on the combination of the choices made, only six countries—The former Yugoslav Republic of Macedonia, Belarus, the Plurinational State of Bolivia, Togo, Oman, and the United Republic of Tanzania—shift rank by 20 positions or more.

All in all, the published GII 2018 ranks are reliable and for the vast majority of countries the simulated 90% confidence intervals are narrow enough for meaningful inferences to be drawn. Nevertheless, the readers of the GII 2018 report should consider country ranks in the GII 2018 and in the Input and Output Sub-Indices not only at face value but also within the 90% confidence intervals in order to better appreciate to what degree a country's rank depends on the modelling choices. Since 2016, following the JRC recommendation in past GII audits, the developers' choice to apply the 66% indicator coverage threshold separately to the Input and Output Sub-Indices in the GII 2018 has led to a net increase in the reliability of country ranks for the GII and the two sub-indices. Furthermore, the adoption in 2017 of less stringent criterion for the skewness and kurtosis (greater than 2.25 in absolute value and greater than 3.5, respectively) has not introduced any bias in the estimates.

Efficiency frontier in the GII by Data Envelopment Analysis

Is there a way to benchmark countries' multi-dimensional performance on innovation without imposing a fixed and common set of weights that may not be fair to a particular country?

Several innovation-related policy issues at the national level entail an intricate balance between global priorities and country-specific strategies. Comparing the multi-dimensional performance on innovation by subjecting countries to a fixed and common set of weights may prevent acceptance of an innovation index on the grounds that a given weighting scheme might not be fair to a particular country. An appealing feature of the Data Envelopment Analysis (DEA) literature applied in real decision-making settings is to determine endogenous weights that maximize the overall score of each decision-making unit given a set of other observations.

In this section, the assumption of fixed pillar weights common to all countries is relaxed once more; this time country-specific weights that maximize a country's score are determined endogenously by DEA.[11] In theory, each country is free to decide on the relative contribution of each pillar to its score, so as to achieve the best possible score in a computation that reflects its innovation strategy. In practice, the DEA method assigns a higher (lower) contribution to those pillars in which a country is relatively strong (weak). Reasonable constraints on the weights are applied to preclude the possibility of a country achieving a perfect score by assigning a zero weight to weak pillars: for each country, the share of each pillar score (i.e., the pillar score multiplied by the DEA weight over the total score) has upper and lower bounds of 5% and 20% respectively. The DEA score is then measured as the weighted average of all seven pillar scores, where the weights are the country-specific DEA weights, compared to the best performance among all other countries with those same weights. The DEA score can be interpreted as a measure of the 'distance to the efficient frontier'.

Table 6 on page 84 presents the pie shares and DEA scores for the top 25 countries in the GII 2018, next to the GII 2018 ranks and efficiency ratio ranks. All pie shares are in accordance with the starting point of granting leeway to each country when assigning shares, while not violating the (relative) upper and lower bounds. The pie shares are quite diverse, reflecting the different national innovation strategies. These pie shares can also be seen to reflect countries' comparative advantage in certain GII pillars vis-à-vis all other countries and all pillars. For example, Switzerland and Singapore are the only two economies this year that obtain a perfect DEA score of 1.00. In the case of Switzerland this is achieved by assigning 18% to 19% of its DEA score to a mix of input and output pillars, namely Human capital and research, Business sophistication, Knowledge and technology outputs, and Creative outputs. Instead, merely 6% to 10% of Switzerland's DEA score comes from three input pillars, namely Institutions, Infrastructure, and Market sophistication. Using a different mix, Singapore would assign 14% to 20% of its DEA score of 1.00 to all five input pillars—Institutions, Human capital and research, Infrastructure, Market sophistication, and Business sophistication—while merely 5% to 6% of its DEA score comes from the two output pillars capturing Knowledge and technology outputs and Market sophistication. Switzerland and Singapore are closely followed by Sweden, the Netherlands, the United Kingdom, Finland, the United States of America, and Denmark, which score between 0.94 (Denmark) and 0.98 (Sweden) in terms of efficiency. Figure 5 on page 85 shows how close the DEA scores and the GII 2018 scores are for all 126 economies (Pearson correlation of 0.993). Note that, by construction, the version of DEA used herein is closer to the GII than to the Efficiency Ratio calculated as the Output Sub-Index score divided by the Input Sub-Index score (with a Pearson correlation of 0.680).

The Efficiency Ratio and the DEA score embed very different concepts of efficiency, leading to completely different results and insights. A high score in the Innovation Efficiency Ratio is obtained by scoring higher on the Output Sub-Index than on the Input Sub-Index, irrespective of the actual scores in these two sub-indices. In contrast, a high score in the DEA approach can be obtained by having comparative advantages on several GII pillars (irrespective of these being input or output pillars). The DEA scores are therefore closer to the GII scores than to the Innovation Efficiency Ratio.

Table 6: Pie shares (absolute terms) and efficiency scores for the top 25 economies in the GII 2018

	INPUT PILLARS					OUTPUT PILLARS						
Country/Economy	Institutions	Human capital and research	Infrastructure	Market sophistication	Business sophistication	Knowledge and technology outputs	Creative outputs	Efficient frontier rank (DEA)	GII rank	Difference from GII rank	Efficiency Ratio rank	Difference from GII rank
Switzerland	0.08	0.18	0.10	0.06	0.19	0.19	0.19	1	1	0	1	0
Netherlands	0.20	0.10	0.20	0.05	0.20	0.05	0.20	4	2	–2	4	–2
Sweden	0.20	0.20	0.20	0.05	0.20	0.05	0.10	3	3	0	10	–7
United Kingdom	0.20	0.20	0.20	0.20	0.05	0.05	0.10	4	4	0	21	–17
Singapore	0.18	0.20	0.14	0.18	0.19	0.06	0.05	1	5	4	63	–58
United States of America	0.20	0.05	0.20	0.20	0.20	0.05	0.10	7	6	–1	22	–16
Finland	0.20	0.20	0.20	0.06	0.20	0.05	0.09	6	7	1	24	–17
Denmark	0.20	0.20	0.20	0.20	0.05	0.05	0.10	7	8	1	29	–21
Germany	0.20	0.20	0.20	0.10	0.05	0.05	0.20	10	9	–1	9	0
Ireland	0.20	0.20	0.20	0.05	0.20	0.05	0.10	13	10	–3	13	–3
Israel	0.05	0.20	0.20	0.20	0.20	0.05	0.10	13	11	–2	14	–3
Korea, Republic of	0.20	0.20	0.20	0.20	0.05	0.05	0.10	10	12	2	20	–8
Japan	0.20	0.09	0.20	0.20	0.20	0.05	0.06	10	13	3	44	–31
Hong Kong (China)	0.20	0.05	0.20	0.20	0.20	0.05	0.10	9	14	5	54	–40
Luxembourg	0.20	0.05	0.20	0.10	0.20	0.05	0.20	20	15	–5	2	13
France	0.20	0.20	0.20	0.20	0.05	0.05	0.10	16	16	0	32	–16
China	0.05	0.05	0.20	0.20	0.20	0.10	0.20	24	17	–7	3	14
Canada	0.20	0.20	0.20	0.20	0.08	0.05	0.07	16	18	2	61	–43
Norway	0.20	0.20	0.20	0.20	0.07	0.05	0.08	18	19	1	52	–33
Australia	0.20	0.20	0.20	0.20	0.05	0.05	0.10	13	20	7	76	–56
Austria	0.20	0.20	0.20	0.08	0.20	0.05	0.07	20	21	1	53	–32
New Zealand	0.20	0.20	0.20	0.20	0.05	0.05	0.10	19	22	3	59	–37
Iceland	0.20	0.05	0.20	0.10	0.20	0.05	0.20	22	23	1	23	0
Estonia	0.20	0.05	0.20	0.20	0.10	0.05	0.20	24	24	0	12	12
Belgium	0.20	0.20	0.20	0.07	0.20	0.05	0.08	22	25	3	38	–13

Source: European Commission, Joint Research Centre, 2018.

Notes: Pie shares are in absolute terms, bounded by 0.05 and 0.20 for all seven pillars. In the GII 2018, however, the five input pillars each have a fixed weight of 0.10; the two output pillars each have a fixed weight of 0.25.

Conclusions

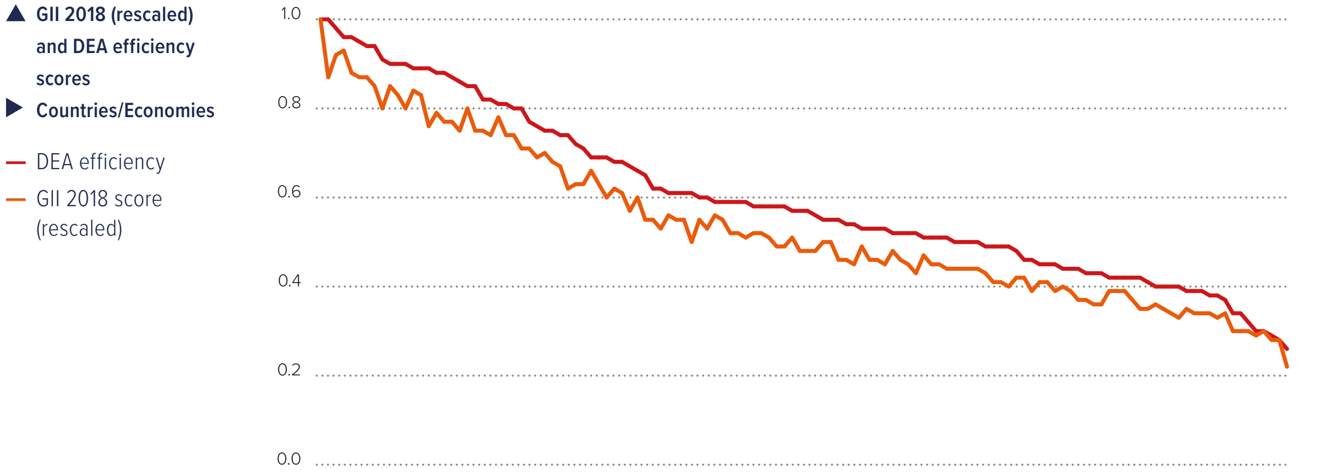
The JRC analysis suggests that the conceptualized multi-level structure of the GII 2018—with its 80 indicators, 21 sub-pillars, 7 pillars, 2 sub-indices, up to an overall index—is statistically sound and balanced: that is, each sub-pillar makes a similar contribution to the variation of its respective pillar. This year, the refinements made by the developing team have helped to enhance the already strong statistical coherence in the GII framework, where for all 80 indicators their capacity to distinguish countries' performance is maintained at the sub-pillar level or higher.

The no-imputation choice for not treating missing values, common in relevant contexts and justified on grounds of transparency and replicability, can at times have an undesirable impact on some country scores, with the additional negative side-effect that it may encourage countries not to report low data values. The adoption, since 2016, by the GII team of a more stringent data coverage threshold (at least 66% for the input- and output-related indicators, separately) has notably improved the confidence in the country ranks for the GII and the two sub-indices.

Additionally, the choice of the GII team, which was made in 2012, to use weights as scaling

Figure 5.

GII 2018 scores and DEA 'distance to the efficient frontier' scores



Source: European Commission, Joint Research Centre, 2018.

Note: For comparison purposes, we have rescaled the GII scores by dividing them with the best performer in the overall GII 2018.

coefficients during the development of the index constitutes a significant departure from the traditional, yet erroneous, vision of weights as a reflection of indicators' importance in a weighted average. It is hoped that such a consideration will be made also by other developers of composite indicators to avoid situations where bias sneaks in when least expected.

The strong correlations between the GII components are proven not to be a sign of redundancy of information in the GII. For more than 38.9% (up to 64.3%) of the 126 economies included in the GII 2018, the GII ranking and the rankings of any of the seven pillars differ by 10 positions or more. This demonstrates the added value of the GII ranking, which helps to highlight other components of innovation that do not emerge directly from looking into the seven pillars separately. At the same time, this finding points to the value of duly taking into account the GII pillars, sub-pillars, and individual indicators on their own merits. By doing so, country-specific strengths and bottlenecks in innovation can be identified and serve as an input for evidence-based policy making.

All published GII 2018 ranks lie within the simulated 90% confidence intervals that take into account the unavoidable uncertainties in the estimation of missing data, the weights (fixed vs. simulated), and the aggregation formula (arithmetic vs. geometric average) at the pillar level. For the vast majority of countries these intervals are narrow enough for meaningful inferences to be drawn: the intervals comprise fewer than 10 positions for 73% (92 out of 126) of the economies. Some caution is needed mainly for six countries—Panama, The former Yugoslav Republic of Macedonia, Belarus, Rwanda, the Plurinational State of Bolivia, and Niger—with ranks that are highly sensitive to the methodological choices. The Input and the Output Sub-Indices have the same modest degree of sensitivity to the methodological choices related to the imputation method, weights, or aggregation formula. Country ranks, either in the GII 2018 or in the two sub-indices, can be considered representative of the many possible scenarios: 75% of the countries shift fewer than three positions with respect to the median rank in the GII or either of the Input and Output Sub-Indices.

All things considered, the present JRC audit findings confirm that the GII 2018 meets international quality standards for statistical soundness, which indicates that the GII index is a reliable benchmarking tool for innovation practices at the country level around the world.

Finally, the 'distance to the efficient frontier' measure calculated with Data Envelopment Analysis could complement the Innovation Efficiency Ratio as a measure of efficiency, even if it is conceptually closer to the GII score than to the efficiency ratio. A word of caution on taking Innovation Efficiency Ratios alone as a yardstick for the identification of and relation between innovation input and output indicators has been added in this year's GII audit. In fact, the same amount of uncertainty in the Input and Output Sub-Indices propagated to their sum—that is, to the GII or to their ratio—is found to result in notably different impact on country ranks: six countries shifting more than 20 positions in the case of the GII compared to 60 of the 126 economies shifting more than 20 positions in the case of the Innovation Efficiency Ratio. Not being a challenge specific to the GII framework but a statistical property that comes with ratios of composite indicators, developers and users of indices alike need to be very careful when considering efficiency ratios of this nature. The JRC recommendation to the GII team would be to gain policy insights from plots of Input against Output performance, and from plots of the Innovation Efficiency Ratios against either the GII scores or economies' GDP per capita levels.

The GII should not be seen as the ultimate and definitive ranking of countries with respect to innovation. On the contrary, the GII best represents an ongoing attempt by the Cornell University, the business school INSEAD, and the World Intellectual Property Organization to find metrics and approaches that better capture the richness of innovation, continuously adapting the GII framework to reflect the improved availability of statistics and the theoretical advances in the field. In any case, the GII should be regarded as a sound attempt to pave the way for better and more informed innovation policies worldwide.

Notes

1 OECD/EC JRC, 2008, p. 26.

2 The JRC analysis was based on the recommendations of the OECD/EC JRC (2008) *Handbook on Composite Indicators* and on more recent research from the JRC. The JRC audits on composite indicators are conducted upon request of the index developers and are available at https://ec.europa.eu/jrc/en/coin and https://composite-indicators.jrc.ec.europa.eu.

3 Groeneveld and Meeden (1984) set the criteria for absolute skewness above 1 and kurtosis above 3.5. The skewness criterion was relaxed in the GII case after having conducted ad-hoc tests in the GII 2008-2018 timeseries.

4 An indicator can explain 9% of the countries' variation in the GII sub-pillar scores if the Pearson correlation coefficient between the two series is 0.3.

5 Nunnally, 1978.

6 See note 4.

7 Saisana et al., 2005; Saisana et al., 2011; Vértesy 2016; Vértesy and Deiss, 2016.

8 The Expectation-Maximization (EM) algorithm (Little and Rubin, 2002; Schneider, 2001) is an iterative procedure that finds the maximum likelihood estimates of the parameter vector by repeating two steps: (1) The expectation E-step: Given a set of parameter estimates, such as a mean vector and covariance matrix for a multivariate normal distribution, the E-step calculates the conditional expectation of the complete-data log likelihood given the observed data and the parameter estimates. (2) The maximization M-step: Given a complete-data log likelihood, the M-step finds the parameter estimates to maximize the complete-data log likelihood from the E-step. The two steps are iterated until the iterations converge.

9 Munda, 2008.

10 In the geometric average, pillars are multiplied as opposed to summed in the arithmetic average. Pillar weights appear as exponents in the multiplication. All pillar scores were greater than zero, hence there was no reason to rescale them to avoid zero values that would have led to zero geometric averages.

11 A question that arises from the GII approach is whether there is a way to benchmark countries' multi-dimensional performance on innovation without imposing a fixed and common set of weights that may not be fair to a particular country. The original question in the DEA literature was how to measure each unit's relative efficiency in production compared to a sample of peers, given observations on input and output quantities and, often, no reliable information on prices (Charnes and Cooper, 1985). A notable difference between the original DEA question and the one applied here is that no differentiation between inputs and outputs is made (Cherchye et al., 2008; Melyn and Moesen, 1991). To estimate DEA-based distance to the efficient frontier scores, we consider the $m = 7$ pillars in the GII 2018 for $n = 126$ countries, with y_{ij} the value of pillar j in country i. The objective is to combine the pillar scores per country into a single number, calculated as the weighted average of the m pillars, where w_i represents the weight of the i-th pillar. In absence of reliable information about the true weights, the weights that maximize the DEA-based scores are endogenously determined. This gives the following linear programming problem for each country j:

$$Y_i = \max_{wij} \frac{\sum_{j=1}^{7} y_{ij} w_{ij}}{\max_{y_c \in \{dataset\}} \sum_{j=1}^{7} y_{cj} w_{ij}} \qquad \text{(bounding constraint)}$$

subject to

$$w_{ij} \geqq 0, \qquad \text{(non-negativity constraint)}$$

where

$j = 1, \ldots, 7,$
$i = 1, \ldots, 126$

In this basic programming problem, the weights are non-negative and a country's score is between 0 (worst) and 1 (best).

References and related reading

Barbosa, N. and A. P. Faria. 2011. 'Innovation across Europe: How important are institutional differences'. *Research Policy* 40: 1157–69.

Becker, W., M. Saisana, P. Paruolo, and I. Vandecasteele. 2017. 'Weights and Importance in Composite Indicators: Closing the Gap'. *Ecological Indicators* 80: 12–22.

Charnes, A. and W. W. Cooper. 1985. 'Preface to Topics in Data Envelopment Analysis'. *Annals of Operations Research* 2: 59–94.

Cherchye, L., W. Moesen, N. Rogge, T. Van Puyenbroeck, M. Saisana, A. Saltelli, R. Liska, and S. Tarantola. 2008. 'Creating Composite Indicators with DEA and Robustness Analysis: The Case of the Technology Achievement Index'. *Journal of Operational Research Society* 59: 239–51.

Groeneveld, R. A. and G. Meeden. 1984. 'Measuring Skewness and Kurtosis'. *The Statistician* 33: 391–99.

Little, R. J. A. and D. B. Rubin. 2002. *Statistical Analysis with Missing Data.* 2nd edition. Hoboken, NJ: John Wiley & Sons, Inc.

Melyn, W. and W. Moesen. 1991. 'Towards a Synthetic Indicator of Macroeconomic Performance: Unequal Weighting when Limited Information Is Available'. *Public Economics Research Paper* 17. Leuven: Centre for Economic Studies.

Munda, G. 2008. *Social Multi-Criteria Evaluation for a Sustainable Economy.* Berlin Heidelberg: Springer-Verlag.

Nunally, J. 1978. *Psychometric Theory.* New York: McGraw-Hill.

OECD/EC JRC (Organisation for Economic Co-operation and Development/European Commission, Joint Research Centre). 2008. *Handbook on Constructing Composite Indicators: Methodology and User Guide.* Paris: OECD.

Paruolo, P., M. Saisana, and A. Saltelli. 2013. 'Ratings and Rankings: Voodoo or Science?' *Journal of the Royal Statistical Society* A 176 (3): 609–34.

Saisana, M., B. D'Hombres, and A. Saltelli. 2011. 'Rickety Numbers: Volatility of University Rankings and Policy Implications'. *Research Policy* 40: 165–77.

Saisana, M., A. Saltelli, and S. Tarantola. 2005. 'Uncertainty and Sensitivity Analysis Techniques as Tools for the Analysis and Validation of Composite Indicators'. *Journal of the Royal Statistical Society* A 168 (2): 307–23.

Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. 2008. *Global Sensitivity Analysis: The Primer.* Chichester, England: John Wiley & Sons.

Schneider, T. 2001. 'Analysis of incomplete climate data: Estimation of mean values and covariance matrices and imputation of missing values. *Journal of Climate* 14: 853–71.

Vértesy, D. and R. Deiss. 2016. *The Innovation Output Indicator 2016: Methodology Update.* EUR 27880. European Commission, Joint Research Centre.

Vértesy, D. 2016. 'A Critical Assessment of Quality and Validity of Composite Indicators of Innovation'. Paper presented at the OECD Blue Sky III Forum on Science and Innovation Indicators,19–21 September 2016, Ghent, Belgium.

CHAPTER 2

ENERGY FOR ALL

How Innovation Is Democratizing Electricity

Norbert Schwieters, PwC
Barry Jaruzelski and Robert Chwalik, PwC's Strategy&

In Rwanda, an estimated 600,000 households in remote areas are accessing the Internet, charging mobile phones, and lighting their homes for the first time thanks to off-grid solar energy.[1] With support from local government, private companies are installing solar systems on residential roofs and using a 'pay as you go' business model to sell energy as a service. Consumers gain partial use of solar systems they could not afford to purchase outright and use their mobile phones, frequently supported by Wi-Fi routers installed by the solar companies, to make weekly or monthly payments.

Opportunities such as this abound in today's fast-evolving power industry. This is particularly true in the developing world, where demand for electricity is high but centralized power grids are scarce, inefficient, and unreliable. Many of these countries face a huge population expansion in the decades ahead, with limited infrastructure to meet existing and future demand. Currently, an estimated 1.2 billion people worldwide lack electricity,[2] and 2.8 billion people live without clean and safe cooking facilities.[3]

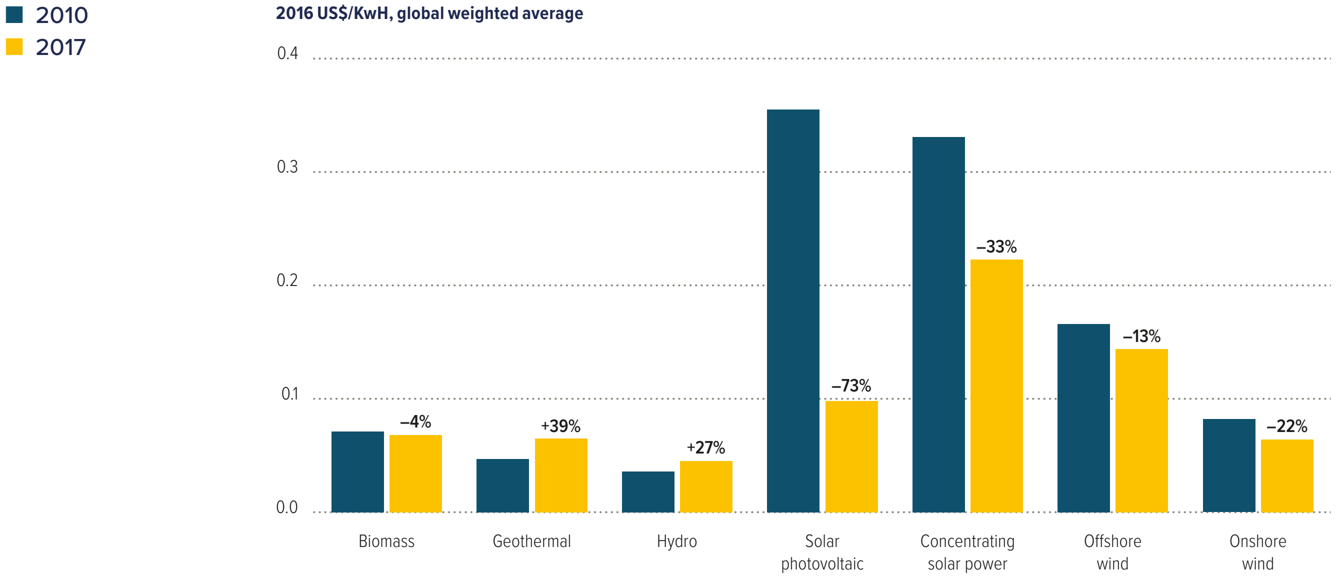
Various international initiatives are underway to address the issue of 'affordable, reliable, sustainable, and modern energy for all,' [4] as set out in the UN's Sustainable Development Goal 7 (see also Box 2 in Chapter 1). In Africa, where programmes are active in Côte d'Ivoire, Ghana, Rwanda, and Tanzania, to name just a few, off-grid renewable energy technology makes it possible to build distributed energy systems from the ground up. In Asia, innovative models are emerging that can transmit stored geothermal energy across national boundaries. In Central America, governments are democratizing energy by mandating the construction of micro-grids to serve remote communities.

In developed countries, the shift towards new energy sources and distribution models is happening at a relatively slower pace, in part because centralized power generation via long-distance power grids is well established and to a large extent runs on marginal cost. The considerable cost of building these grids has already been covered in the past. Hence in these areas, the transition towards renewable energy is primarily a function of political will and burgeoning environmental awareness movements, often alongside strong incentive schemes, technology breakthroughs, and decreasing costs. Indeed, despite the legacy impediments, it is no longer rare for energy consumers in developed countries to take on the mantle of so-called prosumers—for example, by producing their own energy through a rooftop solar panel, using what they need, and sending the excess out to the grid for a fee. This bottom-up nature of energy transformation is a paradigm shift for utilities, which previously generated energy and cascaded it down to the consumers through their transmission and distribution grids.

Viewed broadly, across the globe, the traditional energy frameworks are no longer viable. Energy companies will have to adapt quickly to these changes or risk being rendered irrelevant. Indeed, how well companies innovate using new types of energy and distribution technologies will determine their ability to survive the transformation—and,

Figure 1.

Global levelized cost of electricity from utility-scale renewable power-generation technologies, 2010–17



Source: IRENA, 2018.

importantly, to compete against the many start-ups and entrepreneurial firms eyeing the energy market. Energy executives are well aware of the shifting ground they face. In PwC's most recent Global Power and Utilities survey,[5] 47% of power company executives said that there is a medium-to-high probability that new models of distributed generation could shrink the role of some utilities to providers of back-up power.

A study by the International Renewable Energy Agency (IRENA) revealed that the costs of renewable power generation are already 'very competitive' for meeting the needs of new generation capacity.[6] In fact, in 2017 auctions of offshore wind power in Europe required no government subsidies because bidders could rely on falling technology costs and rising power prices to anticipate profits. And an analysis by the global financial services firm UBS predicts that shrinking battery and solar costs will make the combination of electric vehicles, solar panels, and stationary batteries for excess power in the home or businesses a practicable option in many markets within the next 10 years.[7]

The renewables environment

Of all renewables, solar photovoltaics (PVs) have arguably benefited the most in the past couple of years from scale and technology breakthroughs. Many of the recent improvements in this arena have emerged from advances in cadmium telluride (CdTe), the semiconductor material with the smallest carbon footprint and shortest energy payback time of all solar technologies. Other so-called thin film silicon technologies, primarily copper indium gallium selenide (CIGS), as well as non-silicon approaches (chiefly perovskite) are also beginning to impact the direction that PVs will take in the future. Annual research budgets for the top 12 solar panel manufacturers increased by nearly 500% between 2006 and 2016.[8]

As this R&D blitz has played out, the cost of solar PV electricity has fallen some 73% since 2010, according to IRENA,[9] down to an average of roughly US$0.10 per kilowatt-hour (KwH) compared to a range of $0.05 to $0.17 per KwH for fossil fuels (Figure 1). (Swanson's Law observes that that the price of solar photovoltaic modules tends to drop 20% for every doubling of cumulative shipped volume.[10])

In developed countries, consumers are being courted with plenty of attractive options to make the shift to solar energy. For example, solar PV wafer and cell manufacturers—such as China's JA Solar and Minnesota-based start-up SolarPod[11]—have designed modular assembly systems that simplify the installation of solar panels and reduce maintenance costs, critical improvements needed to overcome consumer reluctance to jump off of the relatively reliable existing utility grid. And some renewables companies, such as Tesla's SolarCity and Utah-based Vivint Solar (in partnership with Mercedes Benz),[12] have stoked latent residential demand through leasing programmes for home PV systems, thereby addressing potential customer concerns about financing these systems.

In less-developed regions, government energy departments are developing aggressive programmes to expand the presence of PVs. South Africa's government has rolled out a national solar water heater programme with the goal of 1 million installations in households and commercial buildings by 2019, although the campaign has been slowed a bit by financial constraints.[13] In fact, across Africa,[14] where the population is expected to double by 2050—well beyond the capacity of power utilities to satisfy demand—M-Kopa, the continent's market leader in home PVs, has installed some 400,000 PV systems. At its current rate of growth, the company may add another 200,000 to that number over the next year. During the same period, smaller rivals such as Off Grid Electric, Bboxx, and Azuri Technologies could double their client base.[15] These solar home systems offer cleaner, safer, and cheaper lighting over time than kerosene, the primary alternative for lighting in developing nations.

In South America, Chile has set a target of generating 70% of its power from renewables by 2050 and, consequently, has opened its energy grid to private investment by PV companies (see Chapter 10).[16] One of the most ambitious projects is a constellation of solar fields in the Atacama Desert. Among the big investors is Italy's large global utility Enel.

In India, the government is aiming to install 1 million solar water pumps by 2021—which would have a huge impact on the agriculture sector through improved irrigation. In fact, Bloomberg's recent New Energy Finance report estimates that some 8 million irrigation pumps powered by diesel in India could eventually be converted to solar pumps.[17] In Madhya Pradesh province, the local government is currently operating a large procurement programme for solar pumps and is considering replacing even grid-connected electric pumps with solar pumps based on cost economics.

Technology innovation has also transformed the prospects for wind energy, making it the least expensive renewable energy source. Modern wind turbines are increasingly cost-effective and reliable, and they have scaled up in size to achieve multi-megawatt (MW) power ratings. Because of longer, lighter rotor blades, taller towers, and better drivetrains and performance-optimizing control systems, an average onshore wind turbine with a capacity of 2.5–3 MW can produce more than 6 million kWh in a year—enough to supply 1,500 average European households with electricity.[18] Currently, at least 24 countries around the world are meeting 5% or more of their annual electricity demand with wind power.[19]

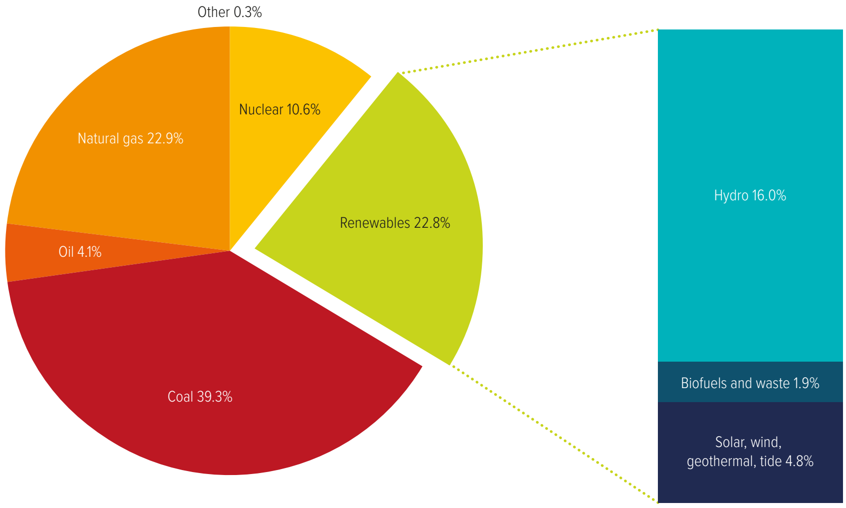
China is the planet's largest wind energy producer, with nearly 100,000 turbines—one-third of the world's volume—that can generate 145 gigawatts (GW) of electricity, nearly double the capacity of wind farms in the United States of America (U.S.).[20] The U.S., Germany, Spain, and India round out the top five producers of wind energy, and all are experiencing steady growth.[21] Exports of wind-powered generating sets from the U.S. rose from US$16 million in 2007 to US$488 million in 2014, but fell back to US$17 million in 2016.[22]

Less well-known innovations in power generation will also have a substantial impact on the energy upheaval underway. For instance, geothermal power,[23] which is generated from steam produced from reservoirs of hot water found a couple of miles or more below the Earth's surface, is an attractive alternative in areas where drilling into the Earth is relatively easy and inexpensive. In California's dried up Salton Sea, the independent power company CalEnergy Generation is managing 10 massive geothermal plants that generate 327 MW, enough to power half a dozen small cities.[24]

Lao People's Democratic Republic, Malaysia, and Thailand recently signed an historic multi-lateral geothermal power trade deal.[25] This comes on the heels of 16 cross-border energy projects targeted by countries in the Association of Southeast Asian Nations (ASEAN) with the goal of transferring up to 23,200 MW of power across the region. Government leaders view regional renewable energy power trading agreements as an effective way for countries with excess installed capacity to export power to neighbours facing blackout issues as well as for those who

Figure 2.

Fuel shares in global electricity production, 2015



Source: OECD/IEA, 2017b.

Note: 'Other' includes electricity from non-renewable wastes and other sources not included elsewhere, such as fuel cells, chemical heat, and so on. Because of rounding, totals in the figure may not add up exactly.

need more energy to speed up economic, industrial, and infrastructure development.

Another renewable advance with some promise is converting waste to energy (WtE), which involves primarily incinerating biomass to produce clean electricity, heat, or fuel. Methane is perhaps the most familiar WtE application, but more sophisticated and environmentally safer approaches are under design. Most of the WtE activity is taking place in developing countries, providing vital sources of energy for cooking, lighting, and agricultural uses. For instance, biogas has especially high potential in Kenya,[26] where in 2017 the Gorge Farm Plant debuted to power the cultivation of vegetables and flowers, heat greenhouses, and provide surplus energy to up to 6,000 rural homes. In India, cities produce some 62 million tons of waste annually, of which only 82% is collected—and of that only 28% is treated.[27] But WtE projects are now on the rise. It was reported in 2016 that some 24 waste-to-energy projects that would produce 233 MW of electricity were in various stages of construction,[28] and research by PwC estimates that 20 jobs will be created for every MW produced from WtE in India.

Transmission turmoil

Even as the renewables movement evolves (Figure 2), there will still be a place for fossil fuel power. But the latter's influence will wane as it morphs into a supplemental energy source, satisfying demand when sufficient electricity is not available from renewables. Facing this instability in their main power source, utilities are struggling to find growth opportunities in their primary business lines: distribution and transmission grids. Moreover, although utilities offer customers numerous plans for offloading excess generated renewable energy either at a residential site or a larger power facility to the grid, so it can be delivered as needed, many private non-utilities are interceding and creating their own local off-grid transmission solutions. For instance, GE Energy Connections is installing renewable energy distribution hubs in France, Canada, and Singapore,[29] while ABB has a large operation in Australia.[30]

Fuelling off-grid activities are significant breakthroughs in energy storage devices. Such devices primarily include batteries that can warehouse renewable power in people's homes or in local facilities, providing a steady stream of energy regardless of the solar or wind conditions in the area. Battery storage technology has gotten a big boost from the automotive industry, where battery innovation for electric vehicles has been a priority and has led to a sharp drop in the cost of energy storage solutions.

Indeed, since 2012, the price of lithium-ion batteries has dropped some 70%;[31] analysts forecast that lithium-ion storage could fall below US$200/kWh by 2019 and perhaps hit US$100 by 2025, from about US$250/kWh now.[32] At US$200/kWh, previously uneconomical applications, such as the colocation of battery storage and solar PV systems, suddenly become extremely attractive. Solar industry experts at IHS Markit believe that, by 2025, the world's base of cumulative installed battery storage capacity will reach 52 GW, up from around 4 GW today. And revenue from this sector is forecast to grow at a 16% compound annual growth rate (CAGR), reaching $7 billion.[33]

Befitting its role in electric vehicle development, Tesla has pushed battery storage across all applications. Already, in South Australia, Tesla has built and installed a 100 MW lithium-ion battery to dispense power into an electricity grid that was crippled during a mass blackout in 2016. But, beyond Tesla's innovations, a lot of other activity will change the face of energy storage and decouple renewable energy from the grid even more. For example, the global power company AES is building a 300 MW battery storage facility that will function as a power plant in the middle of Long Beach, California.[34]

Meanwhile, in China, where transmission limitations are impeding the expansion of power from renewable energy, the government is promoting a 15-year Energy Technology Innovation Action Plan. This plan calls for accelerated research into advanced energy storage to support renewables integration, micro-grid development, and electric vehicles. An initial project is the construction of a vast energy storage installation in the northeast city of Dalian, led by Chinese battery manufacturer Dalian Rongke. The 200 MW facility will nearly triple China's present grid-connected battery capacity when it is completed in 2018.[35]

The possibilities from battery storage are especially welcome in developing regions. Lithium-ion technology promises to offer emerging economic areas the alternative of quickly installing micro-grids as energy distribution sources, rather than having to wait for fully functioning national grids. In Africa, for example, Fenix International and mobile payment provider MTN Group Ltd are partnering to bring solar panel and battery systems to nearly 1 million consumers for as little as $0.20 a day, so they can charge mobile phones and light their homes.[36]

While battery storage will clearly be a mainstream solution within the next decade, the volume of energy innovation research currently underway means that unexpected developments will likely play a role as well, even if they seem far-fetched now. One of these, power to gas (PtG), avoids battery storage altogether while creating a virtuous circle for renewable energy programmes. Under this concept, excess power produced by wind or solar can be converted into methane gas, stored in traditional gas pipelines, and used to fuel cars and heat buildings on a sustainable basis at zero marginal cost. In a pilot project, automaker Audi has two e-gas plants that produce synthetic methane from wind-generated electricity.[37]

Does this mean that traditional transmission lines will be obsolete in future? It is unlikely. But because building long-distance grids is costly and can present environmental challenges, the case for new grids is increasingly difficult to justify—especially as offsite and storage solutions become viable. In Germany, these obstacles are even affecting a renewable resource project: little progress has been seen to date in a planned few thousand kilometres of new transmission lines to transport wind energy north to south because of environmental and political concerns.

Cash flow

A compelling sign that an energy revolution is underway is the amount of money from public and private sectors pouring into activities related to developing and distributing power from renewable sources. It is relatively commonplace for virtually every major private equity firm to have a lending arm devoted solely to developing renewable energy projects. Large investors such as Blackrock and Aon Hewitt are pouring money into the sector.[38] They are attracted by strong demand for new projects, which is increasing valuations and rates of return rapidly. Long-term investors that provide capital upfront can receive a stable bond-like cash flow for decades from an individual project. Moreover, as coal and nuclear plants are retired globally, renewable project assets will only become more attractive to investors.

It is relatively commonplace for virtually every major private equity firm to have a lending arm devoted solely to developing renewable energy projects.

Private-sector investment will be a centrepiece of the new energy ecosystem.

Another significant source of money for renewable energy efforts is pension funds, some of which are flush with cash. One of the biggest pension funds in the world, the California State Teachers' Retirement System, announced plans a few years ago to double its clean energy and technology investments to US$3.7 billion through the end of the decade. This group has already put US$1.9 billion into these projects in the past.[39]

More creative, non-traditional investment vehicles are also emerging. Typical of these are the new renewables' crowdsourcing opportunities. One of the more successful took place in 2013, when Mosaic offered online investors 4.5% returns for loans as small as US$24. Within 24 hours the project was sold out.[40] Since then, there have been dozens of similar investment programmes provided by an array of businesses.

In a likewise novel approach, solar power companies have begun to sell bundled securities backed by pools of residential and commercial solar energy projects. The assets included in these tranches are loans and leases on renewable energy facilities and transmission lines as well as power purchase agreements (PPAs), which organizations use to buy off-grid renewable energy. PPAs are becoming a significant revenue stream in the renewables ecosystem because many of the world's largest companies—such as Google, Heineken,[41] and AB InBev[42]—are investing in PPA-based projects to supply themselves with renewable energy and add capacity and distribution to local grids. Recently General Electric formed its own PPA unit to accelerate renewables project development around the world.[43]

Renewable energy credits (RECs) are providing yet another channel for cash flow in the new power paradigm. Led by firms such as Sterling Planet and Green Mountain Energy, REC companies offer residential and commercial solar and wind farm customers chits for excess energy sold back to large and small grids. These credits can then be resold in various local energy markets.

The 30,000-foot view

With all of the changes that are already being witnessed in the power generation and distribution landscape, it is obvious that we—and the utilities industry, in particular—are in for a rapid period of continuing transformation. International initiatives such as the Kyoto Protocol and the Paris Climate Change Accord have placed an increased focus on renewable energy, and on integrating it with innovative local distribution and storage solutions: micro-grids, batteries, and smart technologies. This trend reflects both a commitment to decarbonize the economy and the falling costs and innovative attractiveness of the technology.

Private-sector investment will be a centrepiece of the new energy ecosystem. Traditional utilities can still play a big role by leveraging their relationships with consumers to offer new types of power distribution and generation programmes. For their own survival, utilities should not think of this period as purely a disruption against which they need to defend. Instead they should view it as an opportunity to use their breadth and scale to provide renewable resource access for consumers and convenient ways for consumers to manage their power use and store or share excess capacity.

At the same time, start-ups and entrepreneurs in developed and developing regions have clearly determined that, as renewables become more viable, the power industry has the potential of being a bonanza. These innovators will continue to follow new research threads and apply new technologies to the full array of renewable resources, even those barely known to us now. Their activities will ensure that the once-staid energy market will be evolving for decades to come.

Meanwhile, local and state governments have a relatively straightforward job ahead: provide private companies with a safe environment to get a return on their investments. Given the increasing cost competitiveness of renewable energy, there is less need for policy makers to offer consumer rebates and investment tax credits for solar, wind, and other types of non-fossil fuels. Instead, regulators should be incentivizing innovation in all types of energy generation and transmission, allowing the marketplace to sort out winners and losers.

In individual countries, the market shape for power distribution will depend on policy direction as well as on other local factors. These can include the extent of competition and customer choice, access to fuel, the nature of existing infrastructure, the degree of electrification, and degrees of interconnectedness or isolation from neighbouring territories. But regardless of how renewable energy is generated, stored, and distributed, it is already boosting local economies; democratizing energy generation and transmission; and giving customers unprecedented access, control, and choice.

Notes

1 The Economist, 2016.

2 Bloomberg New Energy Finance, 2016.

3 OECD/IEA, 2017a.

4 Information about the Africa Renewable Energy Initiative is available at http://www.arei.org/.

5 PwC, 2015.

6 IRENA, 2018.

7 Vidal, 2014.

8 Osborne, 2017.

9 IRENA, 2018.

10 Crooks, 2016.

11 Lewis, 2013.

12 Ferris, 2017.

13 Energy Department, Republic of South Africa, National Solar Water Heater Programme, no date.

14 The Economist, 2016.

15 The Economist, 2016.

16 Londono, 2017.

17 Bloomberg New Energy Finance, 2017.

18 Further information about WindEurope is available at https://windeurope.org/about-us/new-identity/.

19 REN21, 2017.

20 Hernandez, 2017.

21 GWEC, 2018.

22 U.S. Department of Energy, 2016.

23 Nelson, 2017.

24 Further information about CalEnergy Generation is available at https://www.bherenewables.com/imperialvalley_geothermal.aspx.

25 GE Reports Staff, 2017.

26 Kamadi, 2017.

27 Pradhan, 2018.

28 Prasad, 2016.

29 GE Grid Solutions, 2017.

30 Wood, 2017.

31 Clover, 2017.

32 Curry, 2017.

33 Driscoll, 2017.

34 Saltzgaver, 2017.

35 Vest, 2017.

36 Prinsloo, 2017.

37 Audi MediaCenter, 2016.

38 Shankleman, 2017.

391 Baker, 2015.

40 Hymas, 2013.

41 BPVA, 2015.

42 Frangoul, 2017.

43 Peters, 2016.

References

Audi MediaCenter. 2016. 'New Method for Producing the Synthetic Fuel Audi E Gas'. Available at https://www.audi-mediacenter.com/en/press-releases/new-method-for-producing-the-synthetic-fuel-audi-e-gas-5722.

Baker, S. 2015. 'Renewable Energy Sparking Big Interest from Institutions'. *Pensions&Investments,* 14 December. Available at http://www.pionline.com/article/20151214/PRINT/312149945/renewable-energy-sparking-big-interest-from-institutions.

Bloomberg New Energy Finance. 2016. *Off-Grid Solar Market Trends Report 2016.* Washington, D.C., London, and Utrecht: Bloomberg New Energy Finance and Lighting Global, with Global Off-Grid Lighting Association. Available at https://about.bnef.com/blog/off-grid-solar-market-trends-report-2016/.

———. 2017. *Accelerating India's Clean Energy Transition.* Bloomberg New Energy Finance, 28 November. Available at https://data.bloomberglp.com/bnef/sites/14/2017/11/BNEF_Accelerating-Indias-Clean-Energy-Transition_Nov-2017.pdf.

BPVA (British Photovoltaic Association). 2015. 'REC Solar Panels Powering HEINEKEN's Key Brand, Tiger Beer Brewery in Singapore'. 26 November. Available at http://www.bpva.org.uk/members/bpva/news/rec-solar-panels-powering-heineken-s-key-brand-tiger-beer-brewery-in-singapore/.

Clover, I. 2017. 'Lithium-Ion Batteries below $200/kWh by 2019 Will Drive Rapid Storage Uptake, Finds IHS Markit'. *PV Magazine,* 3 August. Available at https://www.pv-magazine.com/2017/08/03/lithium-ion-batteries-below-200kwh-by-2019-will-drive-rapid-storage-uptake-finds-ihs-markit/.

Crooks, E. 2016. 'Swanson's Law Provides Green Ray of Sunshine for PV'. *Financial Times,* 17 January 2016. Available at https://www.ft.com/content/d9f9f1b4-a3f0-11e5-873f-68411a84f346.

Curry, C. 2017. 'Lithium-Ion Battery Costs and Market'. Bloomberg New Energy Finance, 5 July. Available at https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf.

Driscoll, W. 2017. 'Growth Prospects for the Global Grid-Connected Battery Market'. *GreenTech Media,* 16 August. Available at https://www.greentechmedia.com/articles/read/growth-global-grid-connected-battery-market#gs.EQ6xn6s.

The Economist. 2016. 'Africa Unplugged: Small-Scale Solar Power Is Surging Ahead'. *The Economist,* 19 October. Available at https://www.economist.com/news/middle-east-and-africa/21709297-small-scale-solar-power-surging-ahead-africa-unplugged.

Energy Department, Republic of South Africa. No date. *The National Solar Water Heater Programme (NSWH Programme).* Available at https://solarwaterheating-programme.co.za/.

Ferris, R. 2017. 'Mercedes Benz and Vivint Solar Partner to Compete with Tesla in Home Energy'. *CNBC.com,* 18 May. Available at https://www.cnbc.com/2017/05/18/mercedes-benz-and-vivint-solar-partner-to-compete-with-tesla-in-home-energy.html.

Frangoul, A. 2017. 'Anheuser-Busch Enters into Renewable Energy Partnership with Enel Green Power'. *CNBC,* 14 September. A CNBC Special Report. Available at https://www.cnbc.com/2017/09/14/anheuser-busch-enters-into-renewable-energy-partnership-with-enel-green-power.html.

GE Grid Solutions. 2017. 'Implementing Distributed Energy Resources: Making the Journey to Distributed Energy'. White Paper. Available at https://www.gegridsolutions.com/app/DownloadFile.aspx?prod=derm&type=13&file=2.

GE Reports Staff. 2017. *Harnessing the Power of Mother Nature: ASEAN's Geothermal Opportunity. GE Reports,* 21 August. Available at https://www.ge.com/reports/harnessing-power-mother-nature-aseans-geothermal-energy-opportunity/.

GWEC (Global Wind Energy Council). 2018. 'Global Wind Statistics 2017', 14 February. Brussels: GWEC. Available at http://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf.

Hernandez, J. 2017. 'It Can Power a Small Nation: But This Wind Farm in China Is Mostly Idle'. *New York Times,* 15 January. Available at https://www.nytimes.com/2017/01/15/world/asia/china-gansu-wind-farm.html.

Hymas, L. 2013. 'Solar Crowdfunding Project Mosaic Sells Out in under 24 Hours'. *Grist,* 28 January. Available at https://grist.org/climate-energy/crowdfunding-project-solar-mosaic-sells-out-in-under-24-hours/.

IRENA (International Renewable Energy Agency). 2018. *Renewable Power Generation Costs in 2017.* Abu Dhabi: IRENA. Available at http://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

Kamadi, G. 2017. 'Africa's First Grid-Connected Biogas Plant Powers Up'. *Reuters,* 10 January. Available at https://www.reuters.com/article/kenya-energy-biogas/africas-first-grid-connected-biogas-plant-powers-up-idUSL5N1EZ1KL.

Lewis, M. 2013. 'Will DIY Solar Make an Impact?' ZDNet, 1 December. Available at http://www.zdnet.com/article/will-do-it-yourself-solar-make-a-market-impact/.

Londono, E. 2017. 'Chile's Energy Transformation Is Powered by Wind, Sun and Volcanoes'. *New York Times,* 12 August. Available at https://www.nytimes.com/2017/08/12/world/americas/chile-green-energy-geothermal.html.

Nelson, A. 2017. '2017 Outlook: Geothermal Is Trending Upwards'. *Renewable Energy World,* 3 February. Available at http://www.renewableenergyworld.com/articles/print/volume-20/issue-1/features/geothermal/2017-outlook-geothermal-is-trending-upwards.html.

OECD/IEA (Organisation for Economic Co-operation and Development/International Energy Agency). 2017a. *Energy Access Outlook 2017: From Poverty to Prosperity.* IEA/OECD. Available at https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf.

———. 2017b. *Renewables Information: Overview (2017 edition).* IEA Publishing. Available at https://www.iea.org/publications/freepublications/publication/RenewablesInformation2017Overview.pdf.

Osborne, M. 2017. '10 Years of R&D Spending Analysis of 12 Key PV Module Manufacturers'. PV Tech Blog Post, 19 September.

Available at https://www.pv-tech.org/editors-blog/10-years-of-rd-spending-analysis-of-12-key-pv-module-manufacturers.

Peters, A. 2016. 'How Google Became the World's Largest Buyer of Renewable Energy'. *Fast Company,* 7 December. Available at https://www.fastcompany.com/3066300/how-google-became-the-worlds-largest-corporate-buyer-of-renewable-energy.

Pradhan, B. 2018. 'Here's One City Turning India's Mountain of Trash into Cash.' *Los Angeles Times,* 3 January. Available at http://www.latimes.com/business/la-fi-india-trash-20180103-story.html.

Prasad, G. C. 2016. 'Waste-to-Energy Projects See Revival in Investor Interest.' *LiveMint,* 23 March. Available at http://www.livemint.com/Industry/B9q700vtN6YL5jxndS3rjL/Wastetoenergy-projects-see-revival-in-investor-interest.html.

Prinsloo, L. 2017. 'Cell Phones to Bring Solar Power to 1 Million Africans Living Off the Grid'. *Renewable Energy World,* 7 August. Available at http://www.renewableenergyworld.com/articles/2017/08/cell-phones-to-bring-solar-power-to-1-million-africans-living-off-the-grid.html.

PwC. 2015. *14th PwC Global Power and Utilities Survey: A Different Energy Future.* Available at https://www.pwc.com/ca/en/industries/power-utilities/publications/global-power-and-utilities-survey-2015.html.

REN21 (Renewable Energy Policy Network for the 21st Century). 2017. *Renewables 2017 Global Status Report.* Paris: REN21 Secretariat. Available at http://www.solarthermalworld.org/sites/gstec/files/news/file/2017-06-22/170622_gsr_2017_full_report_final.pdf.

Saltzgaver, H. 2017. 'AES Will Break Ground on New Power Generating Plant this Month'. *The Grunion,* 13 July. Available at http://www.gazettes.com/news/aes-will-break-ground-on-new-power-generating-plant-this/article_0ad87f1e-65bd-11e7-8bef-dbecfcdf5fd9.html.

Shankleman, J. 2017. 'BlackRock Busts $1 Billion Green Power Goal with Second Fund'. *Bloomberg News,* 5 July. Available at https://www.bloomberg.com/news/articles/2017-07-05/blackrock-busts-1-billion-green-power-goal-with-second-fund.

U.S. Department of Energy. 2016. *Wind Technologies Market Report,* August 2017. Oak Ridge, TN: U.S. Department of Energy. Available at https://www.energy.gov/sites/prod/files/2017/10/f37/2016_Wind_Technologies_Market_Report_101317.pdf.

Vest, C. 2017. 'China Turns to Energy Storage to Push Renewables'. *Eco-Business,* 18 February. Available at http://www.eco-business.com/news/china-turns-to-energy-storage-to-push-renewables/.

Vidal, J. 2014. 'Big Power Out, Solar In: UBS Urges Investors to Join Renewables Revolution'. *The Guardian,* 27 August. Available at https://www.theguardian.com/environment/2014/aug/27/ubs-investors-renewables-revolution.

Wood, E. 2017. 'ABB to Install Microgrid on Offshore Production Platform'. *Microgrid Knowledge,* 15 December. Available at https://microgridknowledge.com/microgrid-abb-offshore/.

CHAPTER 3

INNOVATION DRIVING THE ENERGY TRANSITION

Francisco Boshell, Dolf Gielen, Roland Roesch, Arina Anisie, Alessandra Salgado, and **Sean Ratka,**
International Renewable Energy Agency (IRENA)

The world is moving towards a more inclusive, secure, cost-effective, and sustainable future based on renewable energy. Energy transition is not a new phenomenon: humanity first relied on wood for energy, followed by peat and then coal, which began to be used around 1750. Oil came later, around 1875, and natural gas around 1950.[1] These past experiences indicate that energy transitions—enabled by technology development—occur regularly and are chiefly caused by economic and geopolitical considerations rather than primary resource scarcity.[2]

The current energy transition

The ongoing energy transition is evolving in the same vein, with innovation as a major driver. But this time it is fostered by unprecedented public pressure and policy action, triggered by rising climate change concerns across the world. The present energy transition may be the swiftest yet, bolstered by rapid renewable power deployment and innovations and technology developments that have enabled the implementation of more ambitious policies. This has created a virtuous circle. In 2017 the world's total renewable power capacity reached 2,179 gigawatts (GW),[3] surpassing the close to 2,000 GW of total global coal power capacity. In the last decade, global installed solar photovoltaic (PV) capacity grew from 6.1 GW to 390 GW by the end of 2017.[4] Cumulative installed wind capacity reached nearly 514 GW the same year.[5] At present, around a quarter of the world's electricity is produced from renewable energy sources.

Decarbonization of the energy sector is the backbone of the current transition. At the Paris climate conference (COP21) in December 2015, countries agreed to set out an action plan to decarbonize the global economy and limit global warming to well below 2°C compared to pre-industrial levels. Around two-thirds of global greenhouse gas emissions can be attributed to fossil fuel energy supply and use.[6] To achieve our climate goals, energy-related CO_2 emissions must decline by 2.6% per year, or 0.6 metric gigatons per year on average, all while ensuring that sufficient energy is available for economic growth.[7]

Innovation in the driver's seat

Innovation has historically been—and will continue to be—a key driver of energy transitions. At its core, innovation is simply the application of new technologies and practices with enhanced and desirable features. At present, technological development is accelerating and renewable energy costs have decreased at a remarkable pace. In the case of wind, onshore projects commissioned in 2017 largely fell within the range of fossil fuel–fired electricity generation costs, with recent auctions indicating a levelized cost of electricity (LCOE) as low as US$0.03 per kilowatt-hour (kWh).[8] The development of larger wind turbines, installed in new locations (including offshore), along with stable incentives, policies, and regulatory frameworks have resulted in an accelerated learning curve for wind power technologies over the last two decades.

PV technologies have made even more remarkable advances. The global weighted average LCOE of utility-scale solar PV fell by 73% between 2010 and 2017, to US$0.10/kWh, due to the 81% decrease in solar PV module prices and increased module efficiencies, along with reductions in the balance of system costs. Increasingly this technology is competing head-to-head with conventional power sources without financial support.[9]

Moving the energy transition forward

Energy efficiency and renewable energy form the core of the energy transition, since they can achieve 90% of the required CO_2 emission reductions by 2050 compared to the Reference Case (the most likely case based on current and planned policies and expected market developments for each country's energy sector).[10] The remaining 10% would be achieved through other options, including fossil fuel switching, continued use of nuclear energy, and carbon capture and storage (CCS).

Energy efficiency and renewable energy must grow in tandem. Decarbonization will require accelerated improvements in energy efficiency across all sectors to keep total primary energy supply at the same level between 2015 and 2050, all while the world economy grows threefold. By 2050, two-thirds of total primary energy supply must come from renewables. This requires the share of renewables to increase at a rate of about 1.4% per year, a sevenfold acceleration compared to recent years.[11] To achieve this, innovation must support both faster deployment of available technologies and the development of new renewable energy technologies.[12]

The role of other energy technology options remains uncertain. CCS and nuclear deployment have lagged behind expectations as a result of related risks, added cost, and limited acceptance. Moreover, efforts to develop nuclear and CCS options have been geographically unevenly distributed.

Economic benefits of a transition beyond climate change

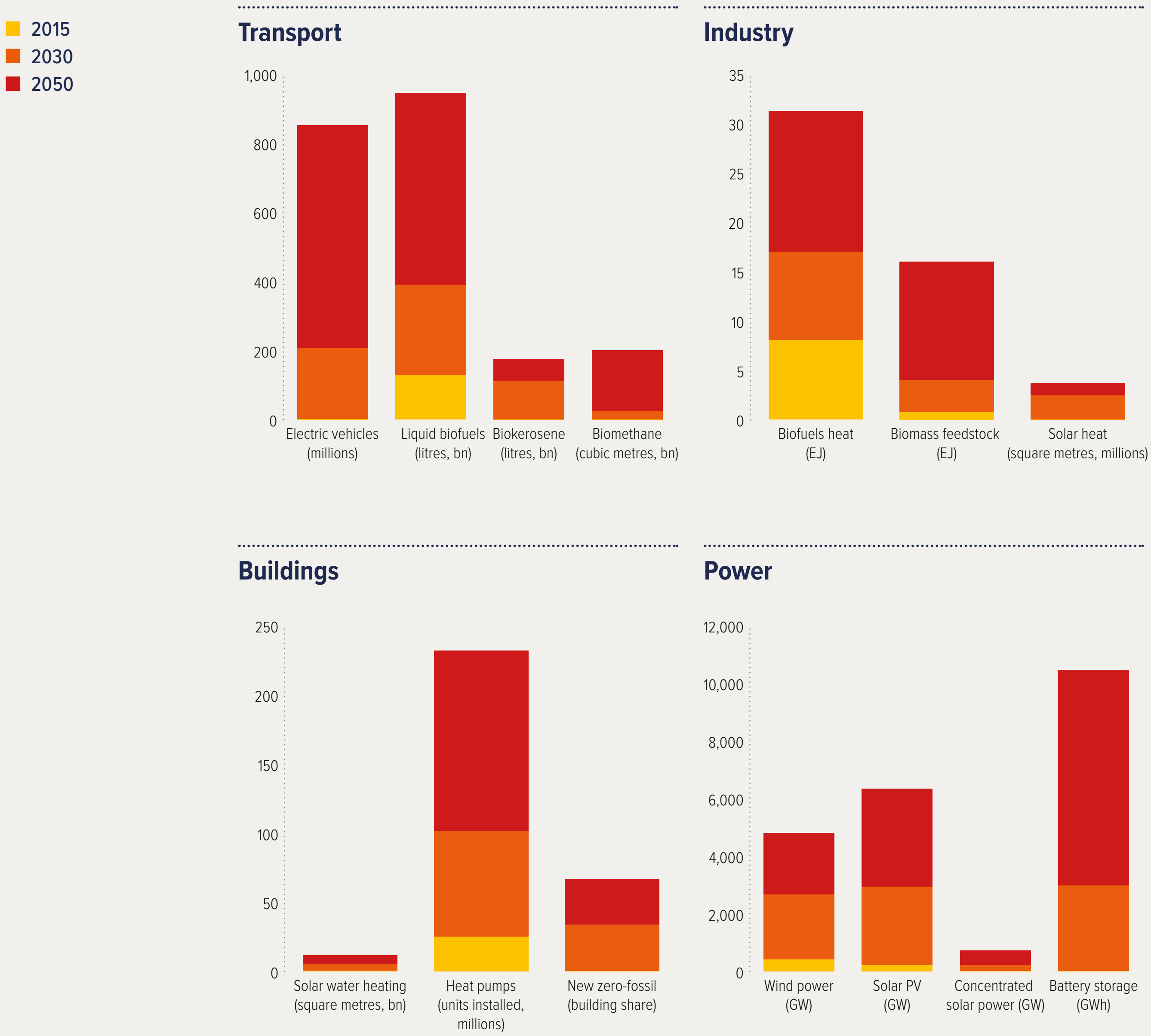
The global energy transition could create around 6 million additional jobs by 2050 compared to the Reference Case.[13] Job losses in fossil fuels would be completely offset by new jobs in renewables alone, with millions of additional jobs created in related sectors as well. Global gross domestic product (GDP) could also be boosted around 0.8% in 2050 compared to the Reference Case. The cumulative gain through increased GDP from 2015 to 2050 would amount to some US$19 trillion.[14] Greater economic growth is driven by the increasingly strong business case of renewable energy and the stimulus of higher investment in renewables and energy efficiency, and is enhanced by pro-growth policies, particularly carbon pricing. Policy makers need to consider strategies to adapt and benefit national economies from this transition.

Challenges ahead

Recent analysis from IRENA indicates that technologies are available today that can significantly advance the low-carbon energy transition through 2030.[15] However, major technology challenges remain to complete the transition to a renewables-based energy supply by the middle of the century. To reach our climate goals within the needed timeframe, competitive low-carbon technologies must rapidly reach commercialization to supply all energy needs. The good news is that technology solutions exist for two-thirds of the global primary energy supply, and deployment rates for solar PV, wind power, heat pumps, and electric vehicles are on track. For bio-jet fuels (biokerosene), biofuels for road transport, solar heat for industrial processes, and battery storage,[16] deployment growth rates need to increase by several orders of magnitude (Figure 1). The important next step is to create enabling frameworks to scale up their deployment.

For the remaining one-third of global primary energy supply, the currently foreseeable solutions are either not yet available at scale or their costs remain too high. The next step is to foster technology innovation, along with enabling policy, social, and financial measures, to rapidly bring emerging clean technologies to the marketplace. Major challenges remain in end-use sectors, namely industry (iron and steel, cement, and chemical/petrochemical), aviation, and freight transport, as shown in Figure 2.

Figure 1.
Technology deployment needs by sector and application in REmap, 2015–50

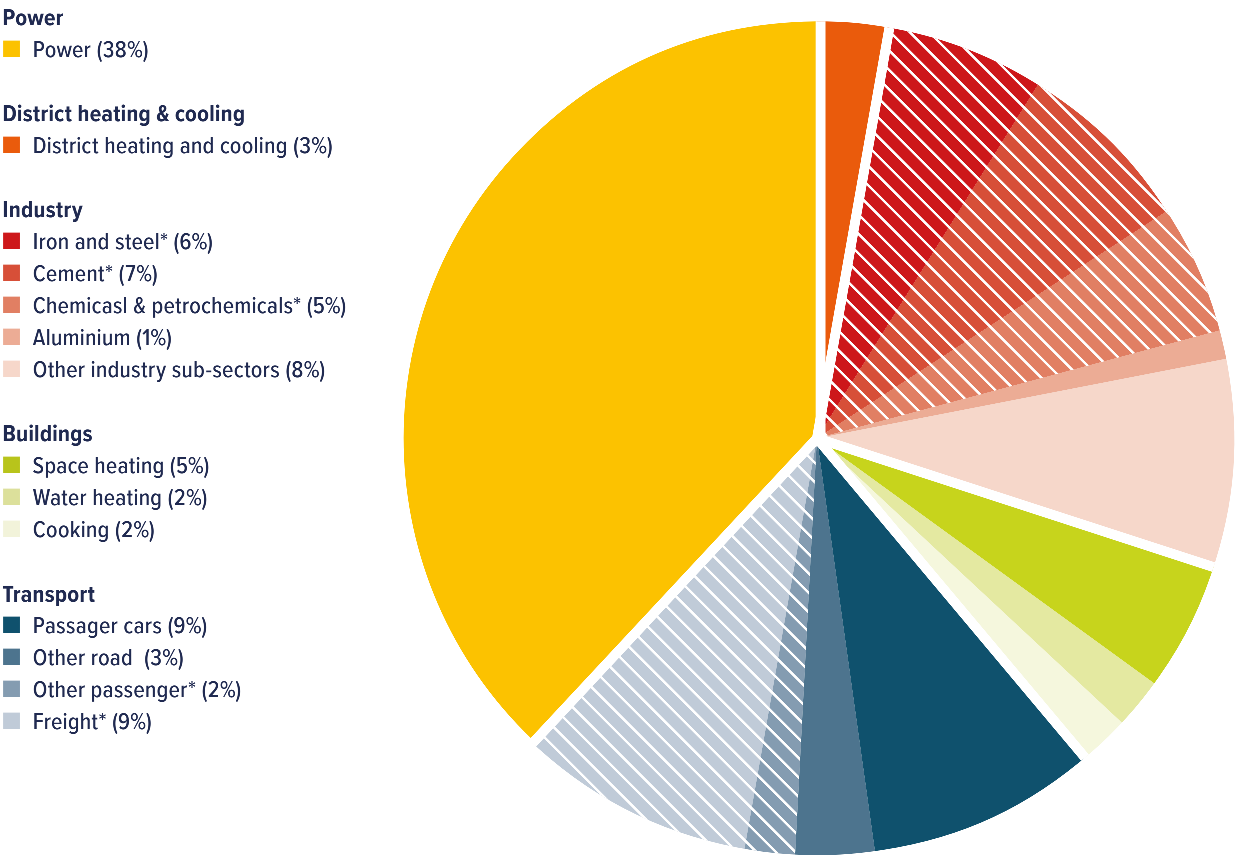


Source: IRENA, 2017a.

Note: 'Biomass feedstock' is biological material that can be used directly as a fuel or converted to another form of fuel or energy product; 'new zero-fossil' refers to new buildings with enhanced insulation resulting in zero or almost zero energy demand for space heating; 'REmap' is a low-carbon technology pathway assessed by IRENA that goes beyond the Reference Case for an energy transition in line with the goal of the Paris Agreement to limit an increase in global average temperature below 2°C in comparison to pre-industrialization levels, with a 66% probability of meeting that target (IRENA, 2017b). EJ = exajoules; GW = gigawatts; GWh = gigawatt-hours; PV = photovoltaic.

Figure 2.

Breakdown of global CO_2 emissions by sector and sub-sector, 2015



Source: IRENA, 2017a.

Notes: 'District heating & cooling' is defined as the centralized heating or cooling of water, which is then distributed to multiple buildings through a pipe network (IRENA, 2017d); 'Other passenger' is passenger transport by air or sea; 'Other road' includes all on-the-ground transport for passengers that is not cars; sectors with no current economically viable option for deep decarbonization are shaded.

* Sectors with no current economically viable option for deep carbonization. These sectors are shaded in the figure above.

Early action is essential, as a full-scale energy transition takes decades because of the different technology development steps needed and the long lifespans of existing infrastructure.

Innovation needs

This section considers the different innovation needs in the power sector and the end-user sectors.

Innovation needs in the power sector

Many renewable generation technologies in the power sector are already economically viable, and innovation, together with economies of scale, will continue to reduce their costs. The next step, therefore, is to focus innovation efforts on integrating high shares of variable renewable energy (VRE) in power systems.[17] This requires options that create flexibility, such as grid strengthening, demand-side management, energy storage, sector coupling (which links the electricity sector with heating, cooling, and transport), and flexible conventional power generation.

The benefits of increased innovation in renewable energy systems integration are clear. Innovation reduces costs of enabling technologies, such as energy storage and grid infrastructure, and unlocks new approaches for operating power systems, designing markets, and creating business models and thus enabling reliable, affordable, and renewable power systems.

Countries such as Denmark, Germany, Portugal, Spain, and Uruguay have proven that power systems with annual VRE shares in excess of 25% are manageable, and have even handled short periods of time with VRE shares close to 100%.[18] Best practices—such as the electricity system operated by 50Hertz in eastern Germany that managed a sustained share of VRE of 50% in 2017—are possible.[19] However, the optimal strategy for integrating shares of VRE in excess of 50% on an annual basis is not yet fully known, and innovation will continue to be crucial for grid integration.

Innovation needed in the end-use sectors

Decarbonizing end-use sectors will require a combination of electrification, technology breakthroughs, and sector-specific global agreements. The electrification of end-use sectors is a win-win, since it reduces emissions while also supporting the integration of higher shares of VRE in power systems. Beyond electrification, no economically viable emission reduction solutions are currently available for carbon-intensive activities such as iron and steel making, cement production, chemical and petrochemical production, maritime transport, aviation, freight transport, or the replacement of non-sustainable traditional biomass. Industry—particularly steel and iron, cement, and chemicals—followed by certain transport modes are the most challenging in this regard and require new technology solutions to be developed and commercialized quickly. Table 1 includes a list of technology options for the energy transition for each sector and their current deployment status. A detailed description of these technology options is available in IRENA's 2017 report *Accelerating the Energy Transition through Innovation.*

New policies are also needed. Energy-intensive industries, such as cement or steel and iron production, have been largely exempt from ambitious climate policies because of international competitiveness issues and potential carbon leakage.[20] Buildings and city designs should facilitate renewable energy integration. Regulations are needed to ensure that new buildings are of the highest efficiency, and the retrofitting and refurbishment of existing buildings needs to be accelerated. In transport, cross-border regulations of jet fuels in aviation and bunker fuels in maritime transport have yet to be addressed.[21]

Some emerging innovation trends for the energy transition

The low-carbon energy transition has begun with renewables deployment at its core. Distributed generation, combined with information and communication technology (ICT) developments, has the capability of transforming the way power systems are operated and regulated, leading to more informed, empowered—and flexible—consumers.

Decentralization and distributed generation

With the rise of distributed generation, individuals and communities have greater control over generation and energy consumption.[22] Incentive programmes to encourage distributed generation, particularly distributed solar PV, have been extremely effective in many countries. Deployment of solar PV has increased dramatically in recent years.[23] In 2016, more than 30% of Germany's installed renewable energy systems were owned by citizens.[24]

Distributed storage has also gained momentum recently with a behind-the-metre business model that allows customers to store electricity generated by their rooftop solar panels and use it when needed—for example, after the sun sets.[25]

Decentralization of the energy sector also brings new innovative business models around peer-to-peer power trading, demand-side responses, and power to buildings. All of this enables consumers to move out of the monopolistic markets driven by utilities and participate in a more transparent and independent manner, leading to a 'democratization of electricity'. Pay-as-you-go (PAYG) business models, which allow customers

Table 1.

Innovation progress of technology options in the energy transition, by sector

	Sector			
Pace of innovation progress	Power generation	Industry	Transport	Buildings
On track	• Hydropower • Solar PV • Onshore wind • Offshore wind • Smart grids • Battery storage • Energy efficiency in end uses	—	• EVs	—
Lagging but viable	• Biopower • Geothermal • Interconnector capacity • Ultra-high-voltage DC • Demand-side response • Solar CSP	• DRI iron-making gas + CCS • Clinker substitutes • Clinker kilns + CCS • Clinker kilns biomass • Gas ammonia production + CCS • Biomass supply at scale	• Conventional biofuels • Energy efficiency • Biomass supply at scale	• Zero-energy buildings • Energy renovation and existing stock • Clean cooking using renewables • Solar-assisted water/ space heating systems • Heat pumps
Not viable at current pace	• CCS for natural gas and biomass (BECCS)	• DRI iron-making hydrogen • Blast furnace iron-making + CCS • Blast furnace iron-making biomass • Biomass for chemicals + recycling • Hydrogen ammonia production • Material efficiency • CO_2 transportation and storage infrastructure	• Hydrogen vehicles • Advanced biofuels • Railway infrastructure for modal shift	• District heating & cooling with renewables
Not currently available	• Various negative emission technologies • New materials for advanced battery storage	• Solar thermal aluminium smelting • Direct conversion of CO_2 to fuels and materials	• Solar passenger cars • Electric aircraft	• Advanced lightweight materials for construction • New appliance technologies such as magnetic refrigerators; breakthrough materials for insulation; and advanced smart heating, cooling, and appliance use and control systems

Source: Based on IRENA, 2017a.

Notes: 'Clinker' is the residue from burnt coal or from a furnace; 'district heating & cooling' is the centralized heating or cooling of water, which is then distributed to multiple buildings through a pipe network (IRENA, 2017d). BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CSP = concentrated solar power; DC = direct current; DRI = direct-reduced iron; EV = electric vehicle; — = not known or not applicable.

to pay directly for the electricity they require at a rate they are willing to pay, are beneficial for developing regions where customers' access to financing is limited. PAYG has been implemented in regions in Africa (e.g., M-Kopa) and India (e.g., Simpa Networks).

Digitalization

Interesting opportunities exist at the crossroads of ICT and energy technology. The application of digital monitoring and control technologies in the generation and transmission domain of the electricity system has penetrated deeper into the local grids. Wider use of smart metres and sensors, along with the application of Internet of Things, has created opportunities to provide new services to consumers. Enhanced communication and control enables aggregators to bundle demand response and create 'virtual power plants'.

Smart technologies are providing data and insights on consumer behaviour that enable better planning by grid operators. With improved communications, system operators gain valuable information about distributed energy sources in real time, thus enabling better production and consumption forecast models. These developments result in greater flexibility to accommodate new and variable energy sources.

Sector coupling

The coupling of diverse energy applications also creates opportunities for the integration of clean technologies. Electric vehicles (EVs), for example, will be a game changer not only for transport, but also for renewable power. Increasing numbers of EVs present both a challenge and an opportunity for further renewable energy integration and sector decarbonization. Over 2 million EVs have now been sold globally, with China, Japan, and the United States of America (notably the state of California) accounting for around two-thirds of the total global EV stock.[26] New EV registrations hit a world record in 2016 with nearly 800,000 units, around 1% of all car sales. Countries such as China, France, Germany, India, Norway, and the United Kingdom are now committing to electric mobility by establishing targets for the coming decades.

In industry sectors such as chemical and steel production, some applications have started using converted forms of power such as hydrogen, ammonia, and others, thus allowing intermittent renewable energy generation to be absorbed during off-peak time. However, further innovation in the industry sector is needed: the share of renewables has remained unchanged for the past few decades at around 10%.[27]

Nurturing innovation at all stages

Innovation efforts should encompass the complete technology life cycle and all aspects of renewable energy integration in all sectors. Governments can play a key role in setting the right framework to foster innovation.

R&D investment

For those end-use sectors with no clear technology solutions commercially available, basic research and engineering efforts are needed. Innovation requires funding. Over the past seven years, government and corporate investment in clean energy technology research and development (R&D) has been stagnant. Although investments in renewable energy have risen to around US$300 billion per year, R&D expenditures for clean energy amount to US$10 billion per year.[28] This 3% R&D investment share is well below that of other innovative sectors, such as ICT and vehicle manufacturing. Additional R&D efforts would result in additional—and cheaper—low-carbon technology solutions, thereby decreasing the overall costs of the energy transition. Today most R&D investment flows into the power sector, such as solar and wind, rather than into end-use technologies, such as bioenergy and solar thermal, where the urgency is greater.

Innovation beyond R&D

The innovation challenge for energy goes beyond traditional R&D efforts. The end-use sectors that have made the least progress in innovation for decarbonization—such as heavy industry, freight transport, and aviation—are those where proper policy incentives and long-term perspectives are lacking. Although costly low-carbon technologies have a role to play here, a uniform global carbon price is needed to create a level playing field. Politically viable, economically viable, and efficient policy frameworks are needed.

This challenge cannot be met by increased R&D investment alone. It requires global sectoral approaches that help to overcome a lack of cost-competitiveness while addressing carbon leakage concerns. Innovation also includes a fundamental rethinking of production processes and energy technologies required for the energy transition. A sustainable solution is one that increases productivity and enhances performance while eliminating emissions.

Efforts to increase innovation must cover the complete technology life cycle, including the demonstration, deployment (technology learning), and commercialization stages. Furthermore, the innovation ecosystem should extend across a range of activities to include creating new market designs, building innovative enabling infrastructure, forming new ways to operate energy systems, establishing standards and quality control systems, and implementing new regulatory measures. It is too early to say what the new sector structure will be, but it is clear that the traditional centralized utility model is being challenged.

Overcoming the valley of death

A sound commercialization strategy is essential to translate ground-breaking concepts in clean energy into marketable outputs—that is, to take ideas from demonstration to commercial diffusion, a phase also known as the 'valley of death'. Commercialization thrives not only in a healthy investment climate but also in an environment supported by strong institutional arrangements and other governmental mechanisms.

Some tools allow both policy makers and entrepreneurs to develop market diffusion mechanisms for innovative technologies. These tools aim to enable matching innovation initiators (e.g., national institutes, private companies, and technology transfer offices) with the neediest innovation recipients (e.g., new customer groups and market niches). Examples include crowdfunding, joint ventures, patents and licenses, spin-offs, and technology incubators.

Increased public investment in R&D will continue to be crucial. Mission Innovation is a recent international initiative announced at COP21 that sets the target of doubling government R&D investment in clean energy technologies. Through Mission Innovation, 22 countries and the European Union have pledged to double their public clean energy R&D investment over five years.[29] Initiatives that increase R&D funding are very encouraging. However, more attention could be paid to monitoring and verifying that those investments have the desired impact.[30]

Private funding is also essential. To take one example, the Breakthrough Energy Coalition is a global group of wealthy investors committed to funding clean energy companies. The coalition is designed to help mobilize 'patient capital', which can wait longer for early-stage technologies to mature from lab to market.

Policy messages

Renewable energy and energy efficiency will be at the core of the energy transition, representing 90% of emission reductions and necessitating a significant transformation of how the world produces and consumes energy.[31] The share of renewables in the energy mix needs to increase to two-thirds of the world's total primary energy supply by 2050, up from 15% today. It is also crucial that current international climate change debates lead to appropriate market signals—for example, carbon pricing or the ban of CO_2-emitting technologies—to accelerate decarbonization.

To avoid carbon lock-in and minimize future stranded assets,[32] investment needs to be significantly scaled up and redirected into renewable capacity, infrastructure, and energy efficiency solutions. The numerous economic, financial, social, and environmental benefits of the transition should be included in cost/benefit assessments while defining energy sector investment strategies.

Electrification will be a key enabler in decarbonizing many energy services in the end-use sectors such as transport, buildings, and industry. However, to reach an 85% share of renewable electricity supply by 2050, increased emphasis on innovation is needed to integrate VRE shares as high as 60%. Policy makers need to study various new technology trends to address this issue, including long-term grid expansion and planning; the interlinkage of demand and supply through smart-grids, and digitalization; and the role of energy storage.

For end-use sectors that cannot be electrified, such as freight transport, aviation, and heavy industries, innovation is needed to bring breakthrough technology solutions to market while also scaling up options lagging in deployment. These options include modern biofuels, solar thermal heat, district energy systems, and hydrogen.

Four elements need to be included in a policy framework for the energy transition:

1. **A systemic innovation approach beyond R&D:** Leveraging synergies between innovations across all sectors and components of the system, and involving all actors, is crucial. Innovations in technology should be pursued equally assiduously as they are in enabling infrastructure and sector coupling, business models, market design, finance instruments, and policy frameworks.

2. **Approaches to nurture innovation:** Innovation is crucial for the decarbonization of the energy sector. International cooperation on innovation for clean energy should be pursued and should take advantage of relevant existing platforms such as IRENA, Mission Innovation, and Clean Energy Ministerial.[33]

3. **Advances in power-system integration:** Renewable power already has a strong business case, but achieving its potential requires additional efforts in innovation for systems integration.

4. **Support for a portfolio of options for the end-use sectors:** Effective support requires a combination of electrification, technology breakthroughs, and sector-specific global agreements.

This chapter has considered a pathway, based on the deployment of renewable energy and energy efficiency, for the ongoing energy transition towards a more sustainable, low-carbon energy sector. It highlights the role of innovation as a key enabler for the energy transition and indicates the low-carbon technology options for each energy sub-sector. Priority innovation areas, where action is urgently required, are discussed; and the elements of a comprehensive policy framework, to foster innovation for the energy transition, are described. This chapter has argued that a policy framework that encompasses these elements is well positioned to succeed.

Notes

1 Gielen et al., 2016; Grübler, 2012; Smil 2016; van Vuuren, 2012.

2 Cherif et al., 2017.

3 IRENA, 2018a.

4 IRENA, 2018a.

5 IRENA, 2018a.

6 IPCC, 2014.

7 IRENA and IEA, 2017.

8 IRENA, 2018b.

9 IRENA, 2018b.

10 IRENA has collected data from the G20 countries about their national energy plans and goals for the period 2015 to 2050. See IRENA and IEA, 2017.

11 IRENA, 2017a.

12 IRENA and IEA, 2017.

13 IRENA and IEA, 2017.

14 IRENA and IEA, 2017.

15 IRENA, 2017a; IRENA, 2017e.

16 IRENA, 2017b.

17 'Variable renewable energy' refers to fluctuating generation such as the energy obtained from solar PV and wind energy sources.

18 IRENA, 2016b.

19 DNV GL, 2017.

20 'Carbon leakage' refers to the increase in CO_2 emissions outside the countries that are taking carbon-mitigation steps that results from the cost associated with their policies.

21 A 'bunker fuel' is any type of fuel used for the maritime and aviation sectors.

22 IRENA, 2016a; Koirala et al., 2016.

23 World Economic Forum, 2017.

24 CLEW, 2018.

25 World Economic Forum, 2017.

26 IRENA, 2017c.

27 IRENA, 2014.

28 Frankfurt School et al., 2017.

29 The countries participating in Mission Innovation, and more information about the initiative, can be found at http://mission-innovation.net/countries/.

30 Ang et al., 2017.

31 IRENA, 2018c.

32 'Carbon lock-in' refers to the inertia perpetuated by fossil fuel–based energy systems that is an obstacle to public and private efforts to introduce alternative energy supplies.

33 Further information about Clean Energy Ministerial is available at http://www.cleanenergyministerial.org/.

References

Ang, G., D. Röttgers, and P. Burli. 2017. 'The Empirics of Enabling Investment and Innovation in Renewable Energy'. OECD Environment Working Paper No. 123. Paris: OECD Publishing. Available at http://dx.doi.org/10.1787/67d221b8-en.

Cherif, R., F. Hasanov, and A. Pande. 2017. 'Riding the Energy Transition: Oil Beyond 2040'. IMF Working Paper No. 17/120. Available at https://www.imf.org/en/Publications/WP/Issues/2017/05/22/Riding-the-Energy-Transition-Oil-Beyond-2040-44932.

CLEW (Clean Energy Wire). 2018. 'Citizens Own One Third of German Renewables Capacity.' News Digest Item. Available at https://www.cleanenergywire.org/news/coalition-transport-agreement-citizens-own-one-third-renewables/citizens-own-one-third-german-renewables-capacity.

DNV GL. 2017. ,'Germany's Power Grid – A Model for the Energy Transition'. DNV GL Talks Energy Podcast Series. Available at https://www.dnvgl.com/energy/publications/podcast/pc-german-power-grid.html.

Frankfurt School-UNEP Centre/BNEF (Frankfurt School – UN Environment Programme/Bloomberg New Energy Finance). 2017. *Global Trends in Renewable Energy Investment 2017.* Frankfurt am Main: Frankfurt School of Finance & Management. Available at http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2017.

Gielen, D.J., F. Boshell, and D. Saygin. 2016. 'Climate and Energy Challenges for Materials Science'. *Nature Materials* 15: 117–20.

Grübler, A. 2012. 'Energy Transitions Research: Insights and Cautionary Tales'. *Energy Policy* 50: 8–16.

Grübler, A. and N. Nakićenović. 1996. 'Decarbonizing the Global Energy System'. *Technological Forecasting and Social Change* 53 (1): 97–110.

IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate Change 2014: Synthesis Report.* Available at https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf.

IRENA (International Renewable Energy Agency). 2018. Resource database. Available at http://resourceirena.irena.org/.

———. 2014. *Renewable Energy in Manufacturing: A Technology Roadmap for REmap 2030.* Abu Dhabi: IRENA. Available at www.irena.org/remap/REmap%202030%20Renewable-Energy-inManufacturing.pdf.

———. 2016a. *IRENA Innovation Week: The Age of Renewable Power.* Abu Dhabi: IRENA. Available at http://innovationweek2016.irena.org/outcomes.aspx.

———. 2016b. *Innovation Outlook: Offshore Wind.* Abu Dhabi: IRENA. Available at http://www.irena.org/publications/2016/Oct/Innovation-Outlook-Offshore-Wind.

———. 2017a. 'Accelerating the Energy Transition through Innovation'. IRENA Working Paper. Abu Dhabi: IRENA. Available at www.irena.org/DocumentDownloads/Publications/IRENA_Energy_Transition_Innovation_2017.pdf.

———. 2017b. 'Executive Summary, Chapter 3, Chapter 4'. *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System.* Abu Dhabi: IRENA. Available at www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

———. 2017c. *Electric Vehicles: Technology Brief.* Abu Dhabi: IRENA. Available at www.irena.org/DocumentDownloads/Publications/IRENA_Electric_Vehicles_2017.pdf.

———. 2017d. *Renewable Energy in District Heating and Cooling: A Sector Roadmap for REmap.* Abu Dhabi: IRENA. Available at http://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_DHC_Report_2017.pdf.

———. 2017e. *Renewable Energy Innovation: Accelerating Research for a Low-Carbon Future.* #Renewables4Climate. Abu Dhabi: IRENA. Available at http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Nov/IRENA_Accelerating_research_2017.pdf?la=en&hash=2A53295A57DD87A0A451E68A2CE7EA020729871F.

———. 2018a. *Renewable Capacity Statistics 2018.* Abu Dhabi: IRENA. Available at http://irena.org/publications/2018/Mar/Renewable-Capacity-Statistics-2018.

———. 2018b. *Renewable Power Generation Costs in 2017.* Abu Dhabi: IRENA. Available at http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf.

———. 2018c. *Global Energy Transformation: A Roadmap to 2050.* Abu Dhabi: IRENA. Available at http://www.irena.org/publications/2018/Apr/Global-Energy-Transition-A-Roadmap-to-2050.

IRENA and IEA (International Renewable Energy Agency and International Energy Agency). 2017. *Perspectives for the Energy Transition: Investment Needs for A Low-Carbon Future.* Abu Dhabi / Paris: OECD/IEA and IRENA. Available at http://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf.

Koirala, B. P., E. Koiloiu, J. Friege, R. A. Hakvoort, and P. M. Herder. 2016. 'Energetic Communities for Community Energy: A Review of Key Issues and Trends Shaping Integrated Community Energy Systems'. *Renewable and Sustainable Energy Reviews* 56 (April 2016): 722–44. Available at https://www.sciencedirect.com/science/article/pii/S1364032115013477?via%3Dihub.

Smil, V. 2004. 'World History and Energy'. In *Encyclopedia of Energy,* ed. C. J. Cleveland. Amsterdam: Elsevier Science. 549–61.

———. 2016. 'Examining Energy Transitions: A Dozen Insights Based on Performance'. *Energy Research & Social Science* 22: 194–97.

van Vuuren, D. P. 2012. 'An Energy Vision: The Transformation Towards Sustainability — Interconnected Challenges and Solutions'. *Current Opinion in Environmental Sustainability* 4: 18–34.

World Economic Forum. 2017. *The Future of Electricity: New Technologies Transforming the Grid Edge.* Geneva: World Economic Forum. Available at http://www3.weforum.org/docs/WEF_Future_of_Electricity_2017.pdf.

CHAPTER 4

EXPORT AND PATENT SPECIALIZATION IN LOW-CARBON TECHNOLOGIES

Georg Zachmann, Bruegel
Robert Kalcik, AIT Austrian Institute of Technology

The low-carbon technology sector is going through a period of disruptive innovation and strongly increased investment, which is likely to continue. Global investment in new renewable power, at US$297 billion in 2016, is the largest area of electricity spending; newly installed capacity is predicted to continue increasing after reaching a record of 164 gigawatts in 2016.[1] The political momentum to combat climate change was reinforced in the Paris Agreement, when almost every country in the world agreed to aim for carbon neutrality in the second half of the century.

This chapter assesses the potential of countries to excel in technologies deemed essential for the low-carbon transition based on their export and technological specializations. Global trade and patenting patterns over the past two decades are analysed to uncover the persistence and current state of competitive advantages in the low-carbon sector.

Moreover, this chapter investigates countries' potential to develop a specialization—in terms of both exports and patenting—in certain technologies, based on their strength in related sectors and developments in similar countries. The analysis relies on systematic evidence originating from the regional growth literature triggered by Hidalgo et al. (2007), which found that countries diversify into industries that are closely related to current export strengths.

After introducing the data and main indicators, the chapter explores global dynamics in low-carbon technologies and the persistence of export and technology specialization profiles. Subsequently, it analyses which countries currently specialize in the low-carbon technologies considered and which countries have the potential to develop a competitive edge in the future.

Quantifying competitiveness in low-carbon technology sectors

This analysis is based on data from 132 countries between 2012 and 2015. The chapter focuses on four emerging sectors of low-carbon technology: photovoltaic (PV) systems and wind turbines (both examples of renewable energy generation), batteries (energy storage), and electric vehicles (which provide low-emission energy consumption). These technologies constitute four product and patent groups, following the concordance tables presented in EPO and UNEP (2015) and Fiorini et al. (2017), respectively.

To measure export specialization, the chapter relies on goods trade data from the UN Comtrade database. Exports are measured in gross terms and based on the six-digit level of the harmonized system (HS code). The assessment of the current competitive status of countries in the four sectors is based on its revealed comparative advantage (RCA). A country's RCA of a certain product is defined as its share of exports on total exports of that country divided by that product's world export share.[2] A high RCA indicates that a country exports more of a certain good than one would expect relative to the volume of its overall exports. Note that a comparative advantage in a good does not necessarily mean that a country is more productive than other countries in producing this good. It means only that, relative to all other goods produced by a country, it is better at producing this particular good.

Innovative activity is approximated by the number of patents filed in a specific patent category in a country. Patent data stem from the European Patent Office (EPO) PATSTAT database.[3] The analysis here is based on technology codes on patents according to the Cooperative Patent Classification scheme. The number of patents attributed to a country is based on the location of the inventor of patents applied for at the EPO or international patents under the Patent Cooperation Treaty (PCT). The earliest application of individual patent families is used and attributed in fractions to all inventor countries and technology codes.

The revealed technological advantage (RTA) is the RCA's equivalent in the patent realm: it provides an index to measure the relative specialization of a country in a technology and is based on patent applications. The RTA is defined as the share of a technology in a country's overall patents, divided by the global share of this technology in all patents.[4] For example, Denmark is highly specialized in wind technology. Although the country accounted for less than 0.7% of all patents globally between 2012 and 2014, around 16% of all wind technology patents during this period were developed by Danish inventors.

Both specialization metrics—the RCA for exports and the RTA for patents—are standardized to fit into a [0, 1] interval, where 0 to 0.5 reflects no specialization and 0.5 to 1 indicates a revealed advantage in a particular export category or technology.[5]

Persistence of specialization

If policy makers want to create or strengthen comparative advantages, they need to understand how volatile or path-dependent a country's specialization actually is. How easy is it to shift a country's export behaviour, and how dynamic are low-carbon sectors over time? It is particularly interesting to understand how easy it would be for countries to develop a comparative advantage in exports that are relevant to the transition to a low-carbon economy, since these are likely to be high-growth sectors.[6]

Figure 1 shows the correlation between current and past specialization patterns across countries in exports (Exports panel) and patenting (Technology panel). The high correlation between PV patenting in 2002 and PV patenting in 2014, for example, implies that many of the countries that were specialized in developing PV patents in 2014 were already specialized in 2002.

Export specialization patterns are found to be typically quite path-dependent.[7] The Exports panel in Figure 1 shows the historical correlations of RCA in the year 2015 in a range of products. For half of the products (the median), the correlation between the 2015 RCA and the RCA in the same product 10 years earlier is 0.7 or more. This persistence implies that countries rarely make large jumps in terms of the products that they are particularly good or bad at exporting.

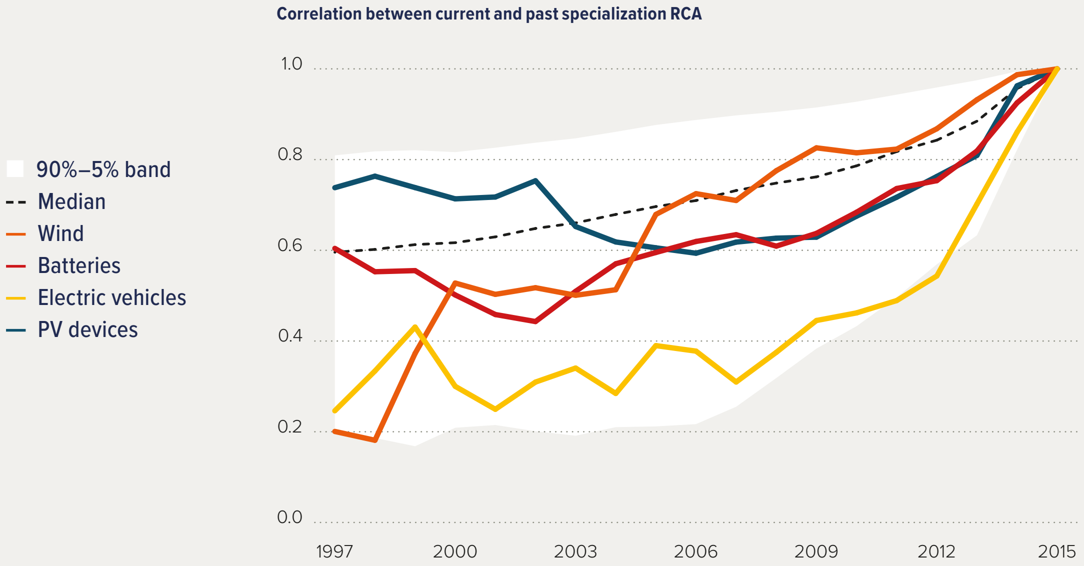
It seems that, compared with other export goods, a country's current strength in exporting these four low-carbon products is overall less correlated to its past strength. This is particularly evident for electric vehicles, which are among the products with the lowest persistence (they sit in the lower part of the shaded area in the Exports panel). But a country's current strength in exporting batteries, wind turbines, and PV technologies also tends to exhibit less correlation with past strengths than most other products. This finding is in line with the common narrative that low-carbon technologies are less mature and more dynamic than the average export sector. That means that these technologies represent opportunities on which policy makers can focus when attempting to foster comparative advantage.

The results illustrate that the comparative advantage of a country's exports is highly path-dependent—hence developing new comparative advantages is likely to be difficult for a country. However, the findings also show that the chances to do so are somewhat higher for immature sectors, such as electric vehicles.

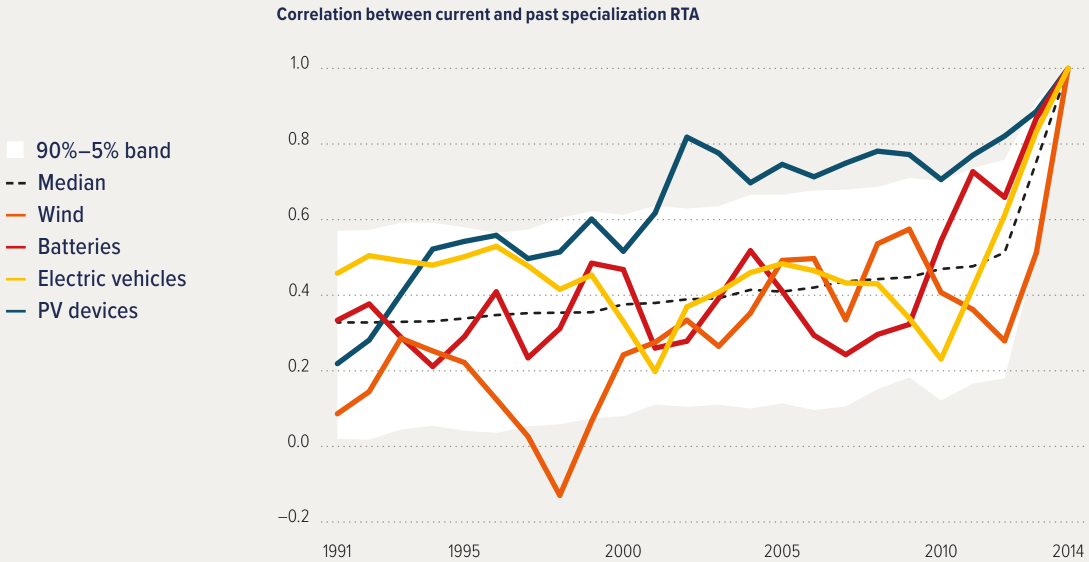
The correlation between current and past patenting activity (the Technology panel in Figure 1) shows that technological specialization is much less path-dependent than trade specialization. For half of all technological fields, a current technological advantage has less than 50% correlation with a technological advantage in the same field only two years ago. In comparison, more than 95% of the

Figure 1.
Correlation of export and technology specialization over time, by sector and technology

Exports, 1997–2015



Technology, 1991–2014



Sources: Calculations based on UN Comtrade Database, 2017, available at https://comtrade.un.org/; EPO PATSTAT, Autumn 2016, available at https://www.epo.org/searching-for-patents/business/patstat.html.

Note: The graphs show the correlation of a sector's RCA in 2015 with the same sector's RCA (Exports panel) and each technology's RTA in 2014 (Technology panel) with the same technology's RTA in each previous year, across countries. The dotted line is the median correlation, across all 5,482 export products and 640 technologies. The shaded area comprises the RCA correlations of all sectors and RTA correlations of all technologies between the 5th and the 95th percentiles of the distribution. PV = photovoltaic; RCA = revealed comparative advantage; RTA = revealed technological advantage.

export-based RCAs had more than 50% correlation with the corresponding two years before. Thus it appears much more likely that a country could develop a technological advantage without a prior specialization in the exact same technological field. These four low-carbon technologies are no exception. Correlations with past years largely track the median, sometimes above, sometimes below, with occasional outliers.

Less clearly defined is the channel linking the trade and technological dimensions. Export specialization in some sectors in 2014 is quite highly correlated with patenting specialization 10 years prior (e.g., for electric vehicles the correlation is around 0.4) but less for other technologies (e.g., in PV technologies the correlation is around 0.2). Hence the link of past patents to current exports might be strong for some products, but weaker for others. At the same time, 2014 patenting specialization is quite highly correlated with export specialization 10 years ago (e.g., for solar the correlation is around 0.4) but much less for other technologies (e.g., in electric vehicles the correlation is around 0.1). One reason for this finding might be that the specialization in a certain—persistent—sector such as the automotive industry stimulates a flow of patents in this sector.

More work needs to be done in this area to establish the direction and size of causality between patenting and export specialization. It can be argued that both export and patenting specialization are somewhat forward-looking indicators for future export strength.

Potential specialization in low-carbon technologies

The aim of this chapter is to determine which countries might have the potential for developing an advantage in patenting any of the four technologies of interest. The analysis builds on the fact that countries find it easier to innovate in technologies that are related to technologies they are already good at, or those that are developed in countries with similar patenting patterns.

To estimate the potential technological specialization of a country, this study uses a methodology developed by Hausmann et al. (2014). They show that a country's future comparative advantage in a particular product category can be estimated from its comparative advantage in related products, even if the country does not yet export these products. For example, export specialization in photovoltaic devices often appears together with the export of transistors or diodes. Furthermore, geographically proximate countries—such as Japan and the Republic of Korea (Korea), or Lithuania and Latvia—often exhibit similar export specialization. Hence Hausmann et al. (2014) use a weighted sum of RCA indicators in similar export sectors and a weighted sum of RCA indicators in similar countries to determine a country's potential RCA.

This approach can also be applied to patenting specialization—to estimate the potential RTA (hereafter *pRTA*) of the four technology groups. Technically, a weighted sum of product and country correlates is constructed to measure similarities.[8] Then an ordinary least squares regression is fitted, using these product and country similarities. The fitted values obtained from this regression are the pRTAs; these values represent the technological specialization expected from a country given current patenting patterns in similar technologies and countries.

To give one example, to establish Ireland's potential for wind turbine innovation, the study looks at related technologies, such as 'machines or engines for liquids' and 'dynamo-electric machines', and related countries, such as Denmark. Although Ireland has not yet developed a specialization in wind turbines, its pRTA is found to be rather high because it is already specialized in the two nearby technologies (see the Wind energy panel in Figure 2).

Figure 2 puts all parts together: the size of the country bubbles shows the number of patents in the sector. The darker a bubble, the higher the country's export specialization. For example, the large, dark red bubble for Denmark in wind-based energy generation depicts this country's high level of export specialization in combination with a large absolute number of patent applications by Danish inventors, comparable in number to those of Germany.

The bubble's position in the chart shows the relation of current technological specialization to potential technological specialization. Countries that appear above the 45° line exhibit a higher indicator of potential specialization than current specialization. Patenting profiles in these countries, together with knowledge about technology patterns in similar countries, suggest that diversifying their technology profile in this direction is low-hanging fruit. Conversely, countries situated below the 45° line can be

Figure 2.
Actual and potential specialization in technology (x,y) and exports (colour), 2012–14

Source: Calculations based on UN Comtrade Database, 2017, available at https://comtrade.un.org/; EPO PATSTAT, Autumn 2016, available at https://www.epo.org/searching-for-patents/business/patstat.html.

Notes: Horizontal axes show standardized RTAs between 2012 and 2014; vertical axes show standardized pRTA—that is, implied specialization in related technologies and similar countries. Bubble size is relative to the size of the technological sector in the number of patents (log scale) while the dark colour shades show revealed comparative advantage (RCA) specialization in exporting goods in this sector. RTA, pRTA, and RCA range from 0 to 1; values above 0.5 indicate a specialization. RTA = revealed technological advantage; pRTA = potential RTA. ISO-2 country codes: CN = China; DE = Germany; DK = Denmark; ES = Spain; FR = France; GB = United Kingdom; IE = Ireland; IT = Italy; JP = Japan; KR = Republic of Korea; US = United States of America.

Countries that are most specialized in patenting in a certain sector are also specialized in exporting in this sector.

seen to have matured sectors and are already leading in terms of relative strength.[9] Based on this methodology, China and the United States of America would be expected to specialize more into battery patents than they already do; and Denmark and Spain would be expected to reduce their outstanding specialization in wind patents.

In general, it can be observed that the upper-right corner in all four technologies is inhabited by countries with strong export specialization (dark red). That is, countries that are most specialized in patenting in a certain sector are also specialized in exporting in this sector. Competitive advantages in sectors such as Danish wind turbines or German electric vehicles coincide with high innovative activity.

However, the converse statement—that countries with high export specialization also exhibit high technological specialization—is not confirmed by the data; there are highly specialized exporters, such as the U.S. electric vehicle sector, that do not exhibit a relative strength in innovation. In these cases, competitive advantages appear to be based on other factors (e.g., factor cost) that are not related to patenting specialization. As mentioned earlier, indicators of relative strength do not capture global leadership but rather a comparative advantage in relation to global peers and in relation to competing industries within the country.

One example of a sector that gained a competitive advantage in the absence of a technological specialization is the Chinese PV sector. China is the world leader in domestic investment in renewable energy and associated low-emission energy sectors in absolute terms.[10] The Chinese PV sector exhibits one of the strongest export specializations globally; five of the world's six largest solar-module manufacturing companies in 2016 are located in China. However, China does not produce more PV patents than other technologies; it has not developed a technological specialization in this sector.

A second general observation is that in some low-carbon technology areas—such as batteries and PV energy—the number of patents is high while less patenting occurs in relation to electric vehicles and wind turbines. The former group are types of technology for which patenting is common practice, commercial interest in the technologies is high, and the categories are broadly defined.

A similar finding relates to the country context. Institutional factors, the legal system, and various domestic factors related to the size of the country affect national patenting activity and largely explain the high number of patent applications in Japan and Korea across all four technologies.[11] Nevertheless, Japan was able to develop a competitive edge both in exporting and innovating in three out of four examined low-carbon technologies (batteries, electric vehicles, and PV energy) and Korea in two out of four (batteries and PV energy). In sectors where Japan and Korea lag in terms of relative technological specialization, the model indicates high potential.

For **electric vehicles,** a dispersed picture emerges. Only five countries (with more than 10 patents in the period between 2012 and 2015) exhibit a larger number of electric vehicle patents than their size would suggest (shown in the top right quadrant of the Electric vehicles panel of Figure 2); these countries also specialize in related technologies. France and Germany have significantly increased the number of patents in electric propulsion technology in the past decade, which has helped them to keep pace with the growing patenting field and develop a comparative advantage. Other car manufacturing countries, such as Italy and the United States of America, have not yet developed a technological specialization but have high potential. These countries lie above the 45° line in the Electric vehicles panel of Figure 2.

Comparable to electric vehicles, patenting in **battery technologies** is characterized by the dominance of few large players. Korea and Japan lead the distribution of technologically specialized countries; both have more than twice as many battery patents as one would expect from their overall patenting activity. Japan has 43% and Korea 14% of all battery patents considered. Germany and France closely trace the technological specialization of Korea and Japan, while many smaller players have a high potential to develop a comparative advantage.

Many countries have developed a specialization in energy generating technologies based on **wind.** Nevertheless, the distribution is topped by the three global wind powerhouses—Denmark, Germany, and Spain—which together accounted for 43% of worldwide wind turbine patents from 2012 to 2014. All three have a high export specialization, but Germany's innovation profile is broader than that of Spain or Denmark, resulting in a lower index of technological specialization.

Despite massive solar subsidies, Germany has not specialized in **photovoltaic** technology innovation. Interestingly, China is also responsible for fewer patents in PV than would be expected for a country with China's total number of patent applications.

The results show that a strong technological specialization correlates with export specialization whereby countries with high relative advantage in patenting also exhibit relative strength in exports, while the absence of technological specialization does not hinder countries from becoming specialists in exporting these low-carbon goods. Whether technological specialization implies a competitive export sector demands further analysis.

Conclusion

Given the global decarbonization push, the wide array of low-carbon technologies now available offers significant growth potential. This study assessed the potential of countries to excel in low-carbon energy sectors based on their export and technological specialization. Global trade and patenting patterns over the past two decades were analysed to uncover the persistence and current state of competitive advantages in the low-carbon sector. Moreover, the chapter investigated countries' potential to develop a specialization in the future based on knowledge spillovers and strength in similar technologies.

A country's relative strength in exporting a certain product was found to be related to its past relative strength of exporting this product, exporting related products, and patenting in the corresponding technology. Concurrently, specialization in patenting a certain technology is itself related to past relative strength of patenting in this technology and patenting in related technologies. Hence a country's product and technology space entails information about the ease with which a country might move into specializing in new sectors. However, the strength of the above relationship depends on the sector. Comparative advantages in exporting low-carbon products are found to be less persistent than similar advantages for the majority of other goods.

Technological advantages measured by patent specialization are less path-dependent than comparative advantages in exports and, thus, possibly more prone to be affected by policy instruments. This finding is more pronounced for immature sectors, such as electric vehicles, which might witness larger shifts in the innovation landscape and global competition in the future. Even if a country is currently not good at exporting or patenting in a certain sector, it might acquire this capability in the future. Spillover effects across countries, as well as strength in related technological fields, may play important roles in developing a competitive advantage in these emerging sectors. Policy can leverage strength in similar technologies by shaping innovation paths; strengthening learning capabilities; targeting sector-specific innovation regimes; and coordinating sectoral, national, and regional policies.

Data show that strong technological specialization often correlates with export specialization, although the absence of technological specialization does not prohibit countries from becoming specialists in exporting low-carbon goods. Although other factors play an important role in determining competitive advantages, technological specialization can promote competitive industries, thereby shaping long-run growth dynamics.

Most of the inspected sectors are dominated by few important players. For batteries and PV systems, China has a strong comparative advantage in exports while Japan and Korea are leaders in terms of both technological and export specialization. Denmark and Spain export and patent more wind technology than their size would suggest. The electric vehicle sector, however, shows a more dispersed picture with a larger number of specialized countries.

Strength in related technologies and patterns in similar countries can provide insight into low-hanging fruit for policy intervention. The small number of leading countries is matched with a large number of countries that have a high potential to develop a technological specialization in the four low-carbon technologies in the future.

Notes

1. IEA 2017a, 2017b.
2. Balassa, 1965.
3. The EOP PATSTAT (Autumn 2016) database is available at https://www.epo.org/searching-for-patents/business/patstat.html.

4 Innovation in low-carbon technologies poses several methodological difficulties, such as the narrow technological scope that leads to low patent counts, missing information, and the classification of relevant patents, all of which are addressed by Haščič and Migotto (2015) and Haščič et al. (2015).

5 Laursen, 2015.

6 Zachmann and Kalcik, 2017.

7 Zachmann and Nano, 2017.

8 What constitutes similarity between technologies and regions is a matter of ongoing research (Alstott et al., 2016; Joo and Kim, 2010; Leydesdorff et al., 2017; Stellner, 2014; Yan and Luo, 2017). Similar to Hausmann et al. 2014, this study opts for an approach based on the correlation of countries' specialization patterns. Alternatively, one can think of the co-occurrence of technology codes on individual patents or what combinations of technologies are researched by inventors or within firms.

9 An interactive version of these findings can be found in the online report at http://www.i2-4c.eu/lowcarbongrowth/.

10 Buckley and Nicholas, 2017.

11 OECD, 2009.

References

Alstott, J., G. Triulzi, Y. Bowen, and J. Luo. 2017. 'Mapping Technology Space by Normalizing Patent Networks'. *Scientometrics* 110 (1): 443–79. Available at https://doi.org/10.1007/s11192-016-2107-y.

Balassa, B. 1965. 'Trade Liberalisation and 'Revealed' Comparative Advantage.1' *The Manchester School* 33 (2): 99–123. Available at https://doi.org/10.1111/j.1467-9957.1965.tb00050.x.

Buckley, T. and S. Nicholas. 2017. *China's Global Renewable Energy Expansion: How the World's Second-Biggest National Economy Is Positioned to Lead the World in Clean-Power Investment.* Institute for Energy Economics and Financial Analysis. Available at http://ieefa.org/wp-content/uploads/2017/01/Chinas-Global-Renewable-Energy-Expansion_January-2017.pdf.

EPO and UNEP (European Patent Office and United Nations Environment Programme). 2015. 'Climate Change Mitigation Technologies in Europe: Evidence from Patent and Economic Data'. EPO-UNEP study. Munich: EPO. Available at http://www.epo.org/news-issues/technology/sustainable-technologies/clean-energy/europe.html.

Fiorini, Al., A. Georgakaki, F. Pasimeni, and E. Tzimas. 2017. 'Monitoring R&I in Low-Carbon Energy Technologies'. EUR 28446 EN, JRC Science for Policy Report. Luxembourg: European Union. Available at https://setis.ec.europa.eu/sites/default/files/reports/monitoring_r_and_i_in_low-carbon_technologies.pdf.

Haščič, I. and M. Migotto. 2015. 'Measuring Environmental Innovation Using Patent Data'. OECD Environment Working Papers No. 89. Paris: OECD Publishing. Available at http://www.oecd-ilibrary.org/content/workingpaper/5js009kf48xw-en.

Haščič, I., J. Silva, and N. Johnstone. 2015. 'The Use of Patent Statistics for International Comparisons and Analysis of Narrow Technological Fields'. OECD Science, Technology and Industry Working Papers No. 2015/05. Paris: OECD Publishing. Available at http://www.oecd-ilibrary.org/content/workingpaper/5js03z98mvr7-en.

Hausmann, R., C. Hidalgo, D. P. Stock, and M. Ali Yildirim. 2014. 'Implied Comparative Advantage'. HKS Working Paper No. RWP14-003. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2410427.

Hidalgo, C. A., B. Klinger, A.-L. Barabasi, and R. Hausmann. 2007. 'The Product Space Conditions the Development of Nations'. *Science* 317 (5837): 482–87. Available at https://doi.org/10.1126/science.1144581.

IEA (International Energy Agency). 2017a. 'Renewables 2017: A New Era for Solar Power'. Market Report Series. Paris: IEA. Available at https://www.iea.org/publications/renewables2017/.

———. 2017b. *World Energy Investment 2017.* Paris: IEA. Available at http://www.iea.org/publications/wei2017/.

Joo, S. H. and Y. Kim. 2010. 'Measuring Relatedness between Technological Fields.' *Scientometrics* 83 (2): 435–54. Available at https://doi.org/10.1007/s11192-009-0108-9.

Laursen, K. 2015. 'Revealed Comparative Advantage and the Alternatives as Measures of International Specialization'. *Eurasian Business Review* 5 (1): 99–115.

Leydesdorff, L., D. F. Kogler, and Y. Bowen. 2017. 'Mapping Patent Classifications: Portfolio and Statistical Analysis, and the Comparison of Strengths and Weaknesses'. *Scientometrics* 112 (3): 1573–91. Available at https://doi.org/10.1007/s11192-017-2449-0.

OECD (Organisation for Economic Co-operation and Development). 2009. *OECD Patent Statistics Manual.* Paris: OECD.

Stellner, F. 2014. 'Technological Distance Measures: Theoretical Foundation and Empirics'. Paper presented at the DRUID Society Conference, 16–18 June 2014, Copenhagen. Available at http://conference.druid.dk/acc_papers/oc0vy5o9iyk8sujx27an39yb0imx.pdf.

Yan, B. and J. Luo. 2017. 'Measuring Technological Distance for Patent Mapping'. *Journal of the Association for Information Science and Technology* 68 (2): 423–37. Available at https://doi.org/10.1002/asi.23664.

Zachmann, G. and R. Kalcik. 2017. 'Europe's Comparative Advantage in Low-Carbon Technology'. In *Remaking Europe: The New Manufacturing as an Engine for Growth,* ed. R. Veugelers. Blueprint Series. Brussels, Belgium: Bruegel. Available at http://bruegel.org/2017/09/remaking-europe/.

Zachmann, G. and E. Nano. 2017. 'Low Carbon Technology Exports: The Race Is Still Open'. Bruegel Blog Post. 24 August. Available at http://bruegel.org/2017/08/low-carbon-technology-exports-the-race-is-still-open/.

CHAPTER 5

TECHNOLOGY-SPECIFIC ANALYSIS OF ENERGY INNOVATION SYSTEMS

Charlie Wilson, Tyndall Centre for Climate Change Research and International Institute for Applied Systems Analysis (IIASA)
Yeong Jae Kim, Tyndall Centre for Climate Change Research

The Global Innovation Index (GII) compiles and analyses quantitative metrics of innovation performance at the country level. The standardization and generalizability of the GII's metrics allow for cross-country comparisons on a like-for-like basis. The GII's metrics capture a wide range of institutional, human, infrastructural, market, and business factors that influence the efficiency with which countries convert innovation inputs into outputs. Put differently, the GII recognizes the importance of analysing 'innovation systems'. The GII's conceptual framework casts a wide net over many different elements of the innovation system, far beyond conventional measures such as research and development (R&D) expenditure and patents. As a result, 'great emphasis is placed on the climate and infrastructure for innovation and on assessing related outcomes'.[1]

Technology-specific analysis as a complement to the GII

This chapter shares the GII's foundational insight that standardized metrics of innovation systems are essential for comparative assessments of innovation performance. But whereas the GII is concerned with country-level assessments and cross-country comparisons, the approach set out here is designed for technology-specific assessments and cross-technology comparisons. This is complementary to the GII by drilling down from the broad 'climate and infrastructure for innovation' at the national level to the innovation system processes relevant and necessary for supporting specific energy technologies.[2] This in turn allows energy innovation portfolios comprising multiple technologies to be assessed, both within and across countries.

Energy innovation portfolios

There are no silver bullet solutions to the challenges facing the global energy system: mitigating climate change, providing universal access to modern energy services, and ensuring a secure and clean energy supply.[3] Instead, a 'silver buckshot' strategy is required to diffuse a wide range of affordable, low-carbon innovations throughout the energy supply and the many different energy-using sectors, from industry to transport and buildings. A portfolio approach to energy innovation recognizes specific challenges and needs in different parts of the energy system.[4]

Future uncertainties about the cost, performance, system integration, and acceptability of specific energy technologies are unavoidable. A portfolio approach to energy innovation helps diversify and manage risk: risk that one technology may fail to live up to expectations; risk that another technology may prove unpopular with potential users; and risk that a third technology may rely on changes to markets, regulations, or infrastructures that themselves prove difficult to implement.

A portfolio approach to energy innovation also raises important questions about how portfolios should be designed to deliver on desired outcomes. For example:

- How much effort should an innovation portfolio invest in supporting specific innovation processes?
- How much weight should an innovation portfolio place on specific energy technologies?

Addressing these questions requires new approaches that can analyse innovation systems for specific technologies, while retaining the generalizability to compare across technologies at the portfolio level.

This chapter sets out one such approach using the novel framework of the energy technology innovation system (ETIS) from which a standardized set of quantitative indicators applicable to specific technologies can be derived. The value of these technology-specific indicators is then demonstrated through two illustrative applications.

First, the full set of ETIS indicators is applied to examine *consistency* between innovation system processes in the European Union (EU)'s current energy innovation portfolio. The analysis reveals how certain energy technologies benefit from stronger support in some areas but much weaker support in others. This alerts innovation portfolio managers to areas of potential concern or tension within the innovation system.

Second, a reduced set of ETIS indicators is applied to consider *alignment* between global energy innovation efforts and public policy goals such as mitigating climate change. The analysis reveals a striking asymmetry between innovation inputs, which strongly emphasize energy-supply technologies, and desirable outcomes and objectives, which strongly emphasize end-use technologies. This signals a need to increase the relative share of end-use technologies in directed innovation efforts globally to address climate change.

The ETIS framework

A systemic approach to innovation is a strong predictor of successful innovation outcomes. This was the central finding of a recent synthesis of 20 historical case studies of energy innovation, ranging from wind power in Denmark and ethanol in Brazil to energy-efficient appliances in Japan and electric vehicles in China.[5] In cases where directed innovation efforts consistently strengthened a wide range of innovation system processes, new energy technologies were more likely to deploy faster, more pervasively, or with fewer adverse consequences. In cases where directed innovation efforts focused on particular innovation stages (such as R&D) or on a narrow set of innovation processes (such as scaling up production), new energy technologies were more likely to lose public policy support, fall into the valley of death between lab and market, or hit other roadblocks on the way to commercial success.

The insights from these case studies were distilled and synthesized into a framework describing the ETIS.[6] This framework identifies the necessary processes throughout the innovation system that help support successful innovation outcomes.

At the centre of the ETIS framework is a simple staged model of the technology life cycle, which runs iteratively from R&D through demonstration and market formation to deployment, diffusion, and eventual saturation and phase-out.

The ETIS framework places this life cycle within an innovation system comprising:

- processes through which *knowledge* is generated, codified, learned, shared internationally, spilled over, or potentially lost through depreciation;
- processes through which financial, human, and policy *resources* are mobilized to enable and support innovation, with a particular emphasis on public policy instruments;
- processes through which *actors and institutions* interact, exchange, network, and collaborate; and
- processes through which the *adoption and use* of technologies in market environments provide feedback and help shape innovators' expectations of future returns on investments.

Energy technologies have markedly different characteristics, maturities, and adoption environments. The ETIS framework can be applied to specific technologies to identify key processes important for innovation systems to function effectively. But, because these processes are generalizable, the ETIS framework also allows for comparative analysis across technologies in different national contexts or at different stages of the technology life cycle.[7]

Indicators for measuring the ETIS framework

Standardized indicators are needed for comparative analysis, as the GII demonstrates at the country level. Using indicators enables a wide range of 'non-observable', intangible, or tacit innovation system processes to be measured and analysed.[8] These processes extend beyond the 'usual suspects' of investments, patents, and publications for which large datasets are readily available. Directed innovation efforts stimulate knowledge spillovers and flows, are guided by strategic roadmaps and collaborations, leverage private-sector resource flows, and are reinforced by users' experiences with technologies once they have been commercialized.[9] Indicators are needed to measure these processes and more. Using quantitative metrics for each indicator opens up innovation systems analysis to transparent, replicable methods for assessing performance, effectiveness, and outcomes.

A wide range of quantitative indicators has been proposed for specific energy technologies.[10] However, few attempts have been made to apply a standardized set of indicators for comparative analyses of different energy technologies.

Table 1 shows all the indicators derived from the ETIS framework. Each indicator is designed to be applied to specific energy technologies, either individually or within an innovation portfolio. However, the indicators can also be measured at a more aggregated sectoral or country level. Table 1 therefore notes where there are conceptual linkages between the ETIS indicators and the GII indicators.

Table 1 also illustrates how the ETIS indicators can be measured, using the EU energy innovation system as an example. Data for some indicators are readily available from existing databases (e.g., the Web of Science for publications); others are collected using data-mining techniques (e.g., the International Energy Agency (IEA)'s Addressing Climate Change policy database); still others are compiled from a range of statistical sources (e.g., potential market sizes).

Using renewable energy to illustrate a technology area, the absolute value of each indicator with its corresponding metric is shown for the EU in 2015 (or 2012 for patents). The term 'technology area' is used to denote a group of related technologies serving a similar function in the energy system. Table 1 also includes a note on the availability of similar data in other countries or world regions.

To illustrate how the ETIS framework can be applied for comparative cross-technology analysis of innovation portfolios, Table 2 reports 2015 data for the top 10 EU countries on one selected indicator: public energy research, development, and demonstration (RD&D) expenditure. The data are shown for each of six technology areas: renewable energy, smart grids, energy efficiency, sustainable transport, carbon capture and storage (CCS), and nuclear power. These six technology areas are all integral to low-carbon transformation and cover both energy supply and energy end-use.

Standardized sets of key words defining each technology area ensure that its scope is consistent across different indicators. For example, 'renewable energy' is defined as comprising solar, wind, geothermal, wave, tidal, hydro, and bioenergy (excluding biofuels, which are allocated to sustainable transport). These are then mapped into search terms for querying the IEA RD&D expenditure database or for assigning pre-defined expenditure categories to the renewable energy technology area.

Analysing consistency and alignment in energy innovation portfolios

As noted above, a systemic perspective on energy innovation points to two important design criteria for innovation portfolios:

- **Consistency:** Are different parts of the innovation system working well together to support the full portfolio of energy technologies?
- **Alignment:** Is the technological emphasis of the portfolio clearly directed towards the desired outcomes?

Two examples show how the technology-specific indicators derived from the ETIS framework allow these criteria to be assessed. The first example applies the full set of ETIS indicators shown in Table 1 to six technology areas in the EU and illustrates the importance of consistency in innovation portfolios. The second example applies a subset of ETIS indicators to two much broader technology areas globally to illustrate the importance of alignment. Each is discussed in turn below.

Table 1: Technology-specific indicators of innovation system processes

Innovation system processes in the ETIS framework	Technology-specific indicators (illustrated for the EU)	Absolute values for renewable energy in the EU in 2015 (with units)	Data availability	Main data source	Similar indicators in the GII 2017 conceptual framework (GII Annex 1)
KNOWLEDGE					
Generation	Public energy RD&D expenditure	880 (euros, millions)	Country*	1	2.3.2 Gross expenditure on R&D
	Demonstration budgets	91 (euros, millions)	Country*	1	None
Codification	Scientific publications	16,030 (number of articles)	Country	2	6.1.4 Scientific & technical articles
	Citation-weighted publication counts	123,372 (number of articles)	Country	2	6.1.5 Citable documents H index
	Patents ^	2,422 (number of patents)	Country	3	6.1.2 PCT patent applications
	Citation-weighted patent counts ^	1,414 (number of patents)	Country	3	5.2.5 Patent families filed in 2+ offices
Spillover	Energy technology imports	12,810 (euros, millions)	Country	4	5.3.2 High-tech imports less re-imports
International Flows	Publication co-authorships between EU and non-EU actors	598 (number of co-authorships)	Country	2	5.2.2 State of cluster development
	Patent co-inventions between EU and non-EU actors ^	1,088 (number of co-inventions)	Country	3	5.2.2 State of cluster development
Learning	Learning-by-doing	17 (% learning rate)	Global†	5	None
Depreciation	Volatility in energy RD&D expenditure	7.1 (coefficient of variation)	Country*	1	None
RESOURCES					
Mobilisation of Finances	Public energy RD&D expenditure (as % of GDP)	0.006 (percent)	Country*	1	2.3.2 Gross expenditure on R&D, % GDP
Mobilisation of Innovators	Patent activity (as % of total patents) ^	0.54 (percent)	Country	3	None
Policy Density†††	Policy instruments: innovation, regulatory, market-based	145 (number of instruments)	Country*	6	None
Policy Durability†††	Policy instruments: innovation, regulatory, market-based	13.05 (cumulative number of instruments, average)	Country*	6	1.1.2 Government effectiveness
Policy Mix	Diversity of policy instruments	0.98 (Shannon index)	Country*	6	None
Policy Stability	Stability of policy instruments	0.03 (cumulative years of all instruments adjusted by revisions, average)	Country*	6	1.2.1 Regulatory quality
Legacy of Failure	Decline in interest following failures	3,390 (exponent of decline function fitted to Google search frequency)	Global†	7	None
Regulatory Capture	Public RD&D expenditure on fossil fuels	164 (euros, millions)	Country*	1	None

(Continued)

Consistency in the EU's energy innovation portfolio

The EU's Strategic Energy Technology (SET) Plan identifies six priority areas for energy innovation: renewable energy, smart grids, energy efficiency (in buildings and industry), sustainable transport (including electric vehicles), CCS, and nuclear power (emphasizing safety).[11] In each of these technology areas, the SET Plan provides strategic planning

Table 1: Technology-specific indicators of innovation system processes *(continued)*

Innovation system processes in the ETIS framework	Technology-specific indicators (illustrated for the EU)	Absolute values for renewable energy in the EU in 2015 (with units)	Data availability	Main data source	Similar indicators in the GII 2017 conceptual framework (GII Annex 1)
ACTORS AND INSTITUTIONS					
Capacity	Top 100 Clean-tech funds	56 (euros, millions)	EU††	8	2.3.3 Global R&D firms. avg. exp. top 3
Heterogeneity	Diversity of types of organisation in European Energy Research Alliance	0.79 (Shannon index)	Country/EU	9	None
	Diversity of types of organisation in publication activity	1.46 (index constructed by authors)	Country	2	None
	Diversity of types of organisation in patenting activity ^	0.99 (index constructed by authors)	Country	3	None
Exchange & Interaction	European Energy Research Alliance activities involving different EU actors	26 (number of activities)	Country/EU	9	5.2.1 University/industry research collaboration
	Publication co-authorships between different EU actors	662 (number of co-authorships)	Country	2	5.2.1 University/industry research collaboration
	Patent co-inventions between different EU actors ^	396 (number of co-inventions)	Country	3	5.2.1 University/industry research collaboration
Shared Expectations	Policy instruments: targets, roadmaps, action plans	112 (number of instruments)	Country*	6	None
	Policy instruments: targets, roadmaps, action plans	1.77 (cumulative number of instruments, average)	Country*	6	None
ADOPTION AND USE					
Market Size	Potential market size (total number of physical units multiplied by cost per unit)	1,809,328 (euros, millions)	Country	5	None
Market Share	Actual market size as percentage of potential market size	34 (percent)	Country	5	

Main data sources: 1 IEA energy RD&D statistics, available at http://wds.iea.org/WDS/Common/Login/login.aspx; 2 Web of Science, available at https://login.webofknowledge.com/; 3 United States Patent and Trademark Office (USPTO) PatentsViews database, available at http://www.patentsview.org/web/; 4 Eurostat EU trade statistics, available at http://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database; 5 Secondary data from peer-reviewed studies; 6 IEA Addressing Climate Change policy database, available at https://www.iea.org/policiesandmeasures/climatechange/; 7 Google Trends, available at https://trends.google.com/trends/?geo=; 8 Global Cleantech 100, available at https://www.cleantech.com/; 9 European Energy Research Alliance (EERA), available at https://www.eera-set.eu/.

Notes: A single GII indicator may map to more than one ETIS indicator, and vice versa. A 'learning rate' is the % reduction in cost per doubling of cumulative experience. The Shannon index is a common measure of diversity. Indicators, metrics, and absolute values in 2015 (or 2012 for patents) are illustrated for renewable energy in the EU (see text for details). ETIS = energy technology innovation system; IEA = International Energy Agency; OECD = Organisation for Economic Co-operation and Development.

^ Data are from 2012 because of truncation issues with more recent patent data.

* Data are readily available for IEA or OECD member countries but may not be available for developing economies.

† Data are not available for specific countries, but only on an aggregated basis at a regional or global level.

†† Data are specific to the EU (used here to illustrate how the ETIS framework indicators can be measured). Alternative data may be available for other regions.

††† This comprises three separate indicators per type of policy instrument: innovation, regulatory, and market-based.

and coordination of research and innovation activities within the EU.[12]

The ETIS indicators can be used to assess consistency in the SET Plan portfolio. 'Consistency' in this case means that a similar level of emphasis is placed on different innovation system processes within each technology area. This helps determine whether different parts of the innovation system are acting in concert to shape innovation outcomes. Consistency is therefore linked to careful

Table 2: Public energy RD&D expenditure in six technology areas for the top 10 countries in the EU ranked by total expenditure, 2015 euros, millions

Country	Renewable energy	Smart grid	Energy efficiency	Sustainable transport	Carbon capture & storage	Nuclear power	Total
Germany	211	102	66	40	7	226	652
France	101	55	45	148	21	76	446
United Kingdom	50	52	43	53	12	153	364
Netherlands	74	11	30	31	2	7	156
Finland	11	17	69	27	—	21	145
Belgium	12	8	30	7	2	77	136
Denmark	47	21	18	31	0	1	118
Austria	12	37	21	11	3	1	86
Spain	43	25	—	2	7	3	80
Sweden	15	22	18	22	0	1	78

Source: IEA energy RD&D statistics, available at http://wds.iea.org/WDS/Common/Login/login.aspx.
Notes: See text for details. RD&D = research, development, and demonstration; — = missing data.

coordination of directed innovation efforts. As the EU states: 'the mobilisation of public and private resources in a coordinated and targeted way . . . is and will continue to be at the SET Plan's centre'.[13]

Figure 1 shows the relative share of different innovation system processes across the six technology areas in the SET Plan portfolio. All the ETIS indicators shown in Table 1 are used to describe the innovation system processes relating to knowledge, resources, and actors and institutions.

Consistency in Figure 1 is shown by narrow variation within a technology area; inconsistency is shown by wide variation. Inconsistency means that, for any given technology, there is a strong emphasis on some innovation system processes but only a weak emphasis on others.

Taking the top panel of Figure 1 as an example, the relatively narrow variation for renewable energy and smart grids across all the knowledge-related indicators shows a consistent emphasis on different innovation system processes. Conversely, the relatively wide variation for sustainable transport shows a rather inconsistent emphasis on knowledge-related processes: some are strongly weighted in the SET Plan's innovation portfolio (e.g., publications); others have a disproportionately low share (e.g., amount and stability of R&D investments).

Overall, Figure 1 shows that the SET Plan's innovation portfolio is most clearly consistent in resources-related processes (including the durability and stability of public policy instruments), with a similar level of emphasis across the six technology areas. This implies that the level of financial, human, and policy resources being mobilized are working in concert to support innovation system functioning. Conversely, Figure 1 shows less consistency in the generation, codification, spillover, and international flows of knowledge in the sustainable transport and energy efficiency areas because they are weighted differently as innovation system processes within the SET Plan portfolio. This helps draws portfolio managers' attention to areas of possible tension or weakness where innovation efforts could be strengthened.

Alignment in global energy innovation portfolios

Mission Innovation is a commitment by 22 countries as well as the EU to double energy R&D investments over five years in order to 'accelerate a clean energy revolution'.[14] This increased investment is spread over diverse innovation challenges, ranging from carbon capture, biofuels, and solar energy to smart grids and heating and cooling in buildings. Like the EU's SET Plan, the Mission Innovation portfolio encompasses both energy-supply technologies and energy end-use technologies.

Besides Mission Innovation, there are many other important publicly supported initiatives for directing global energy innovation. A subset of the ETIS indicators adapted for global-scale analysis can be used to assess alignment between directed innovation efforts on the one hand (inputs), and public policy objectives on the other (desired outcomes).

Figure 1.

Consistency of emphasis on innovation system processes in the six technology areas of the SET Plan

Data source: Kim and Wilson, 2017.

Notes: Red and orange bars show interquartile ranges for all indicators related to *knowledge, resources,* and *actors and institutions.* Yellow bars show the minimum and maximum shares of innovation system processes within each type. For details of processes, indicators, and data sources, see Table 1. Indicators relating to adoption and use are not shown because of their small sample sizes.

Figure 2 summarizes the data for both input and outcome indicators characterizing a select set of global, regional, and national innovation efforts. For each indicator, the relative share (percent) of energy-supply technologies and energy end-use technologies is shown.

The input indicators describe both tangible and intangible contributions to the energy innovation system. They are similar to those shown in Table 1, but are more limited in scope in this example. Input indicators in the top panel of Figure 2 are summarized here:

- *modelling* studies of energy-system transformation for climate change mitigation;[15]
- scientific *research articles* related to energy technologies and system integration challenges;[16]
- technology *roadmaps* and international *collaborations* to strengthen shared expectations and knowledge exchange in key technology areas;[17]
- innovation funding programmes targeting high-risk high-gain *breakthrough projects* as well as more conventional *public R&D* expenditure on energy innovation;[18]
- private-sector *venture capital* leveraged by public funds into energy technologies.[19]

The desired outcomes describe broader sectoral or economy-wide impacts of energy innovation. Outcome indicators in the bottom panel of Figure 2 are summarized here:

- *capital investment* in energy technologies both in financial terms (in U.S. dollars) and in terms of *physical capacity* (in megawatts);[20]
- *cost reductions* as a result of learning-by-doing;[21]
- *economic returns* on innovation investments (e.g., increased economic productivity) as well as *social returns* (e.g., reduced pollution and greater energy security);[22]
- future *expected benefits* from innovation investments (in both economic and social terms);[23] and
- contribution to climate change *mitigation* (i.e., greenhouse gas emission reductions) at both global and national levels.[24]

Technology-specific data on each indicator were compiled from a wide range of sources. An example for each indicator is provided in the endnotes to the list above; full details on all the indicators, data, and sources are available in Wilson et al. (2012).

Figure 2 shows that the global energy innovation portfolio is misaligned. Whereas innovation inputs are strongly weighted towards energy-supply technologies, innovation outcomes that are in line with public policy objectives are dominated by energy end-use technologies. Energy end-use technologies make up a greater share of energy-system investments, leverage higher levels of private-sector activity, reduce more in costs as a result of market deployment, return larger social benefits, and offer greater potential for mitigating climate change.

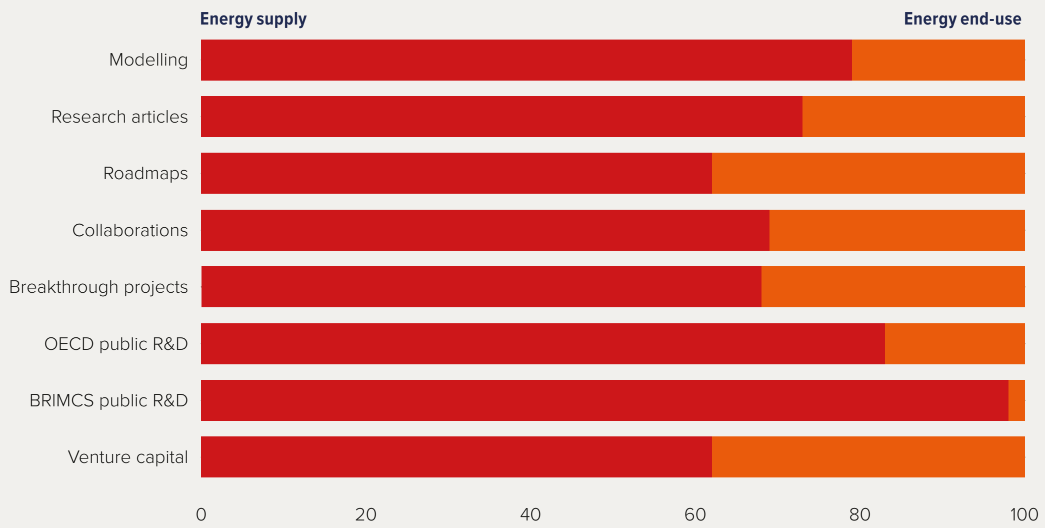
Why do directed innovation efforts privilege energy-supply technologies? Several explanations are possible. End-use technologies are smaller in scale, larger in number, highly dispersed, and varied in form. This makes analysis harder, data less readily available, and innovation efforts less visible and tangible. End-use innovation also lacks the coherent political economic influence of the well-capitalized and long-established energy-supply industry.[25] The heterogeneous and distributed nature of end-use technologies also means there are greater perceived difficulties in scaling up deployment to make step-change reductions in emissions.[26]

The indicators alone cannot establish which of these possible explanations of misalignment is correct. But the technology-specific analysis shown in Figure 2 helps draw policy makers' attention to potential weaknesses within directed energy innovation efforts globally.

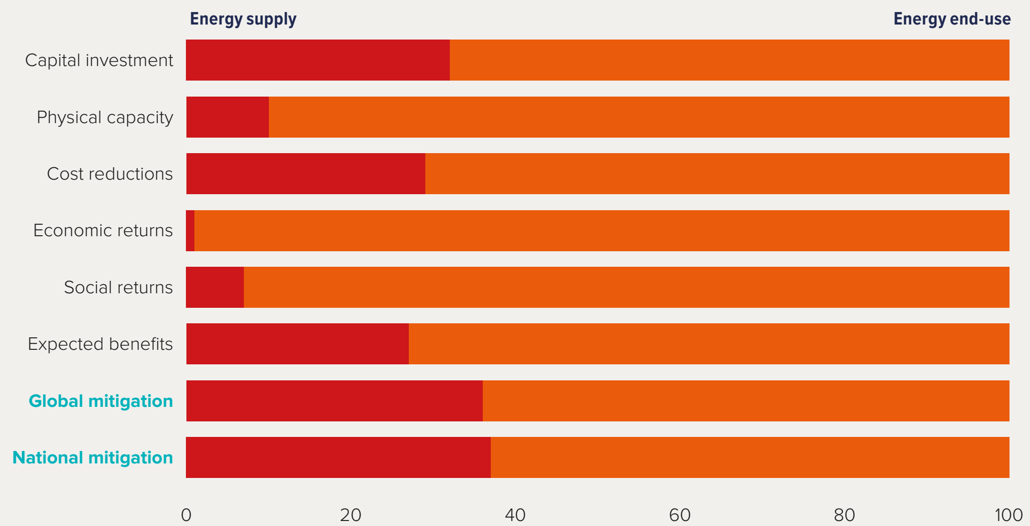
This is one example of how the ETIS framework and its derived indicators can be used to assess alignment. A similar approach could be used to examine alignment between technology-push and market-pull drivers of innovation,[27] between near-term and long-term innovation outcomes,[28] and between breakthrough and incremental innovation efforts.[29]

Figure 2.
Alignment of directed innovation efforts with outcomes and objectives for climate change mitigation: Energy-supply technologies vs energy end-use technologies

Innovation efforts (inputs)



Innovation outcomes and objectives



Source: Adapted from Wilson et al., 2012.

Notes: For details of indicators, data, and data sources, see Wilson et al., 2012. BRIMCS = Brazil, Russia, India, Mexico, China, South Africa; OECD = Organisation for Economic Co-operation and Development.

Conclusions

A systemic view of energy innovation captures the wider conditions that enable successful innovation outcomes. Actors, institutions, policies, finance, and markets all play important roles in energy innovation, so they all need to be measured, tracked, and analysed. The GII's conceptual framework sets out a diverse set of quantitative indicators applicable at the national level to enable cross-country analysis. The ETIS framework sets out a similarly diverse set of indicators applicable to specific energy technologies to enable cross-technology and portfolio-level analysis.

Two important design criteria for energy innovation portfolios at national, regional, and global scales are *consistency* and *alignment*.

A proportionately similar emphasis on related innovation system processes is an indication of consistency. This was illustrated in Figure 1 for the EU's current innovation portfolio across six technology areas ranging from renewable energy to sustainable transport. There is good evidence that different parts of the innovation system need to work in concert to deliver successful outcomes.[30] For example, technology-push and market-pull forces act together to shape innovators' expectations, stimulate innovation investments, and align technology development with users' needs.[31] Evidence of inconsistency in an energy innovation portfolio calls for a redirection of support towards weaker innovation system processes to ensure that the system as a whole works effectively.

Innovation system inputs that are directed, enabled, leveraged, or directly invested by public policy can also be tested for alignment. This was illustrated in Figure 2 for global energy innovation portfolios across two broad technology areas: energy supply and energy end-use. Technology-specific indicators help identify hidden biases within directed innovation efforts. Evidence of misalignment calls for a redirection of support towards technologies within the portfolio that can best deliver on public policy goals.[32]

The ETIS framework and its derived set of indicators are versatile in their applicability. Technology-specific analyses of energy innovation systems provide important insights for policy makers and portfolio managers directing innovation efforts towards a clean, efficient, low-carbon future energy system.

Notes

1 Cornell University et al., 2017, p. 47 (Annex 1).

2 The GII 2017 places a great deal of emphasis on the 'climate and infrastructure for innovation'; see Cornell University et al., 2017, p. 47, Annex 1.

3 Johansson et al., 2012.

4 Grubler and Riahi, 2010.

5 Grubler et al. 2012; Grubler and Wilson, 2014.

6 Gallagher et al., 2012.

7 Grubler et al., 2012; Grubler and Wilson, 2014.

8 Freeman and Soete, 2000.

9 Chan et al., 2017.

10 Borup et al., 2008; Borup et al., 2013; Hu et al., 2018; Klitkou et al., 2012; Miremadi et al., 2018; Truffer et al., 2012; Wilson, 2014.

11 EC, 2015; EC, 2017.

12 Carvalho, 2012.

13 EC, 2017, p. 86.

14 For further information about Mission Innovation, see http://mission-innovation.net.

15 For an example, see Edenhofer et al., 2010.

16 For an example, see D'Agostino et al., 2011.

17 For an example, see IEA, 2010.

18 For an example, see US DoE, 2011.

19 For an example, see UNEP et al., 2009.

20 For an example, see Wilson and Grubler, 2014.

21 For an example, see Grubler et al., 2012.

22 For an example, see NRC, 2001.

23 For an example, see NRC, 2007.

24 For an example, see Riahi et al., 2007.

25 Moe, 2010; Unruh, 2000.

26 Wilson et al., 2012.

27 Nemet, 2009.

28 Sandén and Azar, 2005.

29 Davis et al., 2013; Pacala and Socolow, 2004.

30 Gallagher et al., 2012.

31 Grubler et al., 2012; Nemet, 2009.

32 Grubler and Riahi, 2010.

References

Borup, M., P. D. Andersen, S. Jacobsson, and A. Midttun. 2008. *Nordic Energy Innovation Systems: Patterns of Need Integration and Cooperation.* Roskilde, Denmark: Nordic Energy Research.

Borup, M., A. Klitkou, M. M. Andersen, D. S. Hain, J. L. Christensen, and K. Rennings. 2013. *Indicators of Energy Innovation Systems and Their Dynamics: A Review of Current Practice and Research in the Field.* Lyngby, Denmark: Nordic Institute for Studies in Innovation, Research and Education (NIFU), and Technical University of Denmark (DTU) Department of Management Engineering.

Carvalho, M. G. 2012. 'EU Energy and Climate Change Strategy'. *Energy* 40 (1): 19–22.

Chan, G., A. P. Goldstein, A. Bin-Nun, L. D. Anadon, and V. Narayanamurti. 2017. 'Six Principles for Energy Innovation'. *Nature* 552: 25–27.

Cornell University, INSEAD, and WIPO. 2017. *The Global Innovation Index 2017: Innovation Feeding the World.* Ithaca, Fontainebleau, and Geneva: Cornell University, INSEAD, and WIPO.

D'Agostino, A. L., B. K. Sovacool, K. Trott, C. R. Ramos, S. Saleem, and Y. Ong. 2011. 'What's the State of Energy Studies Research? A Content Analysis of Three Leading Journals from 1999 to 2008'. *Energy* 36 (1): 508–19.

Davis, S. J., L. Cao, K. Caldeira, and M. I. Hoffert. 2013. 'Rethinking Wedges'. *Environmental Research Letters* 8 (1): 011001.

EC (European Commission). 2015. Communication from the Commission C(2015) 6317 final. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation. Brussels, Belgium: European Commission.

——. 2017. *The Strategic Energy Technology (SET) Plan 2007-2017.* Brussels, Belgium: European Commission.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magné, S. Scrieciu, H. Turton, and D. van Vuuren. 2010. 'The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs'. *The Energy Journal* 31 (Special Issue: The Economics of Low Stabilization): 11–48.

Freeman, C. and L. Soete.2000. *The Economics of Industrial Innovation.* Cambridge, MA: MIT Press.

Gallagher, K. S., A. Grübler, L. Kuhl, G. Nemet, and C. Wilson. 2012. 'The Energy Technology Innovation System'. *Annual Review of Environment and Resources* 37 (1): 137–62.

Grubler, A., F. Aguayo, K. S. Gallagher, M. Hekkert, K. Jiang, L. Mytelka, L. Neij, G. Nemet, and C. Wilson. 2012. 'Policies for the Energy Technology Innovation System (ETIS)'. In *Global Energy Assessment,* eds. T. B. Johansson, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri. Cambridge, UK: Cambridge University Press. Chapter 24.

Grubler, A. and K. Riahi. 2010. 'Do Governments Have the Right Mix in their Energy R&D Portfolios?' *Carbon Management* 1 (1): 79–87.

Grubler, A. and C. Wilson. 2014. *Energy Technology Innovation: Learning from Historical Successes and Failures.* Cambridge, UK: Cambridge University Press.

Hu, R., J. Skea, and M. J. Hannon. 2018. 'Measuring the Energy Innovation Process: An Indicator Framework and a Case Study of Wind Energy in China'. *Technological Forecasting and Social Change* 127: 227–44.

IEA (International Energy Agency). 2010. *Energy Technology Initiatives.* Paris: IEA.

Johansson, T. B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri. 2012. *Global Energy Assessment: Towards a Sustainable Future.* Cambridge, UK: Cambridge University Press.

Kim, Y. J. and C. Wilson. 2017. 'Evaluating the EU's Innovation System'. Paper presented at the IAEE (International Association for Energy Economics) European Conference, 3–6 September 2017, Vienna, Austria.

Klitkou, A., M. Borup, and E. Iversen. 2012. *Energy Innovation Systems: Indicator Report 2012.* Lyngby, Denmark: Nordic Institute for Studies in Innovation, Research and Education (NIFU), and Technical University of Denmark (DTU) Department of Management Engineering.

Miremadi, I., Y. Saboohi, and S. Jacobsson. 2018. 'Assessing the Performance of Energy Innovation Systems: Towards an Established Set of Indicators'. *Energy Research & Social Science* 40: 159–76.

Moe, E. 2010. 'Energy, Industry and Politics: Energy, Vested Interests, and Long-Term Economic Growth and Development'. *Energy* 35 (4): 1730–40.

Nemet, G. F. 2009. 'Demand-Pull, Technology-Push, and Government-Led Incentives for Non-Incremental Technical Change'. *Research Policy* 38 (5): 700–09.

NRC (National Research Council). 2001. *Energy Research at DoE: Was it Worth It? Energy Efficiency and Fossil Energy Research 1978-2000.* Washington, DC: Committee on Benefits of DoE R&D on Energy Efficiency and Fossil Energy, NRC.

——. 2007. *Prospective Evaluation of Applied Energy Research and Development at DoE (Phase Two).* Washington, DC: Committee on Prospective Benefits of DoE's Energy Efficiency and Fossil Energy R&D Programs (Phase Two), NRC.

Pacala, S. and R. Socolow. 2004. 'Stabilisation Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies'. *Science* 305: 968–72.

Riahi, K., A. Grubler, and N. Nakicenovic. 2007. 'Scenarios of Long-Term Socio-Economic and Environmental Development under Climate Stabilization'. *Technological Forecasting and Social Change* 74 (7): 887–935.

Sandén, B. A. and C. Azar. 2005. 'Near-Term Technology Policies for Long-Term Climate Targets: Economy Wide versus Technology Specific Approaches'. *Energy Policy* 33 (12): 1557–76.

Truffer, B., J. Markard, C. Binz, and S. Jacobsson. 2012. *Energy Innovation Systems: Structure of an Emerging Scholarly Field and Its Future Research Directions.* Copenhagen: Danish Council for Strategic Research.

UNEP, NEF, and SEFI (UN Environment Programme, Basel Agency for Sustaianble Energy, New Energy Finance, and Sustainable Energy Finance Initiative). 2009. *Analysis of Trends and Issues in the Financing of Renewable Energy and Energy Efficiency. Global Trends in Sustainable Energy Investment 2009,* eds. C. Greenwood, E. Usher, and V. Sonntag-O'Brien. Basel: UNEP, NEF, and SEFI.

Unruh, G. 2000. 'Understanding Carbon Lock-In'. *Energy Policy* 28: 817–30.

US DoE (United States Department of Energy). 2011. ARPA-E Projects Database. Washington, DC: Advanced Research Projects Agency, US DoE.

Wilson, C. 2014. 'Input, Output & Outcome Metrics for Assessing Energy Technology Innovation'. In *Energy Technology Innovation: Learning from Historical Successes and Failures,* eds. A. Grubler and C. Wilson. Cambridge, UK: Cambridge University Press. 75–88.

Wilson, C. and A. Grubler. 2014. 'A Comparative Analysis of Annual Market Investments in Energy Supply and End-Use Technologies'. *Energy Technology Innovation: Learning from Historical Successes and Failures,* eds. A. Grubler and C. Wilson. Cambridge, UK: Cambridge University Press. 332–48.

Wilson, C., A. Grubler, K. S. Gallagher, and G. F. Nemet. 2012. 'Marginalization of End-Use Technologies in Energy Innovation for Climate Protection'. *Nature Climate Change* 2 (11): 780–88.

CHAPTER 6

ENERGY STORAGE IN THE ANTIPODES

Building Australia's New Batteries

Max E. Easton and **Thomas Maschmeyer,** University of Sydney and Gelion Technologies Pty Ltd

Although renewable energy sources such as wind and solar have matured to become a proven component of national energy grids, in countries such as Australia they are still only minor contributors. The missing link in the transition from fossil-based to renewable energy is energy storage—a suite of technologies designed to act as an energy buffer for intermittent power sources, enabling grid stability. However, current energy storage technologies rely on technologies largely optimized for mobile devices or power applications rather than energy applications. There is a large gap between the need for energy storage batteries and the market's need for batteries designed to act as a low-cost, reliable buffer system. This is especially the case for solar photovoltaic installations, which need to bridge times when there is no sunlight to be used as a 24/7 energy solution. This gap between what is currently feasible and what is needed is creating an opportunity for disruptive energy storage technologies to enter the market and boost renewable energy adoption.

This chapter explores some of the opportunities and challenges involved in introducing disruptive energy technologies to the contemporary energy space and reflects on experiences introducing new technologies to Australia's innovation environment. The chapter then looks at some of the diverse requirements for energy storage technologies and the difficulties legacy technologies have in meeting those demands, before discussing an exciting innovative approach to basing new, innovative technologies on the principles of adaptability, affordability, and safety.

Storage: The main challenge for renewable power sources

The energy industry has been in a state of rapid evolution over recent decades. Although concerns around the negative environmental impacts of fossil fuel use are often cited as the force driving the industry towards renewable power sources, alternative energy sources such as solar and wind-derived power generation are making their own case financially. Rapidly falling costs and increasing efficiencies are creating a new regime wherein renewable energy is not just a 'green alternative' but a commercially highly competitive approach when compared with conventional fuel sources on a dollar-for-dollar basis.

A positive feedback loop appears to be materializing, making renewable energy impossible to ignore. Renewables, such as solar photovoltaic energy, have seen massive decreases in costs over the past several decades; these lower costs have combined with rapidly increasing energy efficiencies. Wind power now has greater generation capacity, with every doubling in turbine size approximately halving its manufacturing costs.[1] Technologies for previously fringe energy sources, such as tidal and geothermal power, are all entering the market as genuine players in the contemporary energy space.

Consequently, renewable power sources are moving from minor contributors to national energy supplies to noticeable contributors in many places around the world (e.g., Germany now gets 27% of its energy supply from renewable sources). Australia, with its renewables contribution of 5% wind and solar currently at only 3% of its total need, can see this as a substantial growth opportunity.[2] A key limitation to widespread adoption lies not in the wind and solar technologies themselves (which can be considered reasonably mature), but in the drawbacks of the natural source of energy of which they make use. The intermittency of solar (with its day/night cycles and its dependence on cloud conditions) and wind (which is determined by meteorological variations such as 'gusting' winds) has had these sources pigeonholed as secondary power sources that can be used only as grid support, not as baseload replacements. Clearly, a solution that brings renewable energy as a contender into (partial) baseload replacement is the world of electrochemical energy storage: batteries.

[A] solution that brings renewable energy as a contender into (partial) baseload replacement is the world of electrochemical energy storage: batteries.

Batteries represent a well-known technology. They are used to power portable devices such as smartphones and laptops; they also have larger-scale applications in the transport arena, where the storage technologies present solutions that range from simple batteries to operate starter motors in internal combustion engines to those used in hybrid and fully electric vehicles. Batteries function by storing electric energy as chemical potential energy through carefully designed chemical reactions. Passing an electrical charge into the device creates a high-energy chemical state that can be reversed at will by drawing that charge out again. Different battery chemistries have different advantages, with some being more useful in high-power applications (these are able to discharge quickly, but need to avoid fully discharging to keep battery health); others are more useful in energy storage applications (these are 'slow and steady', and utilize deep or full discharge). Important, but often ignored, is the complication that using one battery type in the primary field of application of another battery type can lead to significant problems regarding longevity, efficiency, and safety.

Coupling renewables with batteries is sometimes posited as a revolutionary new idea for future energy grids, but it is noteworthy that this was, in fact, proposed alongside some of the first solar panels ever designed. As far back as 1885, American engineer Charles Fritts stated, in reference to his selenium-based solar cell:

> The current, if not wanted immediately, can either be 'stored' where produced, in storage batteries [...] or transmitted over suitable conductors to a distance, and there used, or stored as usual till required.[3]

Clearly, the worlds of renewable power generation and energy storage have been intertwined from the very beginning. Energy storage has long been seen among the scientific and engineering community as a foundational aspect of renewable power supply.

Energy storage might contribute to energy networks in many ways. The obvious example, and the one Fritts suggested in 1885, is what is referred to as 'load levelling'—that is, excess solar power that has been stored in a battery during the day can be returned for use in the evening. Alternatively, excess (thus cheap) power at any time of the day can be stored and released when the price is more attractive (energy arbitraging). Such load-levelling schemes can be very sophisticated and powerful and can interact positively with the overall grid, increasing resilience and efficiency. Other applications include improvement to power quality; that is, batteries can also modulate voltaic and harmonic distortions between the generator and the end user, thus improving the quality and reliability of the power.

Innovations in storage technologies

Although significant progress in energy storage technologies has been made over recent decades, activities have been primarily focused on the optimization of small-scale applications (primarily in personal devices and electric vehicles). Clearly, however, coupling batteries with energy generation using solar photovoltaic and wind sources will form the backbone of renewable baseload power.

An innovative approach is that of Tesla, which uses batteries designed for power applications and deploys them for grid support and, to a certain extent, for energy storage. Tesla's 100 megawatt (MW) lithium-ion battery installation in South Australia has shown that it is indeed possible for large-scale energy storage to operate in tandem with the energy grid. So far, the battery array has provided 2.42 gigawatt-hours (GWh) of energy back to the grid with a round-trip efficiency of 80% over one month's operation.[4] This performance is creating optimism for energy storage in Australia with the perception that other significant storage projects are being buoyed by this success. However, it is important to use power batteries in a peak-modulation mode, using them to provide fast responses intermittently because that suits the battery chemistry employed. Daily, deep full-cycling of such batteries will reduce their lifetimes dramatically, since it will accelerate the effects of internal failure mechanisms inherent in their chemistry.

Other chemistries and modes of operation, such vanadium redox flow (Ronke Power) and zinc bromine flow (Redflow), have advantages in that they can be cycled at full discharge and are designed as true energy batteries. Flow batteries operate by cycling a liquid electrolyte, stored in tanks, through a battery electrode system, which is thought to increase longevity and robustness. Gelion's technology is able to capitalize on the attractive chemistry of zinc-bromine in a novel non-flow system based on ionogels with a more convenient and conventional battery footprint.

Furthermore, in the case of lithium-ion batteries, the availability of their primary electroactive components—particularly lithium and cobalt—is expected to face bottlenecks. Currently exploited lithium reserves are largely isolated in Argentina, Bolivia, and Chile, a region referred to as 'the lithium triangle.' New mining capacity elsewhere in regard to lithium might overcome this obstacle. Australia is well placed to benefit from this trend, since it is estimated to hold up to a third of the world's reserves. However, access to cobalt—the other essential chemical in lithium-ion batteries—remains a primary concern for the most commonly employed (and least expensive) types of lithium-ion batteries, given the limitation in international mining capacity and geopolitical concerns, with more than 70% of known reserves located in the Democratic Republic of the Congo. The expected pressures that come with rapidly increasing demand are creating possible long-term challenges in lithium and cobalt supply. This pressure is already starting to be felt—for example, the price of cobalt has gone from US$21,750 per metric tonne in February 2016 to US$92,250 in March 2018.[5]

Indeed, recent modelling by Australia's Office of the Chief Scientist has shown that using the total world's battery production capacity in 2014 (including all commonly produced battery chemistries, such as lithium-ion, lead-acid, etc.), would translate into only 11 minutes and 27 seconds of global electricity consumption stored. The scale is such that the production capacity of Tesla's gigafactory, which began operation in 2017, would need to improve its output by 184 times to provide just one day of back-up power supply.[6] It is clear, then, that new, accelerated thinking is required for this evolving energy paradigm.

From both a materials and a technological perspective, alternatives are needed to supplement current market offerings. Not all energy consumers have the same needs, and not all battery chemistries can meet all the demands placed on them. The requirements of power generators, end users, and every intermediary point are incredibly varied. Existing technologies may not be able to provide the versatility and scalability required without the availability of new technologies. These new technologies, able to adapt and meet the manifold demands made on them, are urgently needed.

The evolving energy space requires innovative new storage technologies based on three main tenets:

- **adaptability** to varied energy battery demands based on modular designs;
- **affordability** based on low up-front cost coupled with a long lifetime, translating to a very low levelized cost of energy storage; and
- **safety** inherent to the chemistry used.

In this context, non-flow batteries are more flexible and cost-competitive than flow batteries for anything other than the very large scale of hundreds of megawatt-hours (MWh), where the utility of flow batteries are yet to be proven.

Modular designs eliminate much of the engineering overhead associated with specific solutions for differently sized applications—for example, when using a simple standard battery cell, different applications are easily accessible by changing the battery cell's connectivity.

Zinc-based batteries are significantly cheaper in terms of materials cost and safer than lithium-based ones. They are also less toxic than lead-acid batteries and do not present a fire hazard.

Design tenets within the Australian context

In the 1980s the University of New South Wales began to develop the vanadium redox flow battery, with a series of commercialization efforts just falling short in the ensuing decades (a reflection of the coal-first energy paradigm of the 1980s and 1990s). However, development of this battery continues optimistically today, and two utility-scale units are being built in China: one with a capacity of 100 MW and 500 MWh in Hubei,[7] and one with a capacity of 200 MW and 800 MWh in Dalian for US$500 million.[8]

In the early 2000s, Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed a hybrid supercapacitor, which has now been commercialized by Cap-XX,[9] and a lead-acid battery termed the UltraBattery that is in early production today.[10] Similarly, Brisbane-based Redflow is successfully manufacturing zinc-bromine flow battery systems.[11]

Most recently, in 2016, Gelion Technologies reported a non-flow variation of the zinc-bromine chemistry.[12] These batteries are in the early stage of commercialization, and beta versions are expected to be sold for evaluation purposes in 2019; initial mass production is scheduled for 2020.

When paired with solar power, the non-flow zinc bromine battery's ability to combine deep discharge resilience with a low price, even at capacities as small as 2 kilowatt-hours (kWh), as well as safety and a high degree of recyclability is a compelling proposition. Gelion's aim is to produce battery cells that cost less than US$100/kWh to manufacture. The objective is to supply a range of different solar photovoltaic applications, including street lighting, solar pumps, micro-grid support, and, eventually, fully scalable solutions in stackable shipping containers (e.g., Tesla's batteries in South Australia).

The expected market growth, in combination with some of the inherent limitations of the established energy storage technologies, means that the time has come for disruptive energy technology in Australia and throughout the world.

The changing regulatory environment favours energy storage as a necessary buffer that will allow the introduction of renewables while retaining grid stability. There is a clear mandate both from business (e.g., Australia's AGL Energy) and consumers to enable a greater portion of renewables in the Australian energy mix. Indeed, the Australian government's 2017 *Independent Review into the Future Security of the National Electricity Market* officially acknowledged energy storage as being a vital contributor to future energy systems.[13] The report contains a range of recommendations, including a key one about price settlement periods that pertain to the adoption of battery and pumped hydropower storage to enable renewable energy adoption. These recommendations immediately led the Australian Energy Market Commission (AEMC), which regulates the market, to draft an essential rule change for the adoption of energy storage that substantially alters Australia's National Energy Market (NEM).[14]

NEM operates on complicated operative rules, a core issue of which revolves around the 'consumer-first market approach' where the price point is averaged over a 30-minute settlement period to determine the cheapest energy supplier. Designed in the absence of renewables and substantial energy storage, this 30-minute rule aimed at protecting the consumer resulted in unintended favouritism towards mature fossil fuel–based power sources. One of the key advantages of batteries lies in their near instantaneous supply of power, meaning that the fossil-fuel advantage is diluted when normalized to the other sources over a 30-minute settling period because it negates much of the disadvantage of coal-fired power plants' lag time in energy provision. The AEMC's rule change has confirmed a reduction of the settlement period from 30 to 5 minutes, starting in 2021. This change will enable agile, fast-responding technologies to compete and open the door to electrochemical energy storage becoming highly cost competitive in Australia's utility sector. However, even this rule may be insufficient: Tesla reports being underpaid as a result of their very fast (200 milliseconds) response times, and further fine-tuning of market rules can be expected as more players and greater capacity come onto the market.

Australia: An environment where energy storage innovation can thrive

With a focus on adaptability, affordability, and safety, new market entrants are an attractive prospect for future energy storage systems. The expected market growth, in combination with some of the inherent limitations of the established energy storage technologies, means that the time has come for disruptive energy technology in Australia and throughout the world.

The combination of Australia's highly suitable weather conditions for renewables, a history of innovative thinking, an interest in adopting energy storage technologies, and a positively evolving regulatory environment make Australia an ideal place for the rapid penetration of batteries into its national energy landscape. Increasing investor confidence that is providing Australian companies with the capital to explore such disruptive technology is creating rapid growth in the development of renewables and batteries.[15] This enables Australian technology to play a significant part in the future of energy supply.

Notes

1 Clark, 2018.

2 Department of the Environment and Energy, 2017a.

3 Fritts, 1885.

4 McConnell, 208.

5 See www.lme.com/en-GB/Metals/Minor-metals/Cobalt.

6 Cuthbertson and Howard, 2016.

7 Information about Pu Neng, the site of this battery, is available at www.punengenergy.com.

8 Further information about the unit in Dalian is available at www.rongkepower.com (in Chinese).

9 Further information about CAP XX is available at www.cap-xx.com.

10 Further information about UltraBattery® is available at www.ultrabattery.com.

11 Further information about Redflow's storage systems is available at www.redflow.com.

12 Further information about Gelion is available at www.gelion.com.

13 Department of the Environment and Energy, 2017b.

14 Information about Australia's Energy Market Operator (AEMO) is available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM.

15 An example of investor confidence is the partnership that created the Powering Australian Renewables Fund; information about this fund is available at https://www.agl.com.au/about-agl/what-we-stand-for/sustainability/powering-australian-renewables-fund.

References

AEMC (Australian Energy Market Commission). 2017. 'Five Minute Settlement – Rule Change: Completed, Overview', 28 November. Available at https://www.aemc.gov.au/rule-changes/five-minute-settlement.

Clark, P. 2018. 'Bigger, Higher and Floating: Advances That Make Wind a Better Power Source'. *Financial Times,* 8 January. Available at https://www.ft.com/content/b7b7f8a0-cb06-11e7-8536-d321d0d897a3.

Cuthbertson, B. and W. Howard. 2016. 'Backing Up the Planet: World Battery Storage'. Office of the Chief Scientist of Australia. Available at http://www.chiefscientist.gov.au/2016/10/backing-up-the-planet-world-battery-storage/.

Department of the Environment and Energy, Australia. 2017a. *Australian Energy Update 2017.* Canberra. Available at https://www.energy.gov.au/publications/australian-energy-update-2017.

——. 2017b. *Independent Review into the Future Security of the National Electricity Market: Blueprint for the Future.* Available at https://www.energy.gov.au/government-priorities/energy-markets/independent-review-future-security-national-electricity-market.

Fritts, C. E. 1885. 'On the Fritts Selenium Cells and Batteries'. *Journal of the Franklin Institute* 119 (3): 221–32.

McConnell, D. 2018. 'A Month In, Tesla's SA Battery Is Surpassing Expectations'. ReNeweconomy, 16 January. Available at http://reneweconomy.com.au/month-teslas-sa-battery-surpassing-expectations-41248/.

CHAPTER 7

THE INNOVATION ECOSYSTEM IN THE BRAZILIAN ENERGY VALUE CHAIN

Robson Braga de Andrade, National Industry Confederation (CNI), Social Service for the Industry (SESI), and the Brazilian National Service for Industrial Training (SENAI)
Heloisa Menezes, Brazilian Micro and Small Business Support Service (Sebrae)

International agreements regarding climate change and the evolution of energy policies point to the increasing incorporation of innovation and the expanding use of renewable energy sources in the worldwide energy mix. The energy sector is going through a process of transition, in which its main challenge is to reduce the trade-off between the cost of energy and the preservation of environment.

Innovations in the energy sector have great disruptive potential. In the power sector, for example, the emergence of intelligent networks and the introduction of small-scale distributed generation have the potential to change the role and business models of distribution companies and present opportunities for small innovative businesses. The way energy is consumed, generated, and stored (or re-injected into the network) determines how the electric power network should be managed to guarantee security and sustainability of supply. The electric energy sector that will result from this process of technological change is likely to be quite distinct from the one we currently know.

Brazil has a strong tradition of innovation in the energy sector. The country experienced a shortage of coal and oil before the discovery of Brazilian oil in the 1990s. This history, along with the large size and significant diversity of the national energy sector, has imposed major technological challenges that have been addressed and overcome. Brazil has developed a complex and advanced innovation ecosystem in energy.

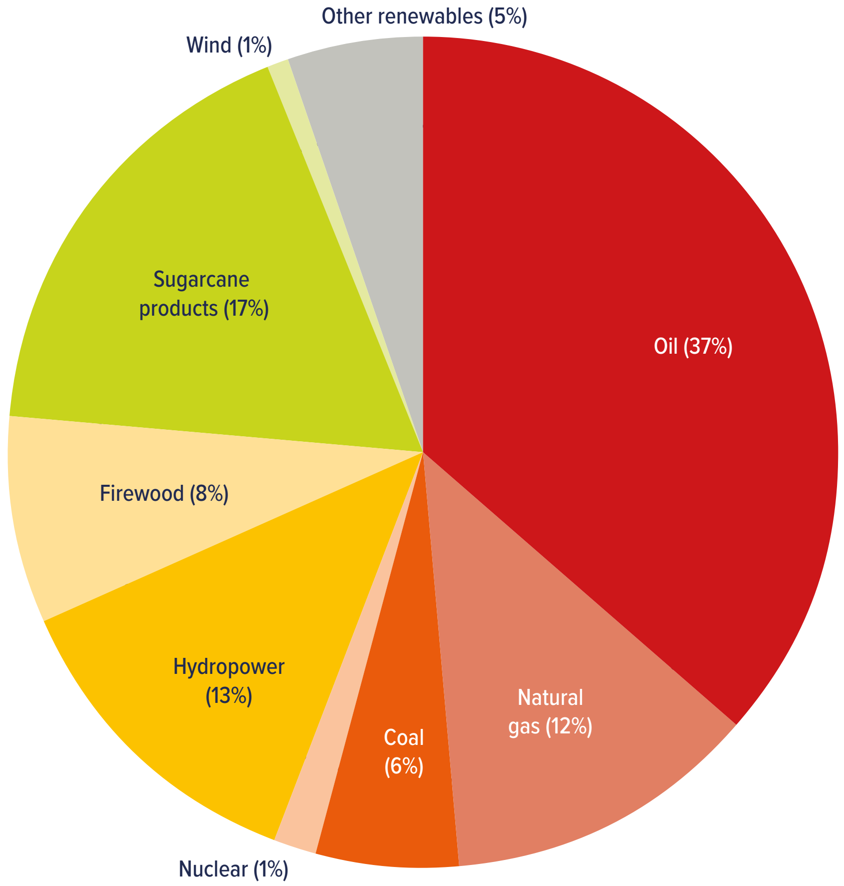
Despite its successful trajectory, new and old challenges must be tackled to ensure an ecosystem of innovation that is adapted to the global energy transition. This chapter seeks to present and discuss the Brazilian experience of innovation in the energy sector and point to the new challenges associated with the ongoing energy transition. The next section of the chapter discusses the main features and particulars of the Brazilian energy value chain; the following section considers elements of innovation in Brazil's energy sector; and the final section describes the main challenges that must be confronted to improve the sector´s innovation ecosystem, including the participation of small businesses.

The Brazilian energy value chain

The most distinctive feature of Brazil´s energy sector is the structure of its energy matrix. Brazil relies on important contributions from renewable energy sources in transport and electricity. In 2016 renewable energy met 43.5% of total energy consumption needs. The contribution of sugarcane energy products used for transport, electricity generation, and heat came to 17% of total energy supply. Hydropower dominates electricity generation, supplying 13% of the country´s energy. Oil plays a larger role in non-renewable sources, providing 37% of total energy.[1] Consumption of natural gas and coal are less prominent in Brazil than the global average. However, natural gas consumption is

Figure 1.

Brazilian energy matrix structure, 2016



Source: Source: EPE/MME, 2017a.

increasing rapidly in the country, and by 2016 was up to 12% (Figure 1).

Brazilian power generation is one of the cleanest of the world. Renewable sources reached 85% of installed generation capacity, totalling 160 gigawatts (GW).[2] Hydropower plants represent 71% of installed capacity. The country confronts the challenge of maintaining this high share of renewables in the context of growing demand and increasing difficulty in building new hydropower plants.[3] Thus other renewable sources (wind and solar) will need to compensate for the future reduction in hydropower participation in the energy matrix.[4] However, it is worth emphasizing that energy produced from solar and wind sources is intermittent and the growth of these sources will require the expansion of backup energy capabilities (such as gas-based thermal power plants, batteries, and other energy storage technologies). With the growing difficulty in constructing large dams with reservoirs, natural gas becomes an important option for ensuring the security of the energy supply.

The high penetration of biofuels in the transport energy mix is another important feature of the

Brazilian energy sector. Currently, ethanol and biodiesel represent 21% of energy consumption for transport in Brazil. The diffusion of biofuels in Brazil emerged as a response to the country's first oil crisis. In 1974, an ambitious programme to substitute gasoline with ethanol in light vehicles was launched (the ProÁlcool Programme).

The introduction of a bi-fuel vehicle in the 2000s re-launched the ethanol industry, offering consumers the possibility of choosing between gasoline and ethanol in gas stations.[5] Bi-fuel vehicles spread quickly and reached 94% of car sales and 65% of the car fleet in 2016.[6]

The addition of biodiesel to diesel began in December 2004, when the Brazilian government launched the National Program of Production and Use of Biodiesel (PNPB). In 2008, the government mandated a 2% biodiesel blend in mineral diesel fuel. The mandatory biodiesel mix percentage has gradually increased until reaching the current mandate of 10%.

It is worth noting that Brazilian energy policy is beginning to consider programmes that promote electric and hybrid vehicles. These vehicles have the potential to become a new technological paradigm in transport. The Brazilian experience with alternative engine technology can become an important driver of the innovation process necessary for the dissemination of this new paradigm.

In spite of its clean energy matrix, Brazil has made international commitments to fight global warming. In the Paris Agreement, Brazil committed to reduce its greenhouse gas emissions by 37% in 2025 and 43% in 2030, compared to its 2005 levels. For the energy sector, Brazil is aiming to increase its share of renewable energy to 45%.[7]

Regarding fossil fuel sources, Brazil's crude oil production has been growing rapidly in recent years as a result of the discoveries of prolific reserves in the pre-salt area.[8] However, a large proportion of the oil produced by this growth is exported, since domestic consumption is growing less quickly than production.

In 2017 average net exports of Brazilian crude oil reached 927,000 barrels per day. Because of restrictions in its refining capacity, Brazil imports large volumes of oil products: 350,000 barrels of oil equivalent per day in 2017. Thus the consolidated balance (crude oil plus oil products) comes to a daily net export of 577,000 barrels of oil equivalent. Brazilian oil production will keep growing in the next decade, with rapid increases in the surplus volume of oil to be exported.[9]

Innovations in the Brazilian energy supply chain

Innovation in the energy supply chain in Brazil was initiated by state-owned enterprises. When the electricity and oil sectors were liberalized in the 1990s, new innovation policies and tools were introduced. These emphasized innovation funds; clauses for mandatory investment in research, development, and innovation (RDI) in the exploration and production of oil contracts; and the legislation of mandatory RDI investment in the electric power sector.

Innovation in the power sector was originally initiated by Eletrobras, the sector's publically owned company. Eletrobras' objective was to promote domestic production and overcome the technological challenges of developing a hydropower-based sector. To face this challenge, Eletrobras created the Center for Research of the Electric Sector (CEPEL). With the liberalization of the power sector in the 1990s, electric utilities were obliged to invest 1% of their gross revenue in RDI and energy conservation projects. In addition, a fund to promote innovation in the power sector (CT-Energ) was established by the government.

Most RDI projects for utilities were developed in cooperation with universities and research centres. Between 2008 and 2015 approximately 2,400 projects were developed, and a total of 4.8 billion Brazilian reais (R$) were invested in these projects.[10]

In 2017 the National Agency of Electric Energy (ANEEL) completed a study, coordinated by the Centre of Management and Strategic Studies (CGEE), on technology prospecting in the power sector. This project mapped the RDI initiatives carried out in the power sector to determine whether the resources for RDI were properly used, aiming to improve innovation policies. The study found that 2,767 different research topics are being pursued in the Brazilian power sector. There are resources and laboratories available for innovation projects, although the country falls short in the terms of registered patents.[11]

In the oil and gas sector, the RDI clause in the area of lease contracts requires the investment of 1% of gross revenue from high-productivity oil fields into RDI. From 1998 until the second quarter of 2017, oil operators spent more than R$12 billion on RDI. Petrobras was responsible for R$11.6 billion and other companies for R$832 million. More than 10,000 projects were contracted through the RDI clause in the oil and gas sector.[12]

In addition, the fund for Science and Technology for the Petroleum and Natural Gas (CT-Petro) was created by the Petroleum Law (Law 9478/97). This fund is financed partially by oil royalties;[13] it is under the administration of FINEP, the Brazilian Innovation Agency, and the National Council for Scientific and Technological Development (CNPq). Between 1998 and 2015, the resources collected by the fund reached R$16.2 billion. However, only 30% of the amount collected was included in the federal government budget for innovation and only 6% was effectively spent in RDI projects.[14] The rest was held back by the National Treasury.

The Inova Petro programme was created in 2015 as an alternative source of financing for technological innovation efforts, geared to meet the challenges of exploration and production imposed by the pre-salt discoveries. The focus of the programme is to encourage and promote domestic suppliers of technology.[15]

With respect to biofuels, the sectoral innovation system was created by the ProÁlcool Programme. This innovation system was traditionally structured around research centres, with projects focusing on sugarcane agriculture. With the recovery of the ethanol market in the 2000s, the aim of developing the capacity to produce second-generation ethanol (E2G) fostered greater involvement from governmental institutions. The Ministry of Agriculture launched the National Plan of Agroenergy (PNA), which led to the creation of the Embrapa Agroenergy research institution. Embrapa Agroenergy is focused on carrying out research for new varieties of sugarcane, including those suitable for E2G, as well as other possible raw materials such as sweet sorghum and forest residues. The Ministry of Science, Technology and Innovation (MCTI) promoted the creation of the Brazilian Bioethanol Science and Technology Laboratory and drew up specific actions for the biofuels sector within the Action Plan in Science, Technology and Innovation (PACTI).[16]

The year 2011 saw changes in the configuration of the sectoral system of innovation in biofuels, after which PAISS—a programme that supports innovation in biofuels and biochemical segments—was created. The programme was formulated jointly by the Brazilian National Economic and Social Development Bank (BNDES) and FINEP, and has two fronts: industry and agriculture. The objective of PAISS industry is to promote the development of innovations in three thematic areas: E2G, new products from sugarcane, and gasification. PAISS agriculture has the following research avenues: (1) new varieties; (2) machinery and equipment; (3) logistics and production; (4) propagation of seedlings; and (5) adaptation of industrial systems. Twenty-five research proposals were received for PAISS dedicated to industry and 35 for PAISS dedicated to agriculture. In total, the programme received R$5.2 billion in funding.

Finally, it is worth noting that technological cooperation and innovation networks represent an important dimension of the innovation ecosystem in the Brazilian energy sector. The National Confederation of Industry (CNI) and the Brazilian Micro and Small Business Support Service (Sebrae) play a fundamental role in the articulation of these innovation networks.

CNI stimulates research and innovation to promote the competitiveness of industry and of the Brazilian economy. Several actions implemented by CNI focus on the energy sector, including launching studies and cooperating with the government and congress to create policies to support the competitiveness of the Brazilian economy.[17]

The Brazilian National Service for Industrial Training (SENAI) Institute for Innovation in Renewable Energy and the SENAI Institute of Innovation in Biomass are important tools used by CNI to promote innovation in the energy sector. These two institutes work with the main stakeholders of the innovation ecosystem in the energy sector, aiming to facilitate financing and cooperation in RDI projects. Together these institutes have developed 30 RDI projects between 2014 and 2017, contributing to the increase in the country's industrial competitiveness.

The Business Mobilization for Innovation (MEI), in turn, considers that the bioeconomy can structure the economy for the future since it is directly linked to the invention, development, and use of biological processes and products in the areas of energy, health, agriculture, livestock, and industrial biotechnology. In October 2017 MEI's Dialogs seminar was dedicated to discussing this matter.

The project entitled 2027 Industry: Risks and Opportunities for Brazil in the Face of Disruptive Innovations, presented by the Euvaldo Lodi Institute (IEL) of CNI in cooperation with the Economics Institute of the Federal University of Rio de Janeiro (UFRJ) and the University of Campinas (Unicamp), has identified electrochemical energy storage (rechargeable batteries, supercapacitors, cells, fuels, and hydrogen-based storage technologies) as one of the technological clusters with influence on the Brazilian industrial complex.[18] Industries such as aerospace, agrobusiness, automotive, and mining will experience a direct disruptive effect in the short (5 years) and medium term (10 years) through technological changes in power generation. These changes open niche opportunities in all related industries.

The Program for the Development and Qualification of Suppliers, an IEL initiative, contributes to increasing the competitiveness of the energy sector by encouraging interaction between large and medium-sized companies (anchor companies) and their suppliers. The objective is to promote the qualification of suppliers in several management areas, including innovation, as well as to foster networks of innovation and productive chains.

To encourage companies to innovate, CNI and Sebrae have published case studies of business innovation. Two of the three collections of case studies have included studies of innovative companies in the energy sector.

From 2004 to 2014, Sebrae and Petrobras worked together to develop small enterprises in order to promote their competitive inclusion in the oil and gas supply chain. Fifty-two projects were carried out in 16 Brazilian states, mobilizing local stakeholders through networks designed to promote cooperation and permanent interaction among companies and governmental, financial, and academic institutions, as well as other players in the oil and gas value chain. Out of the 18,000 companies that participated in the projects, 2,000 joined these networks.[19] Their primary goal was to open a space for small and medium-sized enterprises to innovate in a field dominated by large companies.[20] It is worth highlighting the successful experiments that brought about the inclusion of small companies into Petrobras' open innovation process with three different approaches, all of them beginning with a challenge proposed by the oil company. As a result, 12 technological solutions have been developed and made available in the market; around 22 are under development.

In 2017, Sebrae developed a new initiative with the Oil Industry National Organization (ONIP) in which large and medium-sized suppliers participate as anchors for innovation. These companies present their technological demands and opportunities to small innovative suppliers: more than 20 small businesses showed interest in developing projects in partnership with RDI institutions to meet the anchors' demands.[21]

Sebrae has participated in the design of policies to promote innovation and technological cooperation geared towards small businesses. More recently, it has begun to support start-ups (Sebrae Like a Boss, InovAtiva Brazil, and StartOut projects) and scale-ups.[22] Together with SENAI, it has launched public tenders to promote innovation in small businesses in order to meet challenges proposed by large companies. A similar partnership is being formed with the Brazilian Agency for Industrial Research and Innovation (Embrapii).[23]

Finally, Sebrae is bringing together small innovative companies and investment funds and planning to promote corporate venture initiatives in 2018. These experiences should contribute to improving the mechanisms for inserting small businesses into the innovation processes of large companies in the energy sector, thus fostering technological linkages.

Innovation challenges in the Brazilian energy value chain

The previous sections have shown that Brazil has an active ecosystem of innovation in the energy sector, incorporating initiatives intended to include small businesses into the open innovation process of large companies. In recent decades, the country has not only adopted energy technologies developed in the international market, but also has had a leading role in specific segments of the energy industry, such as offshore exploration in deep and ultra-deep waters,[24] as well as advanced biofuels production.

Despite the successful trajectory of Brazil's energy sector, new and old challenges must be tackled to ensure an ecosystem of innovation adapted to the energy transition scenario. The following challenges for innovation in the Brazilian energy sector must be met.

Establishing an industrial and technological policy, including a clear strategy for innovation

Industrial and technological policy assists in establishing visions and convergent strategies for innovation investment in the uncertain environment of the energy transition scenario. A good policy must include mechanisms to stimulate investment and the diffusion of technologies with disruptive potential and must also promote the attractiveness of projects with high technological risk.

The full development of the energy potential in the pre-salt area, which is currently one of the main challenges of the national energy sector, will depend on the introduction of technological innovations that would help reduce extraction costs and increase the oil recovery factor. This challenge requires the intensification of technological efforts to give economic sustainability to the pre-salt reserves.[25]

Brazil has the potential to be a leader in the development of disruptive technologies in deep water exploration, particularly in the subsea segment.[26] To achieve this objective, it will be necessary to integrate and coordinate the various initiatives of innovation policy in the oil sector, in addition to the intensifying technological cooperation between oil companies and suppliers in the supply chain.

Coordinating public policies and innovation programmes

Once a clear industrial and technological policy has been defined, a path is opened for the coordination of public policies and sectoral innovation programmes. Government initiatives to support innovation in the energy sector have proliferated in recent decades. Evaluating existing programmes and promoting greater synergies and convergence of efforts to support innovation is crucial.

The currently available programmes of innovation support should be revised after considering their effectiveness. It is important to verify whether there are overlaps between programmes; whether there is proper articulation and coordination between them; and whether the financing instruments and conditions are adequate for the proposed objectives.[27] After revising the programmes, it will be important to monitor and evaluate them permanently, elaborating and implementing performance indicators. The study on technology prospection in the electricity sector coordinated by CGEE illustrates this type of initiative, which could be replicated on the oil and biofuel sectors.[28]

Stabilizing funding for national RDI policy

Providing funding for the national RDI policy represents an important challenge for Brazil, given its current fiscal constraints. There are currently three basic financing sources for innovation in the energy sector: (1) the RDI clauses in oil exploration and production contracts and the specific legislation for RDI for the electricity sector; (2) the national budget resources allocated to innovation funds (CTPetro and CT-Energ); and (3) the BNDES and FINEP resources for innovation in general and those allocated to Inova Petro. The funds of the RDI clauses are substantial and relatively stable, varying in accordance with the gross revenues of energy companies subject to those clauses. The national budget resources have historically been very unstable, depending on the fiscal policy of the moment. The availability of funding sources from BNDES faces fewer restrictions, while the resources from FINEP have been recently significantly reduced.

Funding stability is an important issue for innovation policy in the energy sector. The effectiveness of some programmes has been compromised by unpredictability and instability of financing. This is the case for the innovation funds (such as CTPetro and CT-Energ) that depend on national budget resources.

In this context, it is important to adjust the mandatory clauses of RDI investment of the oil and the electric power sectors to increase the efficiency of the investment. These adjustments should consider the possibility of (1) investments in suppliers' RDI projects, (2) reducing legal uncertainty, (3) promoting collaborative innovation projects, and (4) using private management for RDI projects to avoid the risk of projects budgetary discontinuity.

Promoting technology cooperation and including small and medium-sized enterprises in the innovation ecosystem

The Brazilian energy industry is undergoing an important transformation with a reduction of the state company's role. Moreover, the current technological context of the energy sector is riskier now because of the diffusion of disruptive technologies. Thus technological cooperation has an important strategic position in a successful innovation ecosystem.

It is worth stressing the importance of including innovative small and medium-sized enterprises in the innovation ecosystem. The initiatives of technological cooperation promoted by CNI, Social Service for the Industry (SESI), SENAI, and Sebrae can be powerful tools to boost the linkage effects of technological innovation in the energy sector through the greater participation of small and medium-sized enterprises in this process.

It is crucial to include initiatives to insert small businesses into the sectoral innovation ecosystem, both in the implementation and in the periodic review of programmes to support innovation in the energy sector. Several new tools could be contemplated, including seed capital funds, venture capital, and corporate venture. Those tools may incorporate small businesses, including start-ups and scale-ups, in the process of open innovation in large companies that operate in the energy sector.

The rules of the mandatory application of RDI resources in the energy sector can play an important role in the promotion of technological cooperation. It is essential to seek new mechanisms for the enhancement of collaborative projects between energy companies and small innovative businesses. In addition, the purchasing power of state-owned enterprises can be an important tool to promote technology from start-up and scale-up companies in a sector with a strong presence of state-owned companies.

The same applies to the innovation support programmes using national budget resources. It is crucial to have sophisticated policies and tools that support innovation to induce technological cooperation between energy companies and start-ups or scale-ups, as has been done by CNI, SESI, SENAI, and Sebrae.

Some initiatives in this direction would include efforts to:

- encourage the development of local innovation ecosystems for the production of knowledge and technology for the energy sector by means of technological linkage between large companies and their suppliers, including corporate venture actions, and with the support of technological institutions;

- reform the mandatory clauses of RDI's investment in the oil, gas, and electricity sectors, promoting greater effectiveness of private investment;

- promote technological linkages between large companies and small business innovators, among them start-ups and scale-ups, and stimulate venture capital for these companies, using the mandatory investment in RDI by large energy companies;

- prepare and encourage the presentation of innovative small businesses, start-ups, and scale-ups to national and foreign investment funds;

- encourage partnerships between all sizes of domestic and foreign companies interested in expanding their markets. These partnerships can be promoted through national and foreign financing of projects and programmes for technological cooperation with leading countries in innovation in the energy sector; and

- encourage partnerships between Brazilian and foreign technological institutions in innovation research projects.

The six points highlighted above would allow the Brazilian energy value chain to become more innovative and the Brazilian industry to become more competitive worldwide.

Notes

1 EPE/MME, 2017a.

2 EPE/MME, 2017a.

3 Stricter environmental restrictions and lower social acceptance is hindering new hydropower projects.

4 CNI, 2017a.

5 'Bi-fuel' or 'dual fuel' vehicles refer to vehicles with engines that can run on two fuels, such as gas and alcohol.

6 ANFAVEA, 2016.

7 CNI 2017b; EPE, 2016.

8 The discoveries by Petrobras and other companies in the province of the pre-salt layer, located in the Brazilian continental shelf, can mean reserves of over 50 billion barrels of oil. There may be large oil and natural gas reserves up to 200 kilometres wide located under salt layers that extend for 800 kilometres along the Brazilian coast, from Santa Catarina to Espírito Santo.

9 EPE/MME, 2017b.

10 CGEE, 2017.

11 CGEE, 2017.

12 ANP, 2017; Asrilhant, 2017.

13 The funding for CT-Petro corresponds to about 12% of the total collected from royalties.

14 Rocha, 2015.

15 BNDES, 2017.

16 Furtado, 2015.

17 Some of the published studies on the subject include *O financiamento do investimento em infraestrutura no Brasil. Uma agenda para sua expansão sustentada* (CNI, 2016a); *Oportunidades para a privatização da infraestrutura. O que fazer, como fazer* (CNI, 2017c); and *Energia nuclear. Questões para o debate no Brasil* (CNI, 2016b).

18 MEI, 2018.

19 Borges et al., 2014.

20 Petrobras, 2017.

21 Hasner et al., 2016.

22 Scale-ups are start-ups that are experiencing rapid growth as a result of the development of a scalable business model. More information can be found at https://www.inovativabrasil.com.br or http://www.sebrae.com.br/sites/Startup.

23 Embrapii is a research company connected to the Ministry of Science, Technology, Innovation and Communication.

24 Morais, 2013.

25 Almeida et al., 2017; Pinto, 2017.

26 This potential is justified by: (1) the technological requirements for the development of pre-salt; (2) the scale of demand for technological solutions in the sector, which places the country as a major consumer of subsea goods and services; and (3) the presence in the country of the world's leading players in this industry.

27 Almeida et al., 2017.

28 CGEE, 2017.

References and related reading

Almeida, E., H. Pinto Jr., W. Vitto, L. Nunes, F. E. Costa, and R. Filgueiras. 2017. 'A Importância da Inovação para a Competitividade do Setor Petrolífero Brasileiro'. *Texto para Discussão IBP.* Dezembro, 2017. (In Portuguese.)

ANFAVEA (Associação Nacional de Fabricantes de Veículos Automotores). 2016. *Séries Temporais Autoveículos.* (In Portuguese.) Available at http://www.anfavea.com.br.

ANP (Agência Nacional do Petróleo). 2017. Boletim PD&I. Número 42, 2º Trimestre 2017. (In Portuguese.) Available at http://www.anp.gov.br/wwwanp/images/publicacoes/boletins-anp/boletim_petroleo_p-e-d/Boletim_PD-e-I_Ed42_2trimestre2017.pdf.

Asrilhant, B. 2017. 'Cláusula de P,D&I: Situação Atual e Perspectivas'. Powerpoint presentation at the seminar *'Ciclo de Debates de Petróleo e Economia',* IBP, 01 de Dezembro, Rio de Janeiro. (In Portuguese.)

BNDES (National Bank for Social and Economic Development). 2017. Programa Inova Petro. (In Portuguese.) Available at https://www.bndes.gov.br/wps/portal/site/home/financiamento/plano-inova-empresa/programa-inova-petro.

Borges, E. 2012. 'Estratégias para Inserir Pequenas Empresas no Atendimento de Demandas Tecnológicas de Grandes Empresas Participantes do Convênio Petrobras-Sebrae: Metodologia de Desenvolvimento Tecnológico e Inovação'. *Relatório de Pesquisa,* Convênio Petrobras-Sebrae. December. (In Portuguese.)

Borges, E., G. Melo, R. Paiva, and R. Martins. 2014. 'A Estratégia de Encadeamento Produtivo na Cadeia de Petróleo, Gás e Energia'. In *Pequenos Negócios Desafios e Perspectivas Encadeamento Produtivo,* ed. C. A. Santo. Brasil: Sebrae. (In Portuguese.)

CGEE (Centro de Gestão e Estudos Estratégicos). 2017. *Diagnóstico da CT&I no setor elétrico brasileiro.* (In Portuguese.) Available at https://energia.cgee.org.br.

CNI (Confederação Nacional da Indústria). 2016a. *O financiamento do investimento em infraestrutura no Brasil. Uma agenda para sua expansão sustentada.* Brasília: CNI. (In Portuguese.) Available at http://arquivos.portaldaindustria.com.br/app/conteudo_18/2016/07/18/11404/1807-EstudoFinanciamentodoInvestimentoemInfraestrutura.pdf.

———. 2016b. *Energia nuclear. Questões para o debate no Brasil.* Brasília: CNI. (In Portuguese.) Available at http://www.portaldaindustria.com.br/publicacoes/2016/12/energia-nuclear-questoes-para-o-debate-no-brasil/.

———. 2017a. *A Evolução do Setor Elétrico Brasileiro Rumo à Sustentabilidade.* Brasília: CNI. (In Portuguese.) Available at https://static-cms-si.s3.amazonaws.com/media/filer_public/09/de/09de36cb-4f51-4da3-82be-cb9f292269b0/fmase.pdf.

———. 2017b. *Implicações da COP21 Para o Setor Elétrico.* Brasília: CNI. (In Portuguese.) Available at https://static-cms-si.s3.amazonaws.com/media/filer_public/09/de/09de36cb-4f51-4da3-82be-cb9f292269b0/fmase.pdf.

———. 2017c. *Oportunidades para a privatização da infraestrutura. O que fazer, como fazer.* Brasília: CNI. (In Portuguese.) Available at https://static-cms-si.s3.amazonaws.com/media/filer_public/c9/44/c9447842-ee0f-4d16-aeb0-4a1944fd95a9/estudo_cni_-_privatizacao_da_infraestrutura.pdf.

EPE (Empresa de Pesquisa Energética). 2016. O Compromisso do Brasil no Combate às Mudanças Climáticas: Produção e Uso de Energia. Brasília: EPE. (In Portuguese.) Available at www.epe.gov.br.

EPE/MME (Empresa de Pesquisa Energética and Ministério de Minas e Energia). 2017a. *Balanço Energético Nacional – 2017.* Brasília: EPE. (In Portuguese.) Available at www.ben.epe.gov.br.

———. 2017b. *Plano Decenal de Energia 2026.* (In Portuguese.) Available at http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Decenal-de-Expansao-de-Energia-2026.

Furtado, A. 2015. *Políticas de Inovação no Setor Elétrico Brasileiro.* Vitoria: Edufes. (In Portuguese.)

Hasner, C. et al. 2016. 'Os Ativos de Propriedade Intelectual e Sua Relação com o Mercado: Estudo de Caso do Fórum Capixaba de Petróleo e Gás'. In *Rio Oil & Gas Expo and Conference 2016,* Rio de Janeiro, IBP1642_16: 1–9. (In Portuguese.) Available at http://www.prospective.com.br/attachments/article/28/Os%20Ativos%20De%20Propriedade%20Intelectual%20E%20Sua%20Rela%C3%A7%C3%A3o%20Com%20O%20Mercado.pdf.

MEI (Mobilização Empresarial Pela Inovação). 2018. 'Indústria 2027'. (In Portuguese.) Available at http://www.portaldaindustria.com.br/cni/canais/industria-2027/.

Morais, J. 2013. *Petróleo em águas profundas: uma história tecnológica da Petrobras na exploração e produção offshore*. (In Portuguese.) Brasilia: Instituto de Pesquisa Econômica Aplicada (IPEA).

Petrobras. 2017. 'Redes Temáticas e Núcleos Regionais'. (In Portuguese.) Available at http://sites.petrobras.com.br/minisite/comunidade_cienciatecnologia/portugues/redes_tematicas.asp.

Pinto, H. Q. Jr. 2017. 'Nota Técnica do Sistema Produtivo Petróleo e Gás Natural: Foco Setorial Exploração E Produção Em Águas Profundas'. Relatório de Pesquisa, *Projeto Indústria 2027: Riscos e Oportunidades para o Brasil diante de Inovações Disruptivas*. Rio de Janeiro and Campinas: IE-UFRJ and IE-UNICAMP. (In Portuguese.)

Rocha, C. 2015. *Recursos naturales como alternativa para la innovación tecnológica: Petróleo y gas en Brasil*. Santiago: Coordinación de Estudios para América Latina (CIEPLAN). Santiago.

CHAPTER 8

INDIA'S ENERGY STORY

A Quest for Sustainable Development with Strained Earth Resources

Anil Kakodkar, Former Chairman, Atomic Energy Commission, India

India is a rapidly growing economy with a large population aspiring to realize a quality of life comparable to the best in the world. India's energy consumption is thus expected to grow faster than anywhere else in the world. Creating universal energy access, promoting development, and facilitating economic growth are expected to be the key drivers of the growth in energy consumption. Useable energy forms (solid, liquid, gaseous, and electrical) at the consumer end are derived from several conventional as well as non-conventional primary energy sources. India's total primary energy supply basket of around 0.83 billion tonnes of oil equivalent (Btoe) in the year 2015–16 consisted of around 44.8% coal and lignite, 28.2% oil, 5.1% gas, 1.9% renewables (including hydro), and 0.4% nuclear.[1] A significant portion of domestic energy needs was met by using biomass such as firewood and dung cake in a traditional way. Around 42% of the country's total needs were met by imported energy, which was supplied by oil (56.7%), coal (39.1%), and gas (4%).

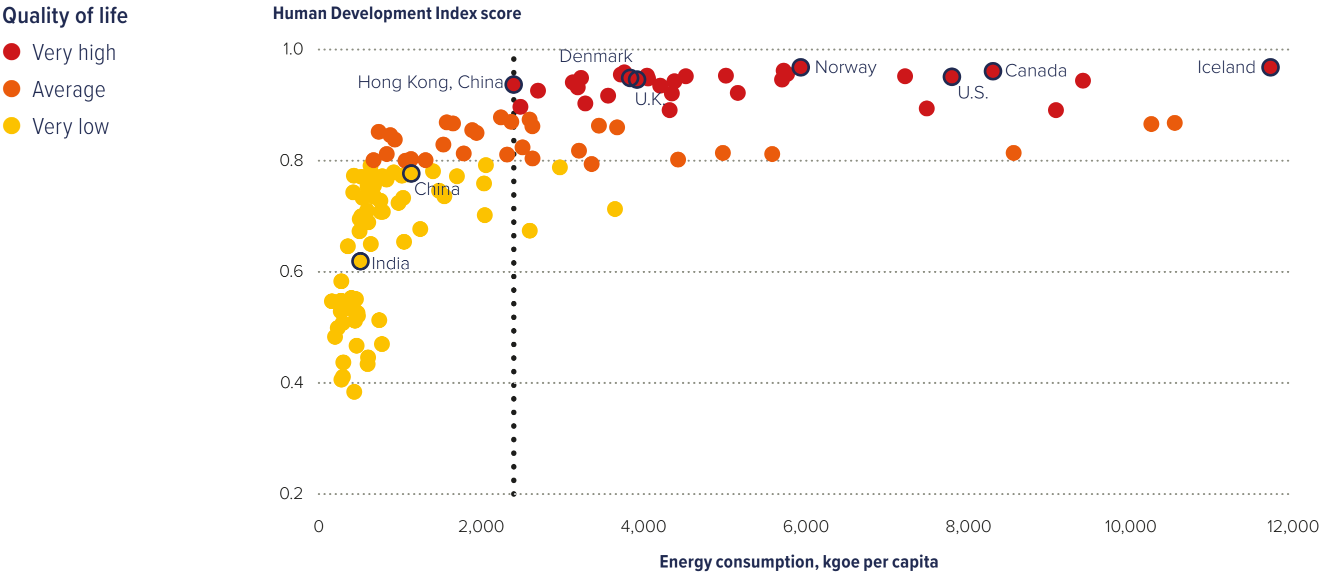
India's average annual per capita energy use stood at around 630 kilograms of oil equivalent (kgoe) in 2014. Going by the correlation between energy use and the Human Development Index (HDI)—which primarily reflects on a country's status with respect to health, education, and income—it is clear that India needs to boost its per capita energy consumption to at least around 2,400 kgoe per year in order to realize an HDI score comparable to the best in world (Figure 1). Such an increase would correspond to a total energy consumption of around 4 Btoe, or around 20–25% of current global energy consumption.

In 2016 India imported 80% of its crude oil and about 40% of its gas.[2] The country's increasing energy requirements, coupled with a slower than expected increase in domestic fuel production, has meant that India requires a rapidly growing volume of imports in its energy mix to meet demand. Clearly, in the business-as-usual mode, rising Indian demand would lead to attendant pressure on oil prices, compounding the rising cost of energy imports. In turn, this would constitute an additional and significant element to the energy security challenge. An exploration of domestic alternatives, beyond aggressive exploration for oil and gas, is urgently needed to meet India's energy needs. New technology and innovation will be essential for India to successfully address this serious challenge alongside the challenge of climate change.

As India moves forward in its development and prepares for higher energy consumption, coal and oil are expected

Figure 1.

Correlation between the Human Development Index score and energy consumption



Source: Data are from the Watt, available at http://www.thewatt.com/.

Notes: The dotted vertical line, at 2,400 kgoe per capita, represents the threshold value for per capita energy consumption beyond which a country reaches the highest quality of life, represented by HDI scores. For India, this corresponds to a total of approximately 4 Btoe. The Human Development Index score ranges from 0 to 1, with 1 being the highest possible score. It combines health, education, and income to measure quality of life. Btoe = billion tonnes of oil equivalent; kgoe = kilograms of oil equivalent.

to continue to dominate the country's energy supply. Sizeable assets in end-use devices and equipment will continue to run on oil. Electricity and gas are expected to increase their share in energy consumption. Electricity is a very convenient energy carrier, which is compatible with most modern equipment. The outlook for gas seems better than oil. The three drivers mentioned earlier—universal energy access, development, and economic growth—also favour the greater use of gas. The share of electricity in India's overall energy consumption is expected to rise in the residential housing/buildings, transport, industry, and commercial sectors. Rapid electrification of the transport sector can be expected to alleviate a significant part of the demand for oil, which is not being met by domestic oil. India's electricity generation, at present, is primarily from coal, which also constitutes the largest component of the country's primary energy supply. Indian coal has a high ash content. To realize its efficient use and minimize its environmental impact, India-specific technological solutions (not normally available from other countries) are needed. India is among the top five greenhouse gas emitters globally.[3] Efforts towards cleaner coal technology have been launched in the form of ultra-super critical technology.[4]. Coal gasification, in unmined coal as well as in plants, could be a game changer in the Indian context. Moreover, coal bed methane and gas hydrates could provide additional gas sources with a high potential for making India energy independent.

A significant share of India's current energy consumption (around 20–25%) is met by biomass,[5] which is used primarily for cooking in rural areas. Apart from poor efficiency in its use, this leads to serious health burdens and environmental issues. To address these difficulties, large-scale deployment of efficient biomass-based smokeless cookstoves as well as affordable cooking gas distribution networks in rural areas are needed.

The Government of India has been aggressively pushing the development of renewable energy to produce electricity from non-fossil fuel energy sources. The country is expected to realize its target of 175 gigawatts electric (GWe) installed capacity, which will consist of solar photovoltaic (100 GWe), wind (60 GWe), bioenergy (10 GWe), and small hydro (5 GWe) sources by 2022. The government has also been strongly supporting the development of nuclear energy, as can be seen from its recent sanction of 10–700 megawatts electric (MWe) nuclear plants of indigenous design to be constructed in fleet mode with an assured annual equity support for the purpose. In addition, around 20 nuclear plants are expected to be set up through international co-operation.

Although these efforts would facilitate the growth of non-fossil energy–based electricity generation in the country, on the hydrocarbon front, the Indian economy will face significant challenges in catering to the country's energy needs in the coming decades. It will therefore be important to explore alternative modes of producing hydrocarbon energy within the country, including solar and nuclear energy sources. Clearly this would require major initiatives in developing and adopting relevant new technologies and their innovative deployment.

India's journey thus far

The energy sector has grown by leaps and bounds, largely driven by short-term demand–supply gaps experienced by different stakeholders at different times. Energy consumption has risen from ~50 million tonnes of oil equivalent (Mtoe) per year in 1965 to present levels of ~800 Mtoe, around a 16-fold increase. Even so, 780 million Indians still lack access to clean cooking facilities and rely on biomass for cooking.[6] Although nearly 100% of households in urban areas and around 80% of households in rural areas have been electrified, as of February 2018 around 35 million households did not have electricity.[7] As of 2015, the number of registered motor vehicles was around 21 crores and over 167 million out of 234 million households had a television set. Out of around 160 million hectares of cultivated land in India, only around 39 million are irrigated by ground water and around 22 million are irrigated by canals. About two-thirds of cultivation in India still depends on monsoon rains. Recent emphasis on standalone solar energy–powered pumps could thus make a big difference to agricultural output, along with the optimum use of water and greater efficiency of grid management.

Several innovations have taken shape to address challenges that arose in the context of efficiency of energy use. It has been difficult to balance demands from energy consumers from diverse sectors such as industry, agriculture, domestic, commercial, and transport in an environment of shortages. The need to support weaker segments of society has also presented a major challenge. This has often resulted in cross subsidies—when industrial production and commercial operations have to pay for electricity for weaker sections of the economy, making commercial operations less efficient and undermining the financial health of electricity companies. There have also been issues related to energy waste by consumers getting free or highly subsidized energy. Separation of consumers paying commercial rates and those getting highly subsidized electricity through using different feeders, subsidized standalone solar-powered pumps for agriculture, incentives for the rapid deployment of renewable energy, and so on have been some of the innovations to usual practice that have made significant impact.

On the technology development front, progress has been made towards the development of ultra-super critical technology in coal-based power generation to enhance efficiency that could lead to significant reduction of carbon emissions. Furthermore, India's strides in taking the refinery sector to a globally competitive level have also been noteworthy. Recently deployed indigenous INDMAX technology at the Indian Oil Corporation's Paradip refinery that leads to a significantly larger LPG output is significant in the context of the relatively larger demand for gas that is expected in the years to come. A 500 MWe Prototype Fast Breeder Reactor (PFBR), a commercial prototype of Fast Breeder Reactor–based power plants that would constitute the second stage of India's nuclear power program, is currently being commissioned.[8]

The Solar Urja Lamps (SoUL) Project of the Indian Institute of Technology, Bombay has been a very successful innovation wherein millions of study lamps for school children are being assembled in rural areas, fulfilling a previously unmet need and creating a new source of income in these areas.[9] This open source technology model is an excellent example of creating momentum in terms of jobs and value addition in rural areas in the new digital society. In fact, a unique initiative implemented in Dungarpur block of Rajasthan through forming of partnership with cluster level federations of self-help groups has gone beyond solar study lamp intervention to include other solar products, such as photovoltaic modules and other lighting solutions.

The development of solar direct current micro grid technology by the Indian Institute of Technology, Madras for both off-grid and on-grid homes,[10] which could lead to better economy as well as efficiency and create a pull for solar power deployment, was recognized for the 2017 Technology in the Service of Society Award by the *IEEE Spectrum*.

Recently introduced direct benefit transfer schemes have helped efficient targeting of subsidies.[11] The country has also done well in terms of more efficient energy use. Driving the prices of light-emitting diode (LED) lights down through policy action as well as mass procurement has resulted in large savings of electricity. Over 28 crore LED bulbs have been distributed under the Ujala scheme, leading to savings of electricity worth around Rs. 14,000 crores. The LED lighting market in India is projected to register a compound annual growth rate of over 30% during 2016–21.[12]

The Bureau of Energy Efficiency has put in place several measures such as prescribing a reduction in specific energy consumption norms for energy-intensive industries, star labelling of 21 appliances, promoting energy efficient LED lamps, and so on that have led to energy savings of about 83 billion kilowatt-hours in the year 2015-16.[13] Thanks to concerted efforts in realizing greater energy efficiency, today several production activities—such as petroleum refining, aluminium and cement manufacturing, and so on—are globally competitive. Vigorous efforts are underway to reduce the emissions intensity of GDP by 33% to 35% from 2005 levels and to achieve about 40% cumulative electric power installed capacity from non-fossil fuel–based energy resources by 2030 as a part of India's Intended Nationally Determined Contribution (INDC) communicated to the United Nations Framework Convention on Climate Change. India's INDC is premised on the help from the transfer of technology and low cost international finance including from the Green Climate Fund.

Momentum on actions taken towards sustainability and climate change issues has opened up a number of opportunities for innovation.

Momentum on actions taken towards sustainability and climate change issues has opened up a number of opportunities for innovation. These include innovations in policy, business, and technology for processes, products, and society engagement. Although it is very heartening to see this momentum, India's innovation ecosystems need to improve significantly, which presents both a governance challenge and a cultural challenge. Specifically, in the context of promoting domestic technology development efforts, it is necessary to pay a lot of attention to smoothing hurdles faced during the transition from laboratory research to marketable products. The resources required for such a transition are at times much larger than the resource expenditure on development in the laboratory per se. Clarity about the relative performance assessment of a diverse set of people who all work together in driving such a transition also needs to evolve. The possibility of a disruptive innovation is higher in a group composed of people with very diverse backgrounds and capabilities working together than in a relatively homogenous group, which might tend to move innovation forward in smaller, incremental steps.

Driving the future with innovation

Although the energy scene will continue to be driven by rising demand and the technologies already available in the market as well as those emerging, it is important to recognize some key opportunities for innovation in the Indian context. The most significant areas of opportunity are described below.

Dependence on imports: As discussed earlier, India's immediate challenge is its growing and already-heavy dependence on imports for its hydrocarbon needs. This dependence has led to intensified activity in terms of exploration, and it is hoped that this will produce positive results quickly. In this context, it may also be prudent to use coal to produce fuel gas and liquid fuel. Some activity has begun to extract coalbed methane.[14] Technologies for in-situ coal gasification as well as on surface conversion of coal to gas or liquid fuels should be developed. A significant India-specific emphasis on R&D in this area is necessary because the country's coal has such a high ash content.

Potential of gas hydrates: Gas hydrates represent a huge energy potential for India and can free the country from energy dependence on external sources. While there has been significant progress in resource mapping, developing the technology needed for stable extraction has been a challenge. Presumably some of the initiatives for field experiments currently being implemented will open up this field to rapid growth in the near future.

Increasing share of gas: Along with electricity, the share of gas in overall energy use in India is expected to increase in the coming years. The development of a gas grid to cater to large industrial consumers as well as city domestic consumers, along with a gas distribution network to cater to the needs of rural consumers, could make a major difference to indoor and outdoor air quality and the demand/supply mismatch. Apart from the increasing role that gas is likely to play in the global energy supply, there are good signs of increase in domestic gas production as well.[15]

Significance of biomass: The potential of biomass as an energy source has significantly gone up as a result of new technologies that can convert a much wider variety of biomass into commercial biofuel. Biomass thus represents a significant energy source that may be large enough to meet current needs. Although agricultural residue and municipal solid waste represent significant energy value, they continue to inflict heavy costs on society by way of serious air and water pollution and an attendant health management burden. Technologies that allow the liquidation of practically any kind of biomass in an environmentally friendly manner and create value are evolving quickly. A decentralized collection and processing network for agricultural residue from fields and for municipal solid waste from residential areas could be a game changer both in terms of reducing the environmental burden and in creating value through energy, manure, and even char. Significant new ways to generate income would be an added advantage. Recent occurrences of large-scale smoke plumes from fires at garbage landfills and from agricultural residue burning by farmers, both causing serious degradation of air quality, should trigger quick actions in this regard. While selecting technology for bio-mass-to-energy conversion plants, it is crucial to keep in mind the need to enrich soil quality by applying manure or char.

Significance of solar energy: Solar energy, as the major primary energy source for India's energy future, needs to be seen as an energy source not only for electricity production but also for the production of non-fossil fuels, including hydrocarbons. Concentrated solar power (CSP; also called 'solar thermal power') capable of producing high temperatures should receive greater attention than it has thus far. India's prevailing commercial dynamics has led to solar thermal power being more expensive than photovoltaic power. The fact is, however, that almost 100% value addition within the country is possible with solar thermal; this is not the case with photovoltaic power generation. Furthermore, with large CSP plants one could get higher efficiency and also energy storage would be much cheaper. Given the needed addition of a large solar energy capacity programme, it makes sense to leverage the large demand to depress costs associated with large domestic CSP plants.

Built-in low-cost energy storage would also prevent additional grid and system costs that would be incurred when the proportion of variable generation sources in the grid increases. This would also pave the way for the use of solar energy for pyro-chemical/pyro-metallurgical applications such as thermochemical splitting of water.[16] Efforts to build megawatt scale solar thermal power demonstration plant (which would allow credible scale up to commercial capacity) with a receiver on the ground (by the Bhabha Atomic Research Centre/Oil and Natural Gas Corporation) as well as a solar thermal plant that can run on a continuous basis despite the variable nature of solar energy (by the Indian Institute of Technology Bombay/National Thermal Power Corporation) are noteworthy in this context. With the development of advanced thermodynamic cycles and the associated advanced power-conversion equipment, the performance of CSP technology could become even better.

On the photovoltaic front, innovative business models for the commercially competitive domestic manufacture of solar products, including silicon and other materials, must be devised.

Decentralized nature of solar energy: Solar energy by its very nature is decentralized and thus well suited for decentralized use. Since solar electricity production generates direct current (dc), and dc end-use devices enable higher efficiency particularly at part loads, it makes sense to directly connect decentralized solar photovoltaic production to direct current end-use devices. There is thus a case for scaling up the IIT/M innovation mentioned earlier. Local low-voltage direct current micro distribution networks would lead to savings both in capital cost as well as in energy consumption. Such networks could be linked to the alternating current grid network at discrete locations optimized to minimize power transmission losses. This would amount to a major reshaping of electricity distribution networks and would produce significant dividends. Some initiatives that are currently underway by the Indian Institute of Technology, Madras and Indian Institute of Technology, Bombay in this context need to be taken forward to reshape the electricity markets.[17]

Built-in low-cost energy storage would also prevent additional grid and system costs that would be incurred when the proportion of variable generation sources in the grid increases.

Potential of nuclear energy: Nuclear energy is the only non-fossil energy source of large magnitude that does support base-load generation without the need for large energy storage. This makes nuclear energy an inevitable energy option for India. Nuclear power plants have large exclusion zones and mandatory green belts to mitigate the risks of a severe nuclear accident. There is thus a good scope for synergy between nuclear, solar, and biomass at nuclear power plants. These three non-fossil primary energy sources together can supply electricity as well as non-fossil hydrocarbon/hydrogen. At coastal sites, nuclear power plants can also be a good source of fresh water. Between high-temperature reactors and solar thermal power plants, some technologies—such as molten salt systems—are common. The systems need to be configured in a manner that virtually eliminates any large-scale impact in the public domain, as the Advanced Heavy Water Reactor has done.[18] There is also a need to better address public sensitivity, particularly through engagement that more directly benefits the local population.

Given the strong technological capability that the country has acquired in all aspects of nuclear power technology, including in the manufacturing of nuclear power plant equipment, it makes sense for India to explore the export potential of nuclear power. With Indian capability in the use of thorium, its vast thorium resources, and the inherent advantages that thorium offers in terms of proliferation resistance as well as safety, India can make a significant contribution to the global energy supply that is free from CO_2 emissions and is safe and nuclear proliferation resistant.

Electric batteries: The development of electric batteries has become crucial for both stationary as well as mobile applications. In the context of additional demands arising out of large-scale renewable energy applications and electric mobility, this perhaps is the most important area for research and innovation. A number of battery variants are possible, each with its relative strengths and weaknesses. Cost, battery life, abundance of the materials involved, energy density, and charge/discharge performance are the key parameters on which various developers are actively working. Along with battery development, the development of fuel cells and steam electrolyzers also needs attention. A paradigm change through decentralized energy production and use may be expected in the near future, once these systems make a significant market entry.

Challenges to transport as a consumer of energy: The transport sector is one of the largest consumers of fuel oil. Electric mobility, which is fast gaining importance in view of its emission-free nature at the user end and its increased operational convenience, could lead to a significant displacement of oil from the energy consumption basket. The country is thus rightly emphasizing the deployment of electric mobility. There are, however, several challenges that must be met. Competitively priced high-energy density batteries that would permit long enough endurance and include a convenient user-friendly recharging infrastructure are the two main challenges. In the interim, hybrids that can lead to considerable fuel efficiency could play an important role.

Cost advantages of integrated renewable energy systems: Building integrated renewable energy systems could lead to significant cost advantages. Energy system elements such as solar panels, electric battery walls, cold storage rooms, hot water systems, water recycle systems, and so on could be configured as building elements. This transition is already becoming visible.

The above is only an illustrative list of several domains where technological innovations could make a large impact in the Indian context. As mentioned earlier, we however need to significantly improve our innovation eco-system that nurtures the working together of diverse groups with complementary capabilities and liberally supports translational efforts over a full spectrum of activities, ranging from laboratory research to entry into market place. There is also a need to pay attention to raw materials, manufacturing technology, and processes as well as the policy issues involved to derive full advantage of domestic innovation efforts.

Closing remarks

Energy is central to human development, and a transition to the use of sustainable, non-fossil energy sources is central to the sustainability of Earth's environment. Embedded within this overall dynamic is the issue of energy sustainability for individual countries. Thus, although generic issues can be addressed through generic solutions, some country-specific issues need country-specific solutions. Clearly, while each country must benefit from developments elsewhere, it must ensure that its specific issues are not ignored and must establish specific solutions through its own priority research and innovation.

In the long term, it is clear that solar and nuclear are the only two sustainable energy sources that can meet India's energy needs. Thus, while working through the ongoing national programmes to address India's growing energy demand, and with due regard to the considerations of the effects on climate change, we should remain focussed on the long-term target of building the country's energy infrastructure based on solar and nuclear as its primary energy sources. This would be consistent with the strategy of ensuring energy sustainability while also meeting the climate change challenge.

Notes

1 Data are from the Central Statistics Office, Ministry of Statistics and Programme Implementation, Government of India, Energy Statistics 2017, available at www.mospi.gov.in.

2 See the Ministry of Petroleum and Natural Gas, Govt. of India, Indian Petroleum and Natural Gas Statistics 2015–16.

3 Janssens-Maenhout et al., 2017.

4 'Super critical technology' refers to technology that uses steam at a temperature of 600–610°C and above.

5 See Technology Information, Forecasting and Assessment Council (TIFAC), TV 2035 – 2015, draft sectoral report on energy.

6 IEA, 2017.

7 Government of India. Saubhagya Dashboard, Garv App 2018. New Delhi. Available at http://saubhagya.gov.in/dashboard/main.

8 500 MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, Tamilnadu, India.

9 Chetan Singh Solanki, IIT Bombay, personal internal Communication 31st January 2018.

10 Jhunjhunwal et al., 2016.

11 Information about the Government of India's Direct Benefit Transfer programme is available at https://dbtbharat.gov.in/.

12 TechSci Research Press Release.

13 Reply to unstarred question no.1839 in Rajya Sabha on 14 March 2016.

14 Abdi, 2017.

15 Abdi, 2018.

16 ABB, 2016.

17 Ali T-Raissi, No date.

18 Information about the Advanced Heavy Water Reactor (AHWR) from the Government of India's Department of Atomic Energy, Bhabha Atomic Research, is available at http://www.barc.gov.in/reactor/ahwr.html.

References

ABB. 2016. 'ABB Partners with Indian Institute of Technology Madras for R&D'. Press Release, 5 April 2016. Available at www.abb.co.in/cawp/seitp202/96794a876f03f14d65257f8c001a4995.aspx.

Abdi, B. 2017. 'India's Coal Bed Methane Productino Jumped More Than 44 Percent to 565 MMSCM Las Fiscal'. *ETEnergyworld,* 25 April 2017. Available at https://energy.economictimes.indiatimes.com/news/oil-and-gas/indias-coal-bed-methane-production-jumped-more-than-44-percent-to-565-mmscm-last-fiscal/58362964.

——. 2018. 'First Growth in India's Natural Gas Production in Sic Years'. *ETEnergyworld,* 25 April 2018. Available at https://energy.economictimes.indiatimes.com/news/oil-and-gas/first-growth-in-indias-natutal-gas-production-in-six-years/63904860.

Ali T-Raissi, No Date. 'Analysis of Solar Thermochemical Water-Splitting Cycles for Hydrogen Production, Hydrogen, Fuel Cells, and Infrastructure Technologies' Available at https://www.eere.energy.gov/hydrogenandfuelcells/ pdfs/iie2_raissi.pdf.

IEA (International Energy Agency). 2017. *Energy Access Outlook 2017: From Poverty to Prosperity.* Government of India, 2018b.

Janssens-Maenhout, G., M. Crippa, D. Guizzardi, M. Muntean, E. Schaaf, J. G. J. Olivier, J. A. H. W. Peters, and K. M. Schure. 2017. *Fossil CO_2 & GHG Emissions of All World Countries.* A JRC Science for Policy Report. Luxembourg: Publications Office of the European Union.

Jhunjhunwal, A., A. Lolla, and P. Kaur. 2016. 'Solar-dc Mkicrogrid for Indian Homes'. *IEEE Electrification Magazine,* June. Available at https://pdfs.semanticscholar.org/4634/c3c3485e3c7853647b7522664734637cbf81.pdf.

TechSci Research. 'LED Lighting Market in India to Grow at 30% until 2021'. Press Release. Available at https://www.techsciresearch.com/news/1177-led-lighting-market-in-india-to-grow-at-30-until-2021.html.

CHAPTER 9

GRASSROOTS INNOVATIONS IMPROVE WOODFUEL IN SUB-SAHARAN AFRICA

Mary Njenga, World Agroforestry Centre (ICRAF) and the Wangari Maathai Institute for Peace and Environmental Studies
Miyuki Iiyama, World Agroforestry Centre (ICRAF) and the Japan International Research Center for Agricultural Sciences (JIRCAS)
James K. Gitau, World Agroforestry Centre (ICRAF) and the Wangari Maathai Institute for Peace and Environmental Studies
Ruth Mendum, Office of International Programs, College of Agricultural Sciences, Pennsylvania State University

Woodfuel (charcoal and firewood) is the most common form of biomass energy used for cooking and heating in Sub-Saharan Africa and is preferred for its affordability, accessibility, and convenience. More than 90% of the population in the region relies on either firewood or charcoal.[1] Charcoal is used mostly in urban centres and firewood in rural areas. Households that lack woodfuel access, for instance, are forced to abandon food stuffs that are nutritious but cooking-energy-intensive and switch to others that are less nutritious but cook more quickly.[2] Others reduce the number of meals or amount of food consumed per day, and a large proportion of income is spent on cooking energy at the expense of purchasing food.[3] At the Kalobeyei Refugee Camp located in northwestern Kenya, an arid land characterized by water scarcity, women desperate to put food on the table for their families exchange maize sufficient to feed the family for five days with firewood that could cook three days' worth of meals.[4]

International debates—including discussions around the Sustainable Development Goals—have pointed to the need to move to 'clean and renewable energies'. In regions such as Sub-Saharan Africa, where woodfuel is the main source of cooking and heating energy, this creates a complex and contradictory landscape for both local authorities and donors. The recommendation to move away from woodfuel is mainly the result of negative implications for the environment and human health that are associated with unsustainable production and inefficient utilization. Instead of hoping that woodfuel will be abandoned, it is more practical for governments and donors to invest in making it sustainable.[5] Solutions exist that have the potential to make woodfuel systems sustainable through interventions at all stages of the value chain, including sustainable wood production, efficient wood-to-charcoal conversion technologies (kilns), and efficient utilization.[6]

The negative impacts of woodfuel systems are associated with unsustainable and inefficient production and consumption. For example, cutting down trees without replanting others results in deforestation and land degradation. The carbonization of wood into charcoal using

The authors extend their gratitude for the financial support offered by ICRAF through the Centre's Programs Development Unit (PDU), the CGIAR research programme on Water Land and Ecosystems, the Swedish Research Council, and the Government of Japan. They also are grateful for the travel support provided to Dr Mendum by the Office of International Programs, College of Agricultural Sciences, Pennsylvania State University. The review of the initial manuscript by Dr Wenda Bauchspies of the Department of Community Sustainability, Michigan State University, is highly appreciated.

inefficient kilns results in air pollution, wood wastage, and land degradation. In this way, unsustainable woodfuel use contributes to climate change. Firewood too has implications for the environment. For instance, collecting deadwood from natural forests interferes with soil nutrient recycling and removes seedbed material, consequently affecting seedling regeneration.[7]

Collecting firewood from the forest is life-threatening, hard work for women and children and limits their ability to take part in productive activities and schooling, respectively. Burning biomass fuel, especially in poorly ventilated kitchens using inefficient cook stoves, has been linked to health problems from illnesses associated with smoke in the kitchen. Globally, over 4 million deaths occur annually from illnesses related to the smoke generated by indoor combustion, which mainly affects women and children.[8]

Decades of attempts by non-governmental organizations and governments to shift usage from open fire to more efficient or less smoky stoves, or away from biomass to other fuels such as liquefied petroleum gas (LPG) or solar photovoltaic systems, have been less than successful, especially because the technologies fail to respond to users' social-cultural practices and needs.[9] Small-scale studies across the global south indicate that the choice of fuel and stove type are complicated decisions that cooks and households make in the context of constraints that include an underestimation of the value of traditional stoves and a mismatch between users' goals and those of stove innovators, among other complex factors.[10]

Instead of documenting why woodfuel innovations have failed, this chapter presents examples of how grassroots communities are applying simple innovations to improve their production and use of woodfuel in ways that address their practical needs.

Instead of documenting why woodfuel innovations have failed, this chapter presents examples of how grassroots communities are applying simple innovations to improve their production and use of woodfuel in ways that address their practical needs. These innovations include (1) sourcing firewood from trees on farms, (2) processing organic residues into fuel briquettes, and (3) using biochar-producing cooking systems. The first and second innovations address energy production issues, and the third addresses energy consumption issues of the local energy value chain described in this Global Innovations Index (GII) 2018 report. For impact and replicability, research and development (R&D) analysts need to apply processes that involve all stakeholders, such as the transdisciplinary methods of generating knowledge and implementation of the understanding gained in the R&D processes.

The chapter shows how transdisciplinary methods work and describes examples of grassroots innovations using biomass energy. In many of the affected communities, women are responsible for sourcing fuel that is used to cook food and, in some instances, to provide heat. The majority of those involved in the grassroots innovations in woodfuel are women in rural areas, low-income urban neighbourhoods, or refugee camps in search of affordable cooking fuel that also meets their needs. Briquettes are produced mainly in low-income urban neighbourhoods and some rural areas where biomass is available. In addition to women, youth—both girls and boys—are also involved and the briquette activities are focused on generating income.

Transdisciplinary R&D

Transdisciplinary research methods are relatively new and still developing as an approach. For the purposes of understanding grassroots needs and innovations in sourcing cooking fuel as well as innovations in kitchens using biomass fuel in Sub-Saharan Africa, a team consisting of biophysical scientists, social scientists, gender specialists, engineers, economists, science facilitation and communications experts, and grassroots researchers has been built. The grassroots researchers are perhaps the most important participants because they help the entire team understand what kinds of changes in social practice are attractive and useful to local communities.

What is at stake is more than just the cooking preferences of local communities. Rather, grassroots researchers are considering the question: What does our community need to adopt from the larger research world and what role can women play in ushering in a new era in energy use? Transdisciplinary research teams differ from interdisciplinary teams and participatory action research teams in several ways: the grassroots researchers are not just research subjects—they should also be considered as part of the team since they share their insights about how their community might choose to change their approaches to energy use. Most importantly, the team using transdisciplinary methods to investigate grassroots biomass innovations integrates several attributes specific to the cultural context of both the researchers and the problem at hand.[11] Furthermore, the team applies natural science methods, such as the quality characterization of cooking fuels in laboratories, and measures emissions through participatory cooking tests performed by women as cooks. In summary, the team works along the innovation process cycle, which includes understanding the context, identifying and developing interventions and technologies, engaging in their implementation, assessing impacts, and communicating lessons.

Enhancing the impact of grassroots innovations in woodfuel through R&D

Understanding community members' needs, aspirations, fears, and solutions to the challenges they face as well as the potential for innovation is critical to achieving sustainable development. The transdisciplinary team's approach targets working with communities on scalable, tailor-made local innovations. It is important, however, to link local innovations to external science and technology because neither grassroots innovations nor science and technology alone can effectively address social, economic, and environmental challenges. Work on biomass energy addresses some of the bottlenecks faced by local communities, including resource scarcity that inhibits the scalability and diffusion of local innovations. These bottlenecks, identified by research on grassroots innovations,[12] can reduce otherwise effective interventions. Furthermore, innovation and community involvement are integrated to encourage participation and technology uptake as well as to tap community creativity, a need identified by the same authors. Research is also carried out in order to generate facts and enhance understanding of the role of local innovations in developing solutions, making a case for their inclusion in development and research agendas.

The grassroots innovations on making woodfuel sustainable include several elements, discussed below.

Sourcing firewood from trees on farms

Multipurpose trees on farms, such as those grown for timber or fruit, need to be pruned as part of the farm management practice that encourages rapid biomass and trunk growth.[13] Farmers practicing agriculture with trees, commonly referred to as 'agroforestry', know that. In the Kibugu village in Embu County, Kenya, the *Grevillea robusta* tree is grown primarily on farm boundaries for timber and is pruned biennially (every two years) during the dry season, mainly in the month of January. Pruning is carried out by young boys in families or by hired youths. The firewood is then carried to the homestead by girls or women, where it is first spread under the sun and then stored under shade for about three months to dry. In this way the firewood dries well and burns more efficiently and with less smoke. Before use, the firewood is removed from the shade and put in a rafter/drying rack in the kitchen close to the roof for further drying. About 40% of the households in this village depend exclusively on firewood from trees on the farm; about 16 trees provide firewood that lasts a household for roughly five months when used in an open fire.[14] Sourcing firewood from trees on the farm reduces women's workload in collecting firewood from forests. Some farmers produce more firewood than they need and sell the surplus for income.

In Malawi, firewood from *Albizzia lebbeck* (18 kilojoules per gram, or kJ/g) and *Senna spectabilis* (18 kJ/g), the two agroforestry tree species being promoted there, have a calorific value slightly higher than the locally sourced firewood (17 kJ/g).[15] The calorific value of firewood sourced from multipurpose trees being promoted in Malawi show that quality firewood can also be sourced from farms in the form of prunings resulting from management of the trees. The innovation here is that the different tree species being grown on farms in different parts of the region can produce quality firewood. Their fuel properties need to be identified and this information disseminated to farmers, who are then able to make informed decisions. The other link with R&D includes the integration of this sustainable source of firewood with efficient cooking systems for optimal benefits. Sourcing firewood from trees on farms depends on the level of adoption of agroforestry as influenced by size of land and crops being grown.

Resource recovery and reuse for energy through briquetting technology

Briquetting technology involves compacting or compressing dry biomass into a solid unit using manual or electric machines or moulding it using bare hands. The resulting briquettes are used like firewood or charcoal.[16] Community groups gather organic residues such as charcoal dust, sawdust, maize cobs, coconut husks, rice husks, or sugarcane bagasse, which they grind and compact. Sometimes, Using the charcoal dust–and-soil briquettes to cook a traditional meal of green maize mixed with dry beans for a Kenyan standard household of five people costs 88% and 93% less than cooking the same meal with charcoal and kerosene, respectively.

when primary materials lack binding capacity, an additional binder is necessary. Commonly used binders include soil, biodegradable paper, molasses, and starch such as that made from cassava or maize.

The briquettes are made either from carbonized materials (that are burned under conditions with a low supply of oxygen into a high carbon content substance carried out mainly using kilns—a process referred to as 'carbonization') or non-carbonized materials. Carbonized briquettes are preferred for cooking because their black colour resembles the colour of charcoal. They also produce less smoke and burn for longer periods than non-carbonized briquettes. Non-carbonized types produce fine particulate matter (PM2.5), burn for shorter periods than carbonized ones, and are popular for industrial use. PM2.5 is one of the key elements of concern about health from burning biomass energy.[17] In Kibera, an informal settlement (slum) in Nairobi, a briquette made from charcoal dust (80%) and bound with soil (20%) produces three times and nine times fewer emissions of carbon monoxide and PM2.5 and burns for one and a half times longer than conventional wood charcoal.[18] This briquette produces PM2.5 of 0.03 milligrams per cubic metre (mg/m3) compared to 123.3 mg/m3 from burning a briquette made from non-carbonized sawdust (74%) bound with gum arabica (26%).[19]

Communities save about 30% and 70% of income spent on cooking energy if they purchase the briquettes or produce them for home use, respectively. The technology creates job opportunities, especially for youth and women. For example, a study carried out in Nairobi and its environs among eight community-based groups showed that 68 female and 101 male members, 78% of whom (45 female and 89 male) were youth below 35 years of age, were involved.[20] Each group earned a monthly income between US$7 and US$1,771 during the dry seasons and between US$7 and US$2,240 during the wet seasons. The range of the income earned is huge because the amount of sales is influenced by the level of awareness about the benefits of briquette within the neighbouring community as well as accessibility to the production site, which are also points of sale.

In northwestern Kenya, after a training conducted in November 2017, a briquetting innovation is being applied by women at the Kalobeyei Refugee Camp and host communities using charcoal dust made from the invasive *Prosopis juliflora* tree and other available organic wastes.[21] In Accra, Ghana, briquette technology is being scaled up by linking research on quality characterization, mapping sources of raw materials, and identifying market opportunities to development initiatives. This involves working with the private sector and with women's groups that use firewood in smoking fish.[22] Using the charcoal dust–and-soil briquettes to cook a traditional meal of green maize mixed with dry beans for a Kenyan standard household of five people costs 88% and 93% less than cooking the same meal with charcoal and kerosene, respectively.[23] Briquette processing practices and types produced vary from one locality to another depending on the raw materials available, the capital available to purchase machines, and local preference. The adoption of these community-based processing practices is high in low-income areas where communities face the challenges of accessing affordable cooking and heating energy and low employment opportunities.

The briquettes have climate change mitigation benefits because they reduce demand for trees that would otherwise be cut down for charcoal or firewood; they also consume organic waste, which otherwise poses disposal challenges in cities. Briquettes—especially those made from carbonized biomass—burn cleaner than firewood in terms of the fine particulate matter, which is a critical cause of respiratory illnesses associated with smoke in the kitchen.[24] Areas that can be improved—such as carbonizing raw materials before making briquettes, applying appropriate mixing ratios of raw materials and binding agent, and drying raw materials and the resultant product, among others—have been identified. Capacity building support materials have been developed and trainings carried out in response to local context. Briquettes serve as a complementary fuel to charcoal and firewood, hence reducing demand for the latter two fuel types, with potential for reducing the negative impacts of unsustainable woodfuel. Completely replacing charcoal and firewood with briquettes is unlikely because the availability of raw materials may not be adequate to produce enough fuel to meet the demands of cooking and heating that charcoal and firewood currently meet.

Improved biomass cooking systems

Cooking culture is an important factor in the debate on how best to address sustainable development, including ways to mitigate the effects of climate change. For instance, the chemical and physical properties of fuel, the ventilation needed, the stove type, and how the process is managed all have implications for the amount of fuel used, the burning period of the fuel, and the amount of ash and emissions produced. These effects of the cooking processes have implications for daily life such as health, income, and nutrition, among others. The transdisciplinary R&D team is investigating how to improve cooking systems by working with communities to understand why they resist change and why they prefer to maintain their traditional practices, such as using open fire in cooking and heating. The team is also identifying the improvement the communities aspire to make in their cooking systems. This effort has involved working with cooks in families, mainly women, in participatory cooking tests that compare different fuels and stoves. Men and other members of the households are involved in trainings.

Studies in the participatory cooking processes have shown that the three-stone open fire is better than most improved stoves because it is easy to light and the firewood does not need to be chopped into small pieces. It heats the living space better than most improved stoves, allowing families to socialize, especially in the evenings. It is also preferred for cooking foods that require long cooking times and allows for easy roasting of food such as green maize and sweet potatoes.[25]

The communities have also revealed that the three-stone open fire has some characteristics that the communities find unappealing, such as difficulty in controlling the heat emitted, high consumption of fuel, and the production of a lot of smoke, although some improved stoves produce more smoke than an open fire.[26] Some cooks make slight modifications to the three-stone open fire, such as reducing the number of open spaces between the stones into which firewood is fed from three to one, hence reducing fuel consumption. Another popular and inexpensive change is to reduce the height of the stones. Just how much impact these changes make in terms of energy use, efficiency, and emissions needs to be studied well. In Malawi, after women produced and used briquettes, they developed a stove suitable for this type of fuel and named it the 'Briquette Mbaula'.[27] The energy efficiency and emission characteristics of this new stove relative to the existing types were studied through cooking tests in an ordinary kitchen, and data analysis of the results is on-going.

To improve cooking systems that meet users' needs and preferences, the transdisciplinary team has also been working with farmers on the use of the Top Lit natural Updraft (TLUD) biochar- producing gasifier stove locally produced in Kenya.[28] When using the stoves, cooks found that the gasifier stoves save fuel, cook faster, and reduce emissions. Cooks' observations were confirmed by measuring emissions during participatory cooking tests in the home. These studies show that the gasifier uses 40% less fuel and reduces emissions of carbon monoxide and PM2.5 by 45% and 90%, respectively, compared to the three-stone open fire.[29] One benefit inspiring the community is that the gasifier burns with a low amount of oxygen, which is easily controlled by using a door on one side of the stove. This process results in 20% of the initial fuel turning into charcoal; this charcoal can be used to cook another meal and can also be used as biochar to improve the soil.[30]

The burning process of the gasifier stove differs from the Briquette Mbaula stove developed by women in Malawi in that the gasifier stove turns fuel into charcoal as a by-product, while the Briquette Mbaula burns the fuel into ashes. The community in Kenya using the gasifier stove has recommended some improvements to the gasifier that would allow for cooking food that takes longer. For instance, they found that firewood burned in the gasifier turns into charcoal in about 50 minutes. The charcoal is then harvested and stored for another day's use. The fuel turns into charcoal in the gasifier stove before food that takes longer (three hours), such as maize and beans, has fully cooked. This necessitates refilling the stove with fresh fuel and relighting it. Such challenges are being addressed together with the community while working with post-graduate students and the Kenya Industrial Research Institute, which produces the gasifier stoves. The gasifier stove is being added into the stove mix and is especially useful for cooking food that gets ready quickly. A total replacement of three-stone open fire has not been achieved because it cooks diverse amounts and types of food.

Improving woodfuel for sustainable development

To advance woodfuel into a sustainable and efficient household energy sector, a systems approach that integrates all the stages of the value chain—including the production of wood, marketing and trade, consumption practices, and policy framework—is critical. The transdisciplinary team's work on woodfuel involves addressing different stages of the value chain in an integrated approach. For example, it seeks to combine the use of prunings from on-farm trees with the use of improved cooking systems.

Work led by the World Agroforestry Centre (ICRAF) in Tanzania found that on-farm firewood supply ranged from 0.5 to 8 metric tonnes per hectare for a variety of tree species. When the utilization of the firewood was compared between three-stone open fire and improved cook stoves, the latter consumed 67% less firewood and reduced gas emissions (PM10) by 60%.[31] Those collecting firewood from forests spent 50% less time because less firewood was consumed in improved stoves. Linking sustainable sources of charcoal dust for briquette production is being made by carbonizing tree branches such as those from the invasive *Prosopis juniflora* and organic wastes such as crop residues in a drum kiln. Using the invasive wood species in arid lands contributes to controlling bush encroachment, which is otherwise a menace in arid lands, while the use of organic waste contributes to cleaning neighbourhoods.

Conclusions, lessons, and impact

This chapter has presented some of the results of a transdisciplinary team approach to cooking fuel. The list below presents some lessons that can be learned and some conclusions about how this approach can increase the impact of the resulting innovative interventions.

- Grassroots innovations have a chance to address global challenges, and the potential of these innovations can be tapped through a transdisciplinary approach that brings together researchers and the community in a way that enables co-learning and co-innovation. The process of involving grassroots communities in co-innovations enhances women's involvement in the development of innovations that address their needs and aspirations as the main users.
- Making woodfuel sustainable through grassroots innovations will have more impact if different stages of the value chain are addressed in an integrated approach. For instance, a combination of sourcing firewood from trees on farms and using improved stoves to reduce consumption will have greater impact than either of these interventions alone.
- Grassroots innovations face challenges in producing quality products that can be addressed through capacity development. Potential consumers are also not aware of the quality and accessibility of the products that can be addressed through awareness campaigns.
- Governments and donors should invest in R&D that scales up grassroots innovations and local communities. Especially women, as the main users of woodfuel, should be involved so that technology development addresses their needs and aspirations.
- While replicating and improving grassroots innovations, it is important to consider their suitability with respect to the local context, including policy, needs, preferences, and potential. Incorporating specific local conditions into large-scale policy changes is always difficult, particularly when an in-depth, comparative understanding of specific conditions is constrained by a lack of adequate research. Comprehensive studies of biomass energy use in India, where far more research has been done, have yielded similar conclusions.[32] A second challenge is bridging the gap between woodfuel users and researchers. Although woodfuel is used by people of many classes, poor women are less able to buy new devices or change to fuels that require purchase.

Notes

1 IEA, 2006, p. 46.

2 Caniato et al., 2017.

3 Sola et al., 2016.

4 Njenga et al., 2018.

5 Mendum and Njenga, 2018.

6 FAO, 2017.

7 Kilian, 1998.

8 Lim and Vos, 2012.

9 Hollada et al., 2017.

10 Khandelwal et al, 2017.

11 Njenga et al., 2017.

12 Seyfang and Smith, 2007.

13 Rocheleau et al., 1988, p. 99.

14 Njenga et al., 2017.

15 Njenga et al., 2017.

16 Njenga et al., 2013.

17 Lim and Vos, 2012.

18 Njenga et al., 2013.

19 Njenga et al., 2013.

20 Njenga et al., 2013.

21 Nienga et al. 2018.

22 Gebrezgabher et al., forthcoming.

23 Njenga et al., 2013.

24 Lim and Vos, 2012.

25 Njenga et al., 2016.

26 Njenga et al., 2016.

27 Njenga et al., 2017.

28 Sundberg et al., 2017.

29 Njenga et al., 2016.

30 Njenga et al., 2017; Sundberg et al., 2017.

31 Sererya et al., 2017.

32 Khandalwal et al., 2017.

References

Caniato, M., D. Carliez, and A. Thulstrup. 2107. 'Challenges and Opportunities of New Energy Schemes for Food Security in Humanitarian Contexts: A Selective Review'. *Sustainable Energy Technologies and Assessments* 22: 208–19.

FAO (Food and Agriculture Organization of the United Nations). 2017. *The Charcoal Transition: Greening the Charcoal Value Chain to Mitigate Climate Change and Improve Local Livelihoods,* by J. van Dam. Rome: FAO.

Gebrezgabher, S., S. Amewu, and M. Njenga. Forthcoming. 'Adoption and Economic Impact of Briquette as Cooking Fuel: The Case of Women Fish Smokers in Ghana'. In Gender and Resource Recovery and Reuse for Energy. Working Paper. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Hollada, J., K. N. Williams, C. H. Miele, D. Danz, S. A. Harvey, and W. Checkley. 2017. 'Perceptions of Improved Biomass and Liquefied Petroleum Gas Stoves in Puno, Peru: Implications for Promoting Sustained and Exclusive Adoption of Clean Cooking Technologies'. *Int. J. Environ. Res. Public Health* 14: 182–96.

IEA (International Energy Agency). 2006. *World Energy Outlook 2006.* Paris: IEA/OECD.

Khandelwal, M., M. Hill, P. Greenwough, J. Anthoney, M. Quill, M. Linderman, and H. S. Udaykumar. 2017. 'Why Have Improved Cookstove Initiatives in India Failed?' *World Development* 92: 13–27.

Kilian, W. 1998. 'Forest Site Degradation: Temporary Deviation from the Natural Site Potential'. *Ecol. Eng.* 10: 5–18.

Lim, S. S. and T. Vos. 2012. 'A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010'. *Lancet:* 380: 2224–60.

Mendum, R and M. Njenga. 2018. 'Integrating Woodfuels into Agriculture and Food Security Agendas and Research in Sub-Saharan Africa (SSA)'. *FACETS* 3: 1–11.

Njenga, M., O. Baloi, M. Iiyama, Y. Terada, and R. Mendum. 2018. 'Resource Recovery for Briquettes and Women's Empowerment in Humanitarian Conditions in Kenya'. A presentation at the Workshop on Sustainable Rural Bioenergy Solutions in Africa, 19 January 2018, Nairobi. Available at http://www.irena.org/events/2018/Jan/Workshop-on-Sustainable-Rural-Biofuel-Strategy-in-Africa .

Njenga, M., C. Chasweka, J. Njoroma, and S. Mng'omba. 2017. 'Sustainable Tree-Based Energy Production and Cooking Systems'. A component of the Empowering Forest Dependent Communities through Commercialization of Small-Scale Forestry Project, supported by EU and DFID. Project report. World Agropforestry Centre (ICRAF), Nairobi, Kenya.

Njenga, M., M. Iiyama, R. Jamndass, H. Helander, L. Larsson, J. de Leeuw, H. Neufeldt, K. Röing de Nowina, and C. Sundberg. 2016. 'Gasifier as a Cleaner Cooking System in Rural Kenya'. *Journal of Cleaner Production* 121: 208–17.

Njenga, M., Y. Mahmoud, R. Mendum, M. Iiyama, R. Jamnadass, K. Roing de Nowina, and C. Sundberg. 2017. 'Quality of Charcoal Produced Using Micro Gasification and How the New Cook Stove Works in Rural Kenya'. *Environmental Research Letters* 12 (9). Available at http://iopscience.iop.org/article/10.1088/1748-9326/aa7499.

Njenga, M., C. Sundberg, and R. Mendum. 2017. 'Sustainable Woodfuel Systems in Sub-Saharan Africa: Application of a Transdisciplinary R&D Approach'. A presentation at the International Transdisciplinarity Conference 2017, Transdisciplinary Research and Education Intercultural Endeavours, Leuphana University of Lüneburg and td-net Network for Transdisciplinary Research. Abstracts booklet, p. 72. Available at https://www.leuphana.de/fileadmin/user_upload/PERSONALPAGES/_uvwxyz/vilsmaier_ulli/files/ITD17_booklet_26.9.17.pdf.

Njenga. M., A. Yonemitsu, N. Karanja, M. Iiyama, J. Kithinji, M. Dubbeling, C. Sundberg, and R. Jamnadass. 2013. 'Implications of Charcoal Briquette Produced by Local Communities on Livelihoods and Environment in Nairobi, Kenya'. *International Journal of Renewable Energy Development* 2 (1): 19–29.

Rocheleau, D., F. Weber, and A. Field-Juma. 1988. *Agroforestry in Dryland Africa.* Nairobi, Kenya: International Council for Research in Agroforestry (ICRAF).

Sererya, O. G., A. Kimaro, L. Lusambo, G. Uckert, J. Hafner, S. Sieber, F. Graef, and T. Rosenstoc. 2017. Resilience and Livelihood Benefits of Climate Smart Agroforestry Practices in Semiarid Tanzania. Poster presented at the Tropentag 2017: Future Agriculture: Social-Ecological Transitions and Bio-Cultural Shifts, 20–22 September, 2017, University of Bonn and the Center for Development Research, Bonn, Germany. Available at http://www.tropentag.de/2017/abstracts/posters/960.pdf.

Seyfang, G. and A. Smith. 2007. 'Grassroots Innovations for Sustainable Development: Towards a New Research and Policy Agenda'. *Environmental Politics* 16 (4): 584–603.

Sola, P., C. Ochieng, J. Yila, and M. Iiyama. 2016. 'Links between Energy Access and Food Security in Sub Saharan Africa: An Exploratory Review'. *Food Security* 8 (3): 635–42.

Sundberg., C., J. K. Gitau, M. Njenga, and J. Mutune. 2017. 'Introducing Biochar-Producing Gasifier Cookstoves in a Rural Community'. A presentation at the Rural Transformation and Urbanization Agricultural Research for Development Agri4D Conference 2017, Swedish University of Agricultural Sciences, SLU, 20–21 September 2017, Uppsala, Sweden. Abstracts available at https://www.siani.se/wp-content/uploads/2017/10/agri4d_abstract_170915_final.pdf.

CHAPTER 10

CHILE AND THE SOLAR REVOLUTION

Andrés Rebolledo, Former Minister of Energy, Chile

Chile has unique characteristics that enable it to develop a globally competitive solar industry. Its vast terrain in the north part of the country has the highest solar radiation on the planet. This solar radiation is in the same region as the country's larger energy consumers, such as the mining industry. Mineral resources, such as copper and lithium—the main raw materials of the sustainable energy revolution to which Chile is transitioning—are also found in this region.

In 2014, when the solar revolution in Chile began, a sustainable supply of electricity was critically lacking. Electricity was generated from a mix highly dependent on imported fossil fuels, primarily coal plants. At that time, the share of solar energy in total energy production was only 1%.[1] Moreover, in 2013 the electricity supply price for householders was US$161 per megawatt-hour (MWh),[2] one of the highest in the Latin American region. The electricity sector had stagnated for 10 years after a crisis in 2004 when Argentina stopped exports of natural gas to Chile.[3]

Chile's public opinion was against the development of more coal plants, but there was also strong opposition to the construction of the large hydropower dams in the south of the country.[4] The solar energy produced in the Atacama Desert was not available for consumption in the central and southern regions. There was no interconnection between the electric systems of the north (SING) and those of the central-south (SIC).[5] High prices, an energy mix dominated by fossil fuels, and scarce competition were a concern from the public policy point of view.[6]

Today the situation has changed radically; one of the main contributors to this transformation has been solar energy production. By December 2017, the installed capacity of renewable energies in Chile (excluding large hydropower systems) reached 19% of total energy production. Solar power represents half of renewable capacity.[7]

The role of government has been crucial in triggering this change. The Energy Agenda of 2014 set up a clear strategy to take advantage of solar resources.[8] The country's Energy Policy 2050, launched in 2016, aims to make Chile a solar energy exporter by 2035.[9]

Why is the Atacama Desert so special?

According to a survey of the Strategic Solar Program,[10] the Atacama Desert area presents unique conditions, including an average annual direct global radiation equal to 3,500 kilowatt-hours (kWh) per square metre (m2) and a horizontal global radiation level of 2,500 kWh/m2 per year. This is one of the highest radiation levels in the world. The Chilean Desert has more than 100,000 square kilometres (km2) of clear, cloudless skies, with an average annual precipitation

The author gratefully acknowledges the support of Javier Bustos for this chapter.

of 2 millimetres (mm) and 4,000 average hours of sun in a year. Medium temperatures over the summer are below 30°C and the ultraviolet B (UVB) radiation is 65% above the highest European level.

These are excellent conditions for supplying solar energy. Using only 6,000 km2 of the Atacama Desert there is enough room to place 200 gigawatts (GW) of installed capacity of solar energy that can supply 30% of the electricity demand in South America.[11] Moreover, the Atacama Desert holds the largest lithium reserves in the world, estimated at 7.5 million metric tonnes. This represents almost half of the world's reserves.[12]

The Atacama Desert is also home to the Chilean copper industry, which consumes large amounts of energy. Chile's share of the world's copper production was around 26% in 2016;[13] copper is one of the country's major exports. Since the mining industry comprises a large portion of the demand for electricity in Chile, an opportunity for mines in the north to obtain a sustainable energy supply from a nearby source is important.

These unique conditions present important challenges that must be met for Chile to take full advantage of the potential benefits of using solar as a competitive renewable energy source. One of these challenges is the need to develop new materials that behave suitably in the radiation levels of the Atacama Desert. Another important issue that must be addressed is how to reduce the soiling effect.[14] Difficulties in introducing larger proportions of variable renewable sources into the electricity system are also evident. By taking these challenges into account, it will be possible to introduce solar energy into industrial processes, particularly in the mining sector. This is a prerequisite to developing a successful local and sustainable solar industry.

Because of the extreme conditions present in the north of the country, regulations for technologies exposed to desert conditions must be developed. These conditions include the effects of the whole spectrum of radiation, the effects of the low atmospheric pressure due to altitude, abrupt changes in ambient temperature, the effects of dust (the soiling effect), and so on.[15] In turn, these conditions also present the opportunity to take advantage of direct solar radiation for applications of concentrated solar power,[16] both to reduce costs and to store thermal energy in molten salts that allow energy savings 24 hours a day.

The public role in the solar revolution

In 2014 the government of President Michelle Bachelet launched an Energy Agenda focused on solving the critical problems of the country's energy sector: high energy prices, low investment in new electricity capacity, and an energy mix that depends on fossil fuels.[17] Part of that agenda included developing a long-term energy policy and establishing goals for 2035 and 2050.[18] After a wide participatory process, the consensus was that Chile does not want just any kind of development, but one that is inclusive, equitable, and respects both the environment and social harmony. A transformation was needed.[19] In this context, innovation emerges as a great opportunity for the energy sector, which is a key element of the competitiveness of the country.[20]

The aim of the Energy Agenda is to make Chile an exporter of solar technology and services by 2035; it would specialize in solar technologies for high radiation and desert conditions. By 2050—in order to satisfy especially the South American future demand for innovative products and services, it plans to accomplish this through the different energy innovation focus points identified.[21] In this way Chile's energy sector will address local challenges and also contribute to the diversification of the economy.[22] In order to implement the actions needed to pursue this objective, the Chilean government has developed a collaborative process through the Chilean Economic Development Agency CORFO to draft a 2025 Roadmap called the Strategic Solar Program,[23] which included participation by over 100 government, corporate, academic, and civil society representatives. This Roadmap seeks to take advantage of the Atacama Desert's unique features to develop a national solar power industry with technological capabilities—one that is export-oriented. To this end, an initial portfolio of 50 initiatives was identified to cover the gaps of the industry, with a total budget of US$800 million for the period 2016–25.[24] See the next section of the chapter for more details about the initiatives underway in this programme.

The main objectives of the Strategic Solar Program are to reduce the levelized cost of photovoltaic technologies for the Atacama Desert conditions from US$80/MWh by 2015 to below US$25/MWh, add 3,000 local jobs to the more than 40,000 new jobs in the local industry, reduce 4.5 million metric tonnes of

Figure 1.
The Solar Energy Program development pillars

SOLAR ROAD MAP
STRATEGIC GUIDELINES

TECHNOLOGICAL DEVELOPMENT

- Solar technology center
  - Desert Module and System technology program
  - Thermal energy storage systems program
  - Solar desalinization program
  - Solar funds program
  - Advanced Human Capital program

INDUSTRIAL DEVELOPMENT

- Open innovation platform
- Financing innovation challenges
- High-tech investment attraction program

STRENGTHENING QUALITY INFRASTRUCTURE FOR SOLAR ENERGY

- Climate characterization
- Metrology network
- Regulation standards
- Conformity assessment schemes
- Drafting of labor skills profiles

Cuenca del Salado Solar Corridor

Solar Technology District

Source: ComiteCorfu, 2017, available at http://www.programaenergiasolar.cl/english/.

CO_2 per year, and introduce 100 companies into the solar industry value chain by 2025.[25] Considering the results of the last bidding process in 2017,[26] where offers were received with an average for renewable energy prices of US$32.5/MWh, it is possible to exceed the targets.

Initiatives underway through the Solar Energy Program

In 2016, a series of actions, focusing on the following areas, were undertaken by the Strategic Solar Program to implement the 2025 Roadmap (Figure 1):

- Technological Development,
- Industrial Development, and
- Strengthening Quality Infrastructure for Solar Energy.[27]

The most important initiative in the Technological Development branch is the desert module and system technology programme[28]—the so-called **AtaMoS-TeC (Atacama Module and System Technology Center).**[29] The AtaMoS-TeC is one of the Solar Roadmap initiatives that brings together the government, national and international companies, and technology centres in a partnership to implement a portfolio of research, development, and innovation (RDI) projects to develop photovoltaic systems created specifically for desert conditions, The objective of AtaMoS-Tec is to adapt and develop new materials, components, and operation and maintenance (O&M) services for photovoltaic systems, thus ensuring their durability and performance under desert climate conditions.

covering a gap in the knowledge of its own features for solar power generation. The standard technology in the industry has not yet been developed for the extreme conditions of the Atacama Desert. The objective of AtaMoS-Tec is to adapt and develop new materials, components, and operation and maintenance (O&M) services for photovoltaic systems, thus ensuring their durability and performance under desert climate conditions. It will also contribute to the installation of technological capabilities and, in partnership with international companies, foster the creation of a national business ecosystem for the solar power industry. By 2015 there were seven companies identified for solar energy distributed installation, 13 project development companies, and eight companies experienced in large solar power plant construction.[30]

The initiative has already begun, with a joint lab with technological capabilities for obtaining data on critical climatic variables (radiation, UVB, temperature, corrosion, etc.) and developing solar modules adapted to local conditions. There is also a project underway for manufacturing a Desert Module (DEMO) to demonstrate growing efficiency and durability. Technology baselines for drafting standards and creating compliance evaluation systems for photovoltaic technologies under desert conditions are also being developed. For that purpose a consortium of 20 firms and research centres, both national and international, have agreed to work together for the next eight years on these challenges.[31] Finally, DEMO is expected to have specialized services for the O&M of these systems, as well as the development of balance-of-system technology innovations, including component integration, assembly systems, and power inverters.

The **International Solar and Mining Institute of the North (IISM)** began operations in 2018.[32] The Institute aims to develop solutions for specific industry challenges on environment as well as cost and competitiveness issues, based on technological knowledge and technical capacity. The IISM was created to apply and combine existing technologies and develop new ones. It uses a cost-effective and practical approach for and with industry in a continuous improvement process with its business environment. It focuses on industrial development in a broad sense, including services and the development of new business models. It will perform RDI according to the roadmaps for the Solar Program and for the mining sector, always with the participation of the private sector. The IISM is expected to supply simulation services for systems and new technologies, to develop small-scale prototypes, and to test new materials and equipment. Its main beneficiaries will be the local solar industry,[33] with pilot programmes and monitoring and product certification of systems and competences. The IISM is fundamental to strengthening technology transfer and trade by selling and licensing technologies and materials and by fostering spin-offs and the design of new business models.

For the Industrial Development area, an **Open Innovation Platform for Financing and Innovation** has been established.[34] This project aims to develop a virtual supply-and-demand interactive platform as well as a specialized team in charge of studying the main energy-related problems, needs, and opportunities in the national industry so they can translate their findings into business innovation opportunities. It also contemplates a specialized team in charge of incentivizing participation by local suppliers and advising them on the construction of innovative and value propositions to take advantage of those opportunities. The objective is to contribute to closing the existing information and knowledge gaps between suppliers and consumers of energy solutions and to facilitate access to financing in order to materialize the proposed innovations.

To build Quality Infrastructure, and considering the gap between local knowledge and needed understanding of optimal conditions for solar power generation,[35] an **Optical Metrology Lab** was opened at the University of Santiago.[36] Some of the identified gaps are the weak supply of calibration instruments and poor radiometric and photometric standards.[37] This lab is expected to have quality measurements and be able to supply geo-referenced information to the solar industry.

The Strategic Solar Program also has planned global actions such as the **Cuenca del Salado Solar Corridor.**[38] The aim of the Corridor is to study and test technical, social, and productive solutions that allow a massive adoption of solar energy in the cities of Chañaral and Diego de Almagro in the Atacama Region.[39]

One initiative for the future is the **Solar Technology District (DTS).**[40] The concept, which builds on the experience of the Moroccan Agency of Sustainable Energy,[41] refers to the development of territories covering large areas that have been chosen for their optimal conditions for solar power generation, subdivided into lots, and awarded to energy-generation companies in a concession for the development, construction, and operation of solar power plants using different technologies. A Technology Master Plan will determine the choice of technologies and the total installed capacity in these districts. Optimization will occur through criteria that include the technology mix that best contributes to stable energy supply at competitive prices, and with the promotion of the participation by local companies as suppliers. Chile has no record of anything similar being implemented in the past; fostering the deployment of solar energies with a relevant increase of domestic suppliers is an ambitious undertaking. Under current conditions in the Chilean energy market, the first task—a difficult one—will be to obtain a long-term contract for electricity supply.

To introduce the Chilean solar industry into the global energy market it will be important to participate in different international initiatives. Chile's researchers and firms have limited experience participating in international groups dedicated to the development of solar technology. However, Chile has recently joined the International Energy Agency´s **Photovoltaics Power System Programme (PVPS),**[42] as well as the **Solar Power and Chemical Energy Systems Energy Technology Network (SolarPaces).**[43] The objective of both these organizations is to share first-hand information on photovoltaic and concentrated solar power technologies.

Because of the lack of competition in Chile's energy sector, public funding for RDI in energy has been a key driver for research and innovation in Chile because private spending historically has been limited.[44] Several policies have been implemented in order to incentivize private-sector funding (tax exemptions, co-finance loans, etc.), but with the country's current level of development, public funding will continue to play an important role in the short and medium term. In terms of public funding, in February 2015 a special fund—the **Strategic Investment Fund (FIE)**—was created. The FIE supports initiatives aimed at improving productivity, diversifying the economy, and increasing the value added of the national production, with a focus on solar energy among others.[45] Additionally, within the framework of the **Mission Innovation** collaboration programme,[46] Chile has committed to doubling its budget in clean energy R&D to US$9 million by 2020, up from US$4.5 million recorded in 2015. The programme also promotes higher levels of private-sector investment in transformational clean energy technologies by opening calls for proposals from companies to develop specific solutions for the solar industry.

The future of the Chilean revolution

Since 2014, photovoltaic systems with a capacity of 1,776.41 MW have been installed, boosting the photovoltaic component of the total electricity mix from 0.01% to 4.4% by 2017.[47] By 2030, the share of solar energy in total electricity production is estimated to reach between 13% and 22%.[48] Chile currently has the largest solar energy generation capacity in Latin America. Chile also has new technologies that allow it to concentrate solar power, thus providing storage for this type of energy.[49]

What can be expected in the future? Recently, as part of the Ministry of Energy's long-term energy planning process for electric transmission expansion,[50] five installed power mix scenarios over the next 30 years were considered.[51] The five scenarios, which describe possible shares of different sources of power by 2035, are the result of a process involving cross-matrix analysis considering the following drivers: social willingness for projects, energy demand, technology changes in battery storage, environmental externalities costs, investment costs for renewable energy technologies, and the price of fossil fuels. All the scenarios show greater participation of solar power and a more diversified mix of energy sources. By 2035 the most optimistic scenarios for renewable energy show that at least 30% of installed capacity will be solar, including both photovoltaic and concentrated solar power generation systems. That will represent more than 10 GW of photovoltaic generation over the current 2.1 GW, and more than 1.2 GW of concentrated solar power.[52]

Because of the unique conditions of the Atacama Desert, the recent interconnection of the electric systems (SIC and SING) that links the north with the centre and south of the country has been a major change in the electricity market.[53] This was achieved after four years of planning and construction. One of the important goals of the interconnection was the opportunity for more competition that renewable sources can bring to the energy market. The SIC-SING interconnection opens the possibility of an international interconnection with Peru and Argentina. A more integrated system complements the development of the photovoltaic and concentrated solar power potential in the Atacama Desert.

Next challenges

Energy Policy 2050's goals are clear: to generate 60% of power from renewables by 2035 and 70% by 2050. These objectives are crucial to attaining the 30% reduction in emissions by 2030—as committed to under the Paris Agreement.[54] The five scenarios based on the long-term energy planning process show that solar and wind will be the main drivers of electricity supply in the upcoming years.[55] This situation generates special challenges for Chile's local solar industry.

First, it is important to be prepared to have a large proportion of variable renewable energy.[56] Results from previous studies, such as the *Energías Renovables No Convencionales* (ERNC, Non-Conventional Convertible Renewable Energies) Roundtable, show that Chile can have at least 30% solar and wind generation with the current level of flexibility of its power systems.[57] The main source of flexibility in the Chilean market is provided by hydropower generation. Then the country has time to prepare for a greater penetration of variable renewable energy, but actions have to be taken soon. A proper transmission expansion, as well the interconnection with neighbour countries, can help. But that might not be enough. For example, different sources and technologies for storage will also be needed.[58]

Distributed generation has just started to grow in Chile but, considering the potential of the country, it is very likely that distributed solar generation can play an important role in the future. The market will need to deploy new infrastructure on smart grids to take full advantage of this opportunity.

Taking into consideration the high potential of solar generation in Chile,[59] which is estimated at more than 1,640 GW of photovoltaic and more than 550 GW of concentrated solar power,[60] there is an opportunity to use solar energy for other purposes, such as electric mobility and solar fuels.[61] To do this, Chile intends to become a leader in zero-emission mobility,[62] taking advantage of the clean energies of its electrical generation mix and its lithium sources, which comprise the main input needed to develop a new energy storage industry.[63] Another opportunity lies in the generation of hydrogen as an energy vector, for new low-emission mining and for other applications. In 2018, a technology programme was launched by CORFO to develop mining extraction trucks powered by hydrogen, either by mixing hydrogen with diesel,[64] or by powering the trucks with fuel cells.[65]

Chile has already begun its solar revolution and will continue to deepen it. One of its most important challenges is the appropriate integration of increasing amounts of variable renewables into the electric system, which still needs a more flexible power system. In order to develop successfully, new technologies and standards are required that are specially designed for the Chilean desert and extremely high radiation conditions. It is also necessary to foster open innovation processes where entrepreneurs, universities, and research centres provide solutions to specific challenges, and to train the workforce with a new set of skills. These open processes and workers with appropriate skills are needed to contribute to Chile's greater economic development—development that is sustainable and inclusive, where innovation will be the main link to continue on the path of clean energy.

Notes

1 Comisión Nacional de Energía, 2017.

2 Ministerio de Energía, 2016.

3 IEA, 2018.

4 Consejo de Defensa de la Patagonia Chilena, 2013.

5 The Norte Grande Interconnected System (SING, *Sistema Interconectado del Norte Grande*) serves the desert mining regions in the North; the Central Interconnected System (SIC, *Sistema Interconectado Central*) serves the central part of the country.

6 IEA, 2018.

7 See https://www.cne.cl/estadisticas/electricidad/.

8 Ministerio de Energía, 2014a.

9 Ministerio de Energía, 2016.

10 For information about the Strategic Solar Program, see http://www.programaenergiasolar.cl/english/solar-committee/atacama-desert/.

11 Calculations made by the Solar Energy Research Center are available at http://sercchile.cl/.

12 USGS, 2018.

13 Corporación Chilena del Cobre, 2016.

14 Fundación Chile, 2015a. 'Soiling effect' refers to the accumulation of dirt on solar panels. This effect can have a significant impact on the performance of solar systems, particularly in areas—such as in the Atacama Desert—with a large amount of dust or pollution and low or nonexistent rainfall.

15 Fundación Chile, 2015a.

16 'Concentrated solar power' uses mirrors or lenses that reflect and condense light, which is converted to heat that can be stored.

17 Ministerio de Energía, 2014a.

18 Ministerio de Energía, 2016.

19 Ministerio de Energía, 2016.

20 Ministerio de Energía, 2017b.

21 Ministerio de Energía, 2016.

22 Ministerio de Economía, 2014.

23 See Chile's Solar Energy Program website (in English): http://www.programaenergiasolar.cl/english/. Information about CORFO is available at http://www.english.corfo.cl/.

24 Fundación Chile, 2015b.

25 Fundación Chile, 2015b.

26 The results of the bidding process are available here (in Spanish): http://www.licitacioneselectricas.cl/wp-content/uploads/download-manager-files/Acta-Adjudicacion-Oferta-Economica.pdf.

27 Fundación Chile, 2015a.

28 More information on the Technology Development branch of the Solar Program is available at http://www.programaenergiasolar.cl/english/solar-road-map/tecnological-development/development-technological-photovoltaic-systems-deserts/.

29 More information is available (in Spanish) at http://www.programaenergiasolar.cl/lanzamiento-de-atamos-tec-consorcio-publico-privado-busca-desarrollo-de-tecnologias-solares-en-chile/.

30 Fundación Chile, 2015b.

31 See more here (in English): http://sercchile.cl/en/serc-chile-implementara-atamos-tec-iniciativa-que-fomentara-la-industria-solar-local/.

32 For more information about the International Solar and Mining Institute of the North (IISM), see http://www.programaenergiasolar.cl/english/solar-road-map/tecnological-development/international-solar-mining-institute-iism/ (in English).

33 A directory of all beneficiary companies in the local solar sector is available at http://industria.enlacesolar.cl/directorio-sector-solar/.

34 For more information on the Open Innovation Platform for Financing and Innovation, see http://www.programaenergiasolar.cl/english/solar-road-map/industrial-development/open-innovation-platform-financing-innovation/ (in English); see https://fch.cl/proyecto/sustentabilidad/brilla/ (in Spanish). See also http://www.programaenergiasolar.cl/english/solar-road-map/industrial-development/open-innovation-platform-financing-innovation/ (in English).

35 See http://www.programaenergiasolar.cl/english/solar-road-map/strengthening-quality-infrastructure-solar-energy/.

36 See http://www.fisica.usach.cl/laboratorios/laboratorio-metrologia-optica.

37 Fundación Chile, 2015b.

38 For more details, see http://www.programaenergiasolar.cl/english/solar-road-map/global-initiatives/solar-corridor/ (in English).

39 Observatorio de Ciudades UC, 2016.

40 More information is available at http://www.programaenergiasolar.cl/english/solar-road-map/global-initiatives/solar-technology-district-dts/ (in English).

41 More information about Morocco in this context is available at http://www.masen.ma/en/.

42 For more information about the IEA's Photovoltaics Power System Programme, see http://www.iea-pvps.org/.

43 More information about SolarPaces is available at http://www.solarpaces.org/.

44 Consejo Nacional de Innovación para el Desarrollo, 2017.

45 Ministerio de Economía, 2017.

46 Mission Innovation involves 22 countries and the European Union. It aims to strengthen and accelerate public and private global clean energy innovation. Each participating country will seek to double its governmental and/or state-directed clean energy R&D investment over five years. New investments would be focused on transformational clean energy technology innovations that can be scalable to varying economic and energy market conditions.

47 Comisión Nacional de Energía, 2017.

48 Ministerio de Energía, 2017d.

49 See https://cerrodominador.com/.

50 Ministerio de Energía, 2017d.

51 Data and results are available at pelp.minenergia.cl (in Spanish).

52 Ministerio de Energía, 2017d.

53 Coordinador Eléctrico Nacional, 2017.

54 Ministerio de Medio Ambiente, 2017.

55 Ministerio de Energía, 2017d.

56 'Variable renewable energy' is a renewable energy source that fluctuates, such as wind and solar sources.

57 Ministerio de Energía, 2015.

58 See http://valhalla.cl/.

59 The total power capacity by January 2018 in Chile was 22.57 GW and solar was 1.8 GW (Comisión Nacional de Energía, 2017).

60 Ministerio de Energía, 2014b.

61 According to Bloomberg New Energy Finance, the Chilean solar power capacity represented less than 1% of the capacity of overall Central and South America the same year, 2015.

62 Ministerio de Energía, 2017b.

63 Ministerio de Minería, 2015.

64 See https://www.corfo.cl/sites/cpp/convocatorias/2017_pt_combusti%C3%B3n_dual_hidr%C3%B3geno_%E2%80%93_di%C3%A9sel.

65 See https://www.corfo.cl/sites/cpp/convocatorias/movil/2017_pt_equipos_mineros_celdas_de_combustibles.

References and related reading

Bloomberg New Energy Finance. 2016. 'New Energy Outlook 2017'. *Global Overview* (2016): 13. Available at https://about.bnef.com/new-energy-outlook/.

Comisión Nacional de Energía. 2017. *Capacidad instalada de generación - SIC, SING, sistemas medianos de Aysén, sistemas medianos de magallanes, Isla de Pascua - Diciembre 2017.*

Consejo de Defensa de la Patagonia Chilena. 2013. *Patagonia ¡sin represas! Una campaña de educación.*

Consejo Nacional de Innovación para el Desarrollo. 2017. *Ciencias, tecnologías e innovación para un nuevo pacto de desarrollo sostenible e inclusivo.*

Coordinador Eléctrico Nacional. 2017. *Análisis de la operación de los sistemas SIC-SING interconectados. Principales resultados y recomendaciones.* Available at https://www.coordinador.cl/sistema-electrico-nacional/.

Corporación Chilena del Cobre. 2016. *Anuario de estadísticas del cobre y otros minerales 1997-2016.*

Fundación Chile. 2015a. *Informe Hoja de Ruta Programa Estratégico Nacional en Industria Solar (PES). Noviembre, 2015.*

———. 2015b. *Informe levantamiento de brechas Programa Estratégico Nacional en Industria Solar.*

IEA (International Energy Agency). 2018. *Energy Policies Beyond IEA Countries - Chile 2018.*

Ministerio de Economía. 2014. *Agenda de Productividad, Innovación y Crecimiento.*

———. 2017. *Memoria 2016-2017 Fondo de Inversión Estratégica.*

Ministerio de Energía. 2014a. *Agenda de Energía. Un desafío país, progreso para todos.*

———. 2014b. *Energías Renovables en Chile. El potencial eólico, solar e hidroeléctrico de Arica a Chiloé.*

———. 2015. *Mesa ERNC. Una mirada participativa del rol y los impactos de las energías renovables en la matriz eléctrica futura.*

———. 2016. *Energía 2050 – Política Energética de Chile.*

———. 2017a. *Estrategia de Ciencia, Tecnología e Innovación Para el Sector Energía.*

———. 2017b. *Estrategia Nacional de Electromovilidad.*

———. 2017c. *Memoria Programa Techos Solares Públicos.*

———. 2017d. *Proceso de Planificación Energética de Largo Plazo – Informe Final.*

Ministerio de Medio Ambiente. 2017. *Plan de Acción Nacional de Cambio Climático 2017-2022.*

Ministerio de Minería. 2015. *Litio, una fuente de energía, una oportunidad para Chile.*

Observatorio de Ciudades UC. 2016. *Programa de reactivación urbana y productiva sustentable de Atacama.*

USGS (U.S. Geological Survey). 2018. *Mineral Commodity Summaries 2018*. Washington, DC: USGS.

CHAPTER 11

SINGAPORE

A Living Lab for Renewable Energy

Daren Tang, Intellectual Property Office of Singapore

From launching the world's largest floating photovoltaic (PV) test bed to building the first industrial micro-grid test system in South East Asia,[1] Singapore is demonstrating that it can be a 'Living Lab' for renewable energy (RE) innovators to test ideas. Beyond testing, innovators can leverage Singapore's world-class legal framework, robust intellectual property (IP) regime, conducive business environment, and extensive global networks to commercialize their innovative RE ideas, transforming them into viable technologies for global markets.

By 2040, the world's energy demand is expected to grow substantially—by 30%.[2] Coupled with the megatrend of rapid urbanization and the ever-increasing appetite for energy, the pursuit of RE innovation is more pressing than ever before.

The year 2015 marked a milestone: global RE capacity additions exceeded those of fossil fuels and nuclear energy for the first time.[3] Nearly two-thirds of all new net power capacity additions came from renewables in 2016.[4] The confluence of these factors fuelled the global economy's increased investments in RE technologies. Bloomberg estimates that RE will attract a share of US$7.3 trillion in investments between 2016 and 2040, comprising 72% of investments in new power technologies.[5]

Against this backdrop, it has become imperative for policy makers to be kept abreast of the emerging technology trends in RE to make better-informed decisions about their energy needs.

In this chapter, the Intellectual Property Office of Singapore (IPOS) provides some useful insights for decision makers by examining global trends and emerging areas, as well as leading countries in the field of PV, through the lens of a patent landscape analysis. It then discusses, using Singapore as an example, how small nations can play an outsized role in driving RE innovation, and how IP and IP offices can complete the innovation value chain to bring technology to market.

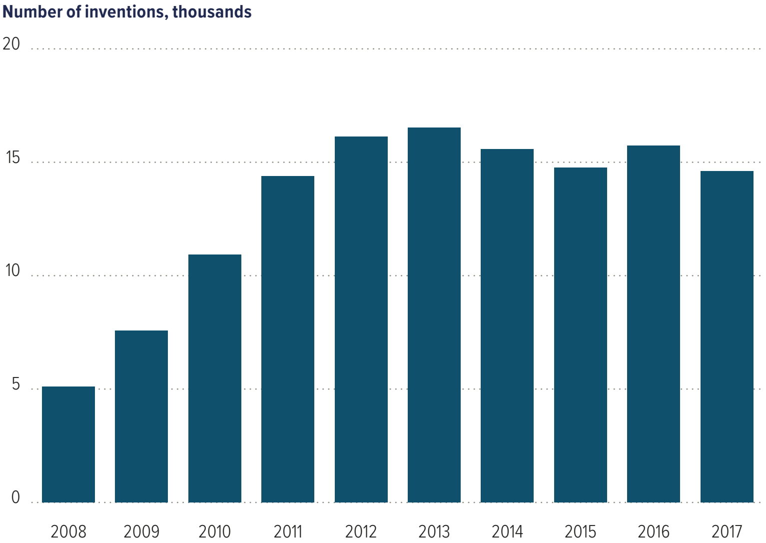
Renewable energy–related patent landscape insights

The rising interest in RE as an alternative energy source warrants a deeper look at global patenting activities in this burgeoning IP-intensive industry. The area of PV technologies is particularly interesting because, within the next 25 years, solar power is expected to become the cheapest source of new electricity generation.[6]

The Intellectual Property Office of Singapore (IPOS) commissioned its subsidiary, IPOS-International, to conduct a PV patent landscape analysis report. This chapter makes substantial reference to the results of this internal report.

Figure 1.

Publication trend of photovoltaic-related inventions, by earliest publication year

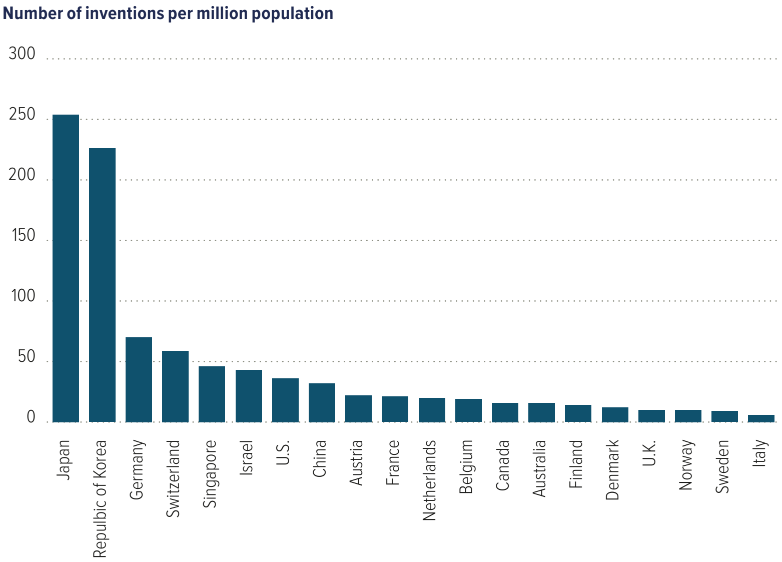


Source: IPOS-International, internal report.

Note: Data for 2017 are incomplete because (1) the cut-off of data extraction is 11 December 2017; and (2) the search string relied on patent classification codes, and some of the patent documents newly published in 2017 might not have been classified by the cut-off date and therefore were not picked up by the search.

Figure 2.

Top 20 countries with the largest number of photovoltaic-related inventions, by applicant's country of origin



Source: IPOS-International, internal report.

Based on worldwide PV-related inventions published from 2008–17 (see Box 1 on page 173), the patent landscape analysis reported that there were indeed escalated PV-related filings globally. From 2008 to 2017, there were a total of 143,403 PV-related inventions (see Figure 1), which were largely dominated by China and East Asia. In fact, the combined contributions from China, Japan, and the Republic of Korea accounted for about 60% of the worldwide PV-related patenting activities in the last decade. However, in the last five years—that is, from 2013 to 2017—a plateau in PV-related patenting activities has been observed, suggesting that PV technologies are maturing. It is noteworthy that small countries such as Switzerland, Singapore, and Israel stand out in terms of inventions per capita, to be ranked behind traditional major hubs for PV technology such as Japan and Germany (Figure 2).

Another pertinent observation from the patent landscape analysis from 2008 to 2017 is the high growth evident in areas such as PV or PV-hybrid power plants (which has seen an increase of 54.5%), management and optimization of PV systems (up 45.9%), and support structures for PV modules (up 39.9%) (Figure 3). Countries such as China and India are delving deeper into these emerging high-growth areas,[7] probably as a result of the escalating reliance on RE to meet the world's growing energy needs, the wide adoption of PV technology, and the quickly declining cost of solar power. Interest in such system-level integration and downstream applications is likely to continue given the strong annual growth that has been seen in these areas over the past five years.

The patent landscape analysis also reported a strong correlation between countries' efforts and achievements in driving PV technologies and their use of these inventions. Three distinct groups—leaders, innovators, and users—surfaced (Figure 4). These data can inform policy makers and enterprises about where the potential competitors, collaborators, and markets are. For brevity, a representative country from each category has been chosen to illustrate the focus of PV patenting activities and installations.

Figure 3.

Top 10 emerging technology sub-domains in photovoltaic (PV), 2008–17

Emerging area	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total	% change per annum, 2012–16
	No. of inventions according to earliest publication year											
PV or PV-hybrid power plants	15	26	59	45	61	40	199	277	353	267	1,342	54.5
Management & optimization of PV systems	1	0	5	9	13	25	51	56	86	105	351	45.9
Support structures for PV modules	51	116	214	202	231	249	352	679	1,030	904	4,028	39.9
Monitoring or testing of PV systems	8	20	44	108	128	129	198	363	402	406	1,806	33.2
Structural details of PV modules	10	21	20	54	61	86	121	191	200	183	947	31.7
PV module components or accessories	54	103	187	231	268	207	420	614	718	735	3,537	30.6
Solar-powered lighting	47	49	85	106	103	119	136	177	197	304	1,323	16.9
Programme-control systems	1	4	11	14	22	43	27	31	49	59	261	12.7
Circuit arrangements for AC mains	67	93	162	294	378	467	550	578	635	567	3,791	12.5
Circuit arrangements for energy storage in batteries	96	116	173	252	224	303	305	303	404	365	2,541	11.8

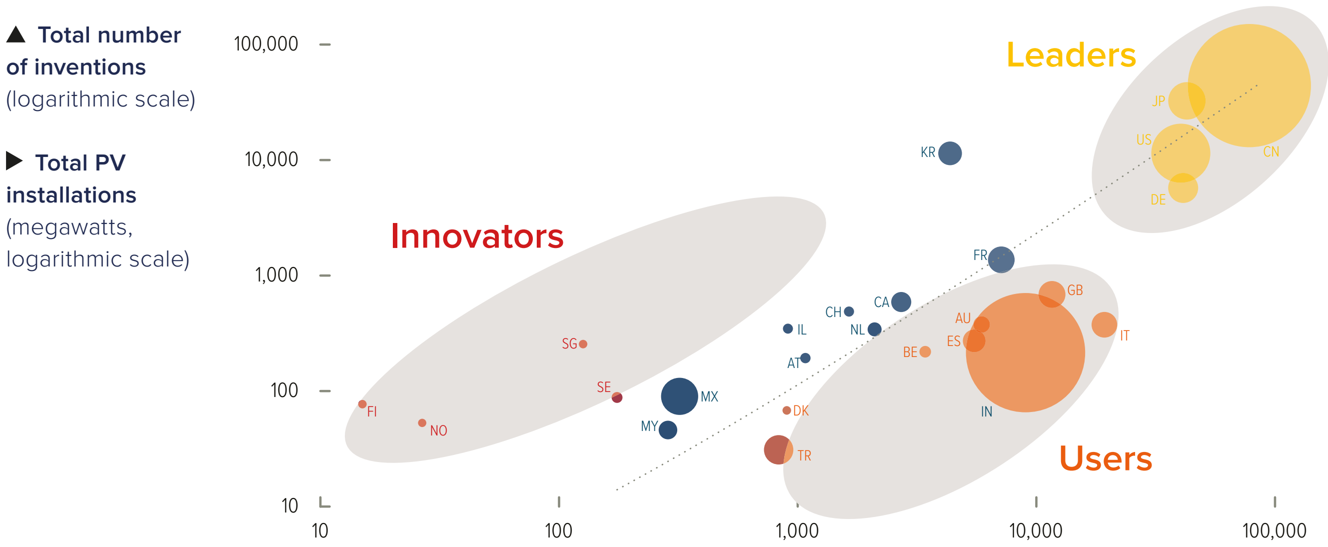
Key: 0–100 101–200 201–400 401–700 >700

Source: Source: IPOS-International, internal report.

Note: Data from 2017 are not used in the calculation of growth per annum because they are incomplete. Technology sub-domains were determined according to International Patent Classification (IPC) codes at the main group level. The IPC codes that correspond to the top 10 emerging areas are (1) H02S 10/00, (2) G06Q 10/00, (3) H02S 20/00, (4) H02S 50/00, (5) H02S 30/00, (6) H02S 40/00, (7) F21S 9/00, (8) G05B 19/00, (9) H02J 3/00, and (10) H02J 7/00. AC = alternating current.

Figure 4.

Photovoltaic (PV) technologies: Leaders, innovators, and users



Sources: UN DESA, 2017; EMA Singapore, 2016; IEA, 2016a.

Note: Bubbles are sized by population. 'Leaders' have the most PV technologies and greatest number of PV system installations; 'Innovators' have higher than average PV inventions compared to system installations (above the curve); and 'Users' have fewer than average PV inventions compared to system installations (below the curve). The trend line is a polynomial of degree 2 with intercept (R^2 = 0.8183). ISO-2 country codes: AT = Austria; AU = Australia; BE = Belgium; CA = Canada; CH = Switzerland; CN = China; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GB = United Kingdom; IL = Israel; IN = India; IT = Italy; JP = Japan; KR = Republic of Korea; MX = Mexico; MY = Malaysia; NL = Netherlands; NO = Norway; SE = Sweden; SG = Singapore; TR = Turkey; US = United States of America.

PV technology leader: China

China's rapid expansion of PV facilities has attracted worldwide attention. It now leads the pack with close to 60,000 PV-related inventions and is the world's largest producer of solar energy, installing more than 34 gigawatts (GW) of solar capacity in 2016—more than double the figure for the United States of America (U.S.) and nearly half of the total added capacity worldwide that year.[8] A government report even suggested that, by 2050, renewables could supply 86% of the country's energy needs, with solar providing about a third of this supply.[9]

Several pro-PV government policies, along with surging global demand, have contributed to this trend. In December 2016, the National Development and Reform Commission—the country's national economic planner—announced a planned investment of US$158 billion as part of the Chinese government's bid to boost PV capacity fivefold.[10] These key fiscal policy measures have encouraged Chinese firms to forge more partnerships with research institutes and pay for technology licenses, which further spurred PV innovation in the country.

PV technology user: India

Since the 1980s, the Indian government has recognized the importance of PV systems and announced plans to bring the country's solar capacity to 100 GW by 2022.[11] This target is a fivefold increase over its previous target and represents a step-change in India's solar ambition. The International Energy Agency (IEA) projected that the country will be the second-largest producer of electricity from solar PV installations by 2040.[12]

Driven by domestic needs where peak demand is expected to exceed 285 GW by the end of 2022,[13] the Indian government has deployed PV installations rapidly through coordinated efforts with its federal institutions, such as the National Thermal Power Corporation and the Solar Energy Corporation of India, as well as its state governments. Several measures have been introduced over the last few years to incentivize and ramp up PV installations. These include waiving interstate transmission system charges and losses for both solar and wind projects, supporting domestic solar PV manufacturing facilities, and instituting appropriate measures for the smooth release of solar panel consignments imported from other countries.

PV technology innovator: Singapore

Since 2006, Singapore has pumped US$1.5 billion into R&D for the clean technology sector, which includes environment and water solutions. With the global shift in the energy sector and its inherent advantage in harnessing PV electricity, Singapore moved swiftly to invest in PV technologies to ensure an affordable, reliable, and resilient energy supply.

Singapore's interest has been focused on two areas: the management and optimization of PV systems, and the development of support structures for PV modules. In the area of management and optimization of PV systems, Singapore launched South East Asia's first industrial hybrid micro-grid test bed on the Semakau landfill in 2014 as part of the Renewable Energy Integration Demonstrator-Singapore (REIDS) initiative led by Nanyang Technological University.[14] This US$6 million hybrid micro-grid platform has since attracted waves of investment from top energy and micro-grid players—such as Accenture, DNV GL, LS Group, Schneider Electric, and Sony—to try out their technologies in Singapore.

In addition, the Energy Market Authority (EMA), the primary public agency responsible for ensuring a reliable and secure energy source for Singapore, announced in October 2017 that it will award a US$4.6 million research grant to a consortium led by the National University of Singapore to develop solar forecasting capabilities.[15] The system will make use of the growing pool of solar irradiance data as well as weather data collected by a dense island-wide network of sensors installed by Meteorological Service Singapore to improve the accuracy of PV output forecasts and grid management. The forecasting model can also be applied to other countries with similar climates and weather patterns.

Singapore successfully developed and installed 10 different floating support structures for PV systems that were constructed by both local and overseas companies on the Tengeh Reservoir in 2016 to determine the most suitable system for Singapore. Building on the results of the test bed, the Public Utilities Board (the nation's water agency) is now exploring the feasibility of deploying a 50 megawatt (MW) floating solar PV system at the Tengeh Reservoir. The amount of energy generated from such a system could potentially power about 12,500 average households in Singapore.[16]

The Singapore story: Experiment, innovate, collaborate

As evidenced by the PV patent landscape analysis, small countries with limited capacity for PV installation can still play an outsized role in the innovation of RE technologies. Singapore's model of a Living Lab to foster open innovation and public-private partnerships, as well as to allow for the rapid development, test-bedding, and deployment of RE technologies, is one example of how this can be achieved.

Singapore has invested and continues to invest heavily to drive PV research. For instance, the National Research, Innovation and Enterprise 2020 plan has specifically set aside US$660 million for R&D and deployment initiatives related to urban solutions and sustainability.[17] The funding will strengthen Singapore's innovation and research capacities in the areas of solar technologies, smart grids, and energy storage systems.

Strong governmental commitment has been instrumental in fostering the growth of numerous research bodies undertaking complementary PV research. For example, the Solar Energy Research Institute of Singapore (SERIS), set up in 2008, was one of the first research bodies to cement the country's position as a solar energy hub in Asia. And the Energy Research Institute at Nanyang Technological University (ERI@N) was set up in 2010 to study wind and marine renewable energy, energy storage, and fuel cells. The Campus for Research Excellence and Technological Enterprise (CREATE), established in 2012, focused its research in energy storage systems and brought together top international universities and research institutes to tackle global energy issues.

In addition to conducting R&D, considerable efforts are directed towards fostering partnerships between relevant government agencies and international and local energy market players to create viable PV solutions. One such partnership is the collaboration between the Singapore Institute of Technology (SIT) and the Singapore Power (SP) Group to build Singapore's first experimental urban micro-grid, which will be housed in SIT's future campus in the Punggol Digital District.[18] The micro-grid will be a national infrastructure open to the research community and businesses. The platform allows new technologies and solutions to be tested in a controlled environment, while providing students with the opportunity to work with industry partners and energy start-ups. When completed, it will be the first university in South East Asia to have a multi-energy micro-grid network.

True to its Living Lab concept, Singapore has been reaching out to researchers and companies from all over the world to experiment, to act as a test bed, and to scale up their RE solutions through Singapore. REC Solar, a subsidiary of the Norway-based REC Group—a leading global provider of solar energy solutions—will inject close to US$150 million into their production plant in Singapore, which is regarded as one of the world's largest fully integrated solar manufacturing facilities.[19] This investment will produce an output sevenfold higher than the current production of Twinpeak, a 120-cell, high-power, multi-crystalline module. The REC Group has also committed to investing another US$37 million in a research partnership with SERIS, which is one of the leading solar research institutes in the world. The collaboration will accelerate the commercialization of innovative solar technologies in Singapore.

In a recent announcement, Germany-based VDE Renewables, together with the Fraunhofer Institute for Solar Energy Systems and ERI@N, will be setting up a Global Energy Storage Competence Cluster to serve the international clean-technology sector along the entire value chain.[20] The Chinese firm Narada will also set up its regional Energy Storage Solution Centre of Excellence in Singapore to develop co-innovation opportunities with local companies.[21]

These activities have created a vibrant PV ecosystem in Singapore. Chinese companies such as GCL Poly Energy Holdings and Linyang Renewable, as well as U.S. wind company Hover Energy, together with 50 other energy market players, have all established their regional headquarters in Singapore to house their various business functions.[22]

Singapore has also nimbly turned rapid digitalization and disruptive technologies to its advantage. Through a highly coordinated policy directive, the island nation is now an accessible launch pad for energy market players to create innovative solutions. In addressing the needs of the energy market, the EMA launched a regulatory sandbox in October 2017 to enable the energy sector to test new products and services, in a creative manner, outside of Singapore's regulatory systems.[23] The sandbox complements ongoing R&D initiatives, whereby market players can tap into new technologies or apply existing technologies in novel ways to create value for electricity and gas consumers, or to improve business and operational procedures. This bold move is essential for growing new, potentially disruptive technologies that do not fit within the existing regulatory environment and infrastructure.

Successes in going to market

Singapore's approach, as illustrated through various examples in this chapter, shows that small countries can drive PV innovation through its Living Lab concept by enabling global innovators in the public and private sectors to experiment, innovate, and collaborate. This section presents two examples of successful spin-offs that have grown out of Singapore's Living Lab model.

A hybrid commercialization approach: Printed Power

In 2010, Singapore set up ERI@N at Nanyang Technology University of Singapore to focus on system-level research in the energy sector. One of their flagship programmes—the ERI@N Accelerator—was launched specifically to galvanize entrepreneurship by nurturing spin-offs that show good potential to translate R&D outcomes into viable products and services for the market. Printed Power is one successful spin-off from this research-based accelerator programme. It was created to build an integrated energy-harvesting wireless sensing device with customizable power management solutions.

For Printed Power, ERI@N management adopted a hybrid approach. An IP holding and commercial unit was set up where the key technology involved was licensed to Printed Power. The technology can potentially be sub-licensed to respective partners for market penetration. At the same time, ERI@N worked through its networks and resources to scale the business. ERI@N was involved in hiring key personnel at Printed Power and mobilized some of its key research scientists to the spin-off to build the business. Additionally, ERI@N developed a viable business plan together with Printed Power and secured early-stage seed funding of US$375million.

Printed Power is now operating as an independent entity. In the first half of 2018, it will be launching its products, which can be used in smart buildings and homes, transportation, industrial applications of Internet of Things and automation, data centres, manufacturing, precision agriculture, supply chain, and logistics industries in Singapore. There are plans to expand to other Asia Pacific countries such as China and India in the next two to three years. Printed Power has also identified Israel and the U.S. as key markets, and plans to move in there subsequently.

Solving a real-world problem: COMMLIGHT

SERIS, the Solar Energy Research Institute of Singapore, is an industry-focused research centre at the National University of Singapore, funded by the National Research Foundation through the Singapore Economic Development Board. One of its research projects was to create a high-efficiency yet low-cost solar-powered streetlight with strong reliability and durability so it can be deployed in remote and rural areas where the electric grid is not available. SERIS' approach was to develop an integrated solar streetlight where the solar panel, battery, lights, and power electronics were housed in a single enclosure. The innovation was eventually documented and filed as a patent.

Given the huge potential of its usage in developing countries, in 2013 SERIS decided not just to license the technology, but to create a spin-off company—Fosera Lighting Pte Ltd—to commercialize the technology out of Singapore. The invention with its innovation and new design approach drew strong interest from investors, and the first products under the COMMLIGHT brand were launched in 2014.[24] Since then, COMMLIGHT has grown its market to cover more than 35 countries.

The COMMLIGHT case study has aptly demonstrated that, in the journey from research and invention to the eventual commercialization of intangible assets, a critical success factor for any innovation-led enterprise is to have a novel patented technology with proven commercial merits to potential investors. Fundamentally, the product must address a market need so that there is a ready demand for the product when the solution is offered.

Completing the innovation value chain with IP

A world-class legal framework and robust IP regime are fundamental enablers that are necessary to creating a Living Lab. Singapore

BOX 1

Methodology

Leveraging its in-house patent search and examination expertise, IPOS-International (IPOS-I) developed the patent analytics capability to serve the needs of the Singapore government. Since then, IPOS-I has partnered with several public agencies to help solve organizational challenges, identify worldwide trends, and spot areas of opportunity as well as support Singapore's R&D capability through patent landscape analytics. This box broadly describes the methodology used in this chapter.

Dataset and search

The dataset comprises worldwide patent applications relating to photovoltaic (PV) technologies encompassing upstream silicon ingot and wafer manufacturing; mid-stream PV cell-, module-, and system-level inventions; and downstream PV-hybrid plants and PV-grid integrations published from 2008 to 2017. The dataset was retrieved on 11 December 2017 from the Derwent World Patents Index™ (DWPI), which is one of the most comprehensive databases containing patent applications and grants from 44 of the world's patent issuing authorities. A 'DWPI patent family' is a group of patent applications and patents related to the same invention. The search strings used incorporated combinations of keywords (and their variants) and/or patent classification codes and indexing—for example, International Patent Classification (IPC) and Cooperative Patent Classification (CPC).

The main keywords used are:

- Solar, photovoltaics; cell, film, panel, module, array, concentrator, system, farm, plant
- Floating platform, structure, lake, waterbody, water surface, reservoir, offshore, pond, pool
- Predict, forecast, outlook, future, trend, anticipate, estimate; sunlight, solar irradiance, solar radiation, weather, cloud, atmosphere
- Optimize, distribute, regulate, manage, control
- Main IPC/CPC codes used are:

H01L-031/04, H01L-031/05, H01L-031/06, H01L-031/07, H02S, Y02B-010/1, Y02E-010/5, Y02E-010/6.

Counting inventions by number of unique DWPI patent families

The patent landscape analysis report counts the number of inventions by the number of unique DWPI patent families. Counting individual patent applications will inevitably result in double counting because each patent family may contain dozens of patent publications if the applicant files the same invention for patent protection in multiple destinations. Therefore, analyses based on counting one invention per DWPI patent family can reflect innovation productivity more accurately.

Categorization of technology sub-domains

Categorization of individual DWPI patent families into respective technology sub-domains was carried out based on patent classifications codes.

Manual review

At each stage—that is, search, data cleaning, and categorizing technology sub-domains—a manual review was carried out to ensure the relevance and the accuracy of the data.

has traditionally done well in these areas.[25] However, IP can go much further in driving innovation. The research, development, and test-bedding of technology comprise but the first half of the innovation value chain. To create a positive impact on society, technologies must be brought to market.

Leveraging Singapore's conducive business environment and extensive global networks, IPOS has evolved from its traditional role as a registry and regulator to become a builder of Singapore's innovation ecosystem. It does so by working with other public agencies and enterprises to use IP as an enabler to transform ideas to assets to the market.

At the policy level, IPOS is working closely with public agencies such as the National Research Foundation, A*STAR, and many others that are involved in managing research projects or driving innovation in their respective fields to develop the National IP Protocol. The new IP Protocol lays down key principles and guidelines on how agencies should manage government IP. The protocol makes it clear that agencies should focus on IP commercialization by allowing the industry access to publicly funded R&D to create and capture greater economic value for Singapore.

IPOS is also deeply involved in helping realize the value of Singapore's IP assets. Through the

IPOS subsidiary IP ValueLab (IPVL), the agency is lending its deep technical IP knowledge to the rest of the government agencies in the areas of identifying, developing, and managing their portfolio of intangible assets that result from their innovation activities. A team of IP management consultants are tasked to advise and work with various government agencies to identify, evaluate, manage, and eventually create value from their intangible assets.

Since the beginning of the year, IPVL has also intensified its engagements with Singapore-based enterprises to assist them in identifying and growing their intangible assets so that they can scale up and grow internationally. In Singapore's recent update to its IP Hub Master Plan, where IP commercialization was identified as one of its key strategic thrusts, IPOS has committed to provide customized one-on-one IP audit and IP strategy assistance to 150 companies.[26]

To equip local businesses with IP know-how and management expertise, IPOS has partnered with the Singapore Business Federation, Singapore's largest business association, to help some 25,000 of its members access its suite of IP services. These include IP training and education as well as advisory services in IP management and strategy.

This suite of IP services complements Singapore's value proposition as a Living Lab, completing the innovation value chain to bring tangible socioeconomic benefits to the society. As it transforms into an innovation agency, IPOS will continue to innovate and update its service offerings to support local and global innovators.

Conclusion

Using Singapore and PV technologies as an example, this chapter has shown how small countries can play an outsized role in driving innovation.

The Living Lab concept can create a significant value to small countries in enabling experimentation, innovation, and collaboration among global innovators, allowing them to rapidly develop, test, and deploy new technologies in their innovation ecosystems. In feeling the pulse of the global innovation landscape, policy makers and enterprises can look at patent analytics and landscaping as a useful decision-making instrument to gain a keen understanding of business or economic sectors where they intend to direct their R&D efforts and investments.

It is clear that the national IP office plays a critical role in developing a vibrant innovation ecosystem by creating a robust legal framework and IP regime. Beyond this, the IP office can complete the innovation value chain by working with other public agencies in the ecosystem, lending its deep IP expertise to enterprises to enable them to bring their technologies to market, and transforming ideas to strategic assets.

Notes

1 Ministry of Environment and Water Resources, Singapore, 2016.

2 IEA, 2017b.

3 IEA, 2016b, p. 407.

4 IEA, 2017a.

5 Bloomberg New Energy Finance, 2017.

6 Bloomberg New Energy Finance, 2017.

7 Frankfurt School, 2016, p. 20.

8 IRENA, 2017.

9 Energy Research Institute, 2015, p. 11.

10 Reuters, 2017.

11 Bajpai, 2017.

12 IEA, 2015, pp. 21, 87.

13 Prayas (Energy Group), 2015, p. 2.

14 Nanyang Technological University, Singapore, 2016.

15 EMA, Singapore, 2017a.

16 PUB, Singapore, 2017.

17 National Research Foundation, Singapore, 2016.

18 Singapore Institute of Technology, 2017.

19 REC Group, Singapore, 2016.

20 Fraunhofer ISE, 2017.

21 Ministry of Trade and Industry, Singapore, 2017.

22 Information about the Economic Development Board, Singapore, is available at https://www.edb.gov.sg/en/our-industries/urban-solutions-and-sustainability.html.

23 EMA, Singapore, 2017b.

24 Information about COMMLIGHT is available at www.commlight.net.

25 For example, see the Intellectual property protection ranking in the World Economic Forum's Global Competitiveness Index 2017–2018, available at http://reports.weforum.org/global-competitiveness-index-2017-2018/competitiveness-rankings/#series=EOSQ052.

26 IPOS, 2017.

References

Bajpai, N. 2017. 'India Takes Giant Leap on Green Energy Targets'. Special Feature, 8 May. Press Information Bureau, Government of India. Available at http://pib.nic.in/newsite/printrelease.aspx?relid=161622.

Bloomberg New Energy Finance. 2017. *New Energy Outlook 2017.* Available at https://about.bnef.com/new-energy-outlook.

EMA (Energy Market Authority), Singapore. 2016. *Singapore Energy Statistics Booklet 2016.* Singapore: EMA. Available at https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES%202016/Booklet_Singapore_Energy_Statistics_2016.pdf.

——. 2017a. 'EMA Awards $6.2 Million Research Grant to Develop Solar Forecasting Capabilities'. Energy Market Authority Press Release, 23 October. Available at https://www.ema.gov.sg/media_release.aspx?news_sid=20171020Hat9GRnq0wX7.

——. 2017b. 'Launch of Regulatory Sandbox to Encourage Energy Sector Innovations'. Energy Market Authority Press Release, 23 October. Available at https://www.ema.gov.sg/media_release.aspx?news_sid=20171020Wab84AqS9NXY.

Energy Research Institute. 2015. *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study: Executive Summary.* 15 April. Energy Foundation and Energy Research Institute, National Development and Reform Commission. Available at http://www.efchina.org/Attachments/Report/report-20150420/China-2050-High-Renewable-Energy-Penetration-Scenario-and-Roadmap-Study-Executive-Summary.pdf.

Frankfurt School. 2016. *Global Trends in Renewable Energy Investment 2016.* Frankfurt am Main: Frankfurt School-UNEP Collaborating Centre for Climate & Sustainable Energy Finance. Available at http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lowres_0.pdf.

Fraunhofer ISE (Institute for Solar Energy Systems).2017. 'VDE Renewables, Fraunhofer ISE, ERI@N Launch Global Initiative for Energy Storage at the Asia Clean Energy Summit in Singapore'. Press Release #19, 24 October. Available at https://www.ise.fraunhofer.de/en/press-media/press-releases/2017/vde-fraunhofer-ise-and-erian-launch-global-initiative-for-energy-storage.html.

IEA (International Energy Agency). 2015. *India Energy Outlook: World Energy Outlook Special Report.* Available at https://www.iea.org/publications/freepublications/publication/IndiaEnergyOutlook_WEO2015.pdf.

——. 2016a. *Snapshot of Global Photovoltaic Markets 2016.* Report IEA PVPS T1-312: 2017. IEA. Available at http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2016__1_.pdf.

——. 2016b. *World Energy Outlook 2016: Part B Special Focus on Renewable Energy.* Available at https://www.iea.org/media/publications/weo/WEO2016SpecialFocusonRenewableEnergy.pdf.

——. 2017a. *Renewables 2017: A New Era for Solar Power.* Available at https://www.iea.org/publications/renewables2017.

——. 2017b. *World Energy Outlook 2017.* IEA Publications. Available at https://www.iea.org/weo2017.

IRENA (International Renewable Energy Agency). 2017. '2016 a Record Year for Renewables, Latest IRENA Data Reveals'. IRENA Press Release, 30 March. Available at http://www.irena.org/newsroom/pressreleases/2017/Mar/2016-a-Record-Year-for-Renewables-Latest-IRENA-Data-Reveals.

IPOS (Intellectual Property Office of Singapore). 2017. *Update to the Intellectual Property Hub Master Plan.* May. Government of Singapore and Intellectual Property Office of Singapore. Available at https://www.ipos.gov.sg/docs/default-source/about-ipos-doc/full-report_update-to-ip-hub-master-plan_final.pdf.

Ministry of Environment and Water Resources, Singapore. 2016. Opening Address by the Minister for the Environment and Water Resources Mr. Masagos Zulkifli at the opening ceremony of the Asia Clean Energy Summit Conference and Exhibition on 25 October 2016. Available at https://www.mewr.gov.sg/news/opening-address-by-mr-masagos-zulkifli--minister-for-the-environment-and-water-resources--at-the-opening-ceremony-of-the-asia-clean-energy-summit--conference-and-exhibition--25-october-2016.

Ministry of Trade and Industry, Singapore. 2017.Opening Remarks for the Asia Clean Energy Summit (ACES) Opening Ceremony by SMS Koh Poh Koon. Available at https://www.mti.gov.sg/NewsRoom/Pages/Opening-Remarks-for-the-Asia-Clean-Energy-Summit-(ACES)-Opening-Ceremony-by-SMS-Koh-Poh-Koon.aspx.

Nanyang Technological University, Singapore. 2016. 'NTU to Build an Offshore Integrated System of Renewable Energy Sources'. Nanyang Technological University Media Release, 25 October. Available at http://media.ntu.edu.sg/NewsReleases/Pages/newsdetail.aspx?news=830aa91e-aa88-4c7b-8f95-00c171c17560.

National Research Foundation, Singapore. 2016. *Research, Innovation and Enterprise 2020 Plan: Winning the Future through Science and Technology.* Available at https://www.nrf.gov.sg/rie2020.

Prayas (Energy Group). 2015. 'Coal and Thermal Power Generation: Inputs to National Energy Policy 2015', November. National Institution for Transforming India, Government of India. Available at http://indiaenergy.gov.in/wp-content/uploads/2017/10/Coal-and-thermal-power-generation-Inputs-to-National-Energy-Policy-2015.pdf.

PUB (Public Utilities Board), Singapore. 2017. 'PUB Studying Clean Energy Solutions from Blue Spaces'. PUB Press Release, 28 September. Available at https://www.pub.gov.sg/news/pressreleases/pubstudyingcleanenergysolutionsfrombluespaces.

REC Group, Singapore. 2016. 'REC Furthers 'Sunny Commitment' with S$250 Million Investment in Singapore'. REC Newsroom Press Release, 30 March. Available at https://www.recgroup.com/en/rec-furthers-%E2%80%98sunny-commitment%E2%80%99-s250-million-investments-singapore.

Reuters. 2017. 'China to Plow 361 Billion into Renewable Fuel by 2020'. *Reuters: Environment,* 4 January. Available at https://www.reuters.com/article/us-china-energy-renewables/china-to-plow-361-billion-into-renewable-fuel-by-2020-idUSKBN14P06P

Singapore Institute of Technology. 2017. 'Singapore's First Experimental Urban Micro-Grid Targets Zero Emission'. *Digital Newsroom,* 23 October. Available at https://www.singaporetech.edu.sg/digitalnewsroom/singapores-first-experimental-urban-micro-grid-targets-zero-emission.

UN DESA (United Nations, Department of Economic and Social Affairs). 2017. *World Population Prospects: The 2017 Revision.* Available at https://esa.un.org/unpd/wpp/.

CHAPTER 12

INNOVATION AS THE DRIVING FORCE FOR CHINA'S RENEWABLE ENERGY POWERHOUSE

Baoshan Li, China Renewable Energy Society (CRES)
Lijuan Fan, Department of International and Regional Cooperation, China National Renewable Energy Centre (CNREC)

There is a consensus among the international community that energy transition is the key to addressing climate change and simultaneously maintaining an approach to economic growth and social development that aims at efficiency, harmony, and sustainability. Progress in renewable energy (RE) technology, in turn, is both the key driving force and a core element of further energy transition. Almost all major economies of the world have put forward their objectives, supportive policies, and measures to keep RE development moving ahead. European Union leading members Denmark and Germany; authorities of some states of the United States of America (U.S.) such as California, as well as Australia, India, Japan; and even Saudi Arabia and the United Arab Emirates, the primary oil and gas producers in the Middle East, are all proactive in the innovative development of RE sources. Most countries in the world have officially joined the Paris Agreement with its commitment to sustainability through the de-carbonization of the energy system. Forty-seven countries most vulnerable to climate change have proposed a target of realizing 100% RE sources by 2030–50.

As a top consumer and producer of energy, China is experiencing a transition from the traditional approach of coal dominance with its high environmental cost to a low-carbon, environment-friendly system. The Chinese government has developed a comprehensive package of strategic policies and measures to promote an overall transition of the energy system towards sustainability and low carbonization, with the goal of raising the share of non-fossil energy to 15% of primary energy consumption by 2020, and to 20% by 2030.[1]

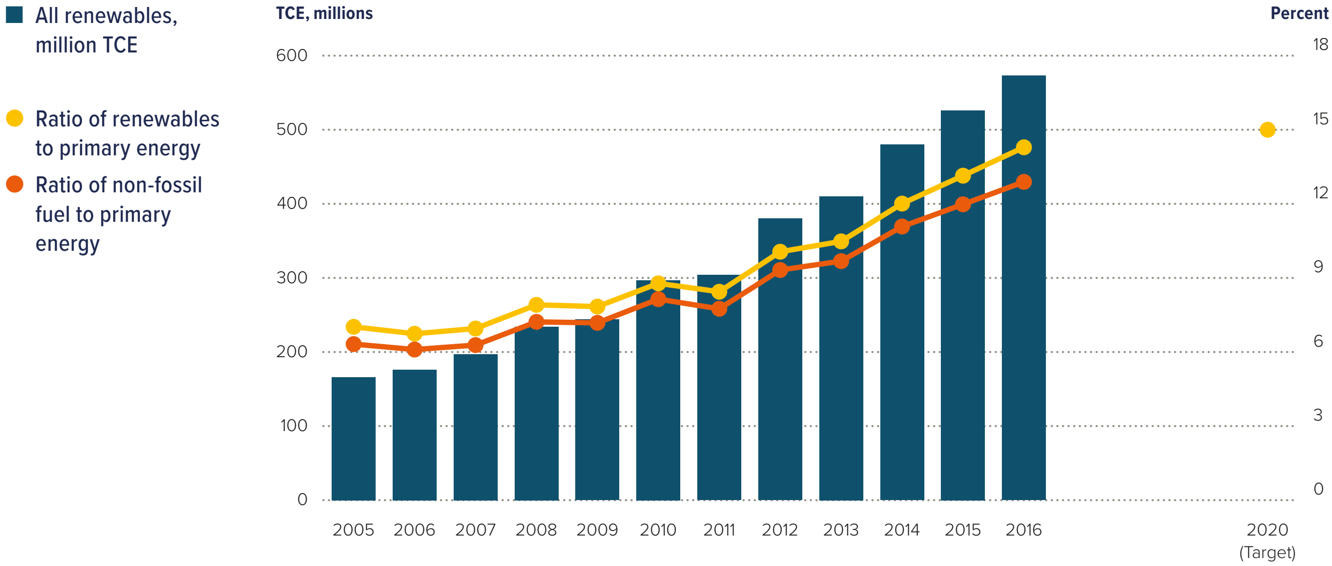
Closely linked to the national energy transition, RE relies on innovative development to efficiently reduce the consumption of coal. Long-lasting policies and measures can safeguard the development of RE technology and industrial innovation, whereas diversified and locally suitable business models along with innovative financial tools will undoubtedly facilitate cost reduction, commercialization, and expansion of its technology.

Innovative development in China's RE sector

In recent years China has enjoyed rapid growth in the RE sector, setting new records in both installed capacity and electric power generation and bringing about a continuous

Figure 1.

China's renewable energy usage, 2005–16



Source: CNREC, 2017b.

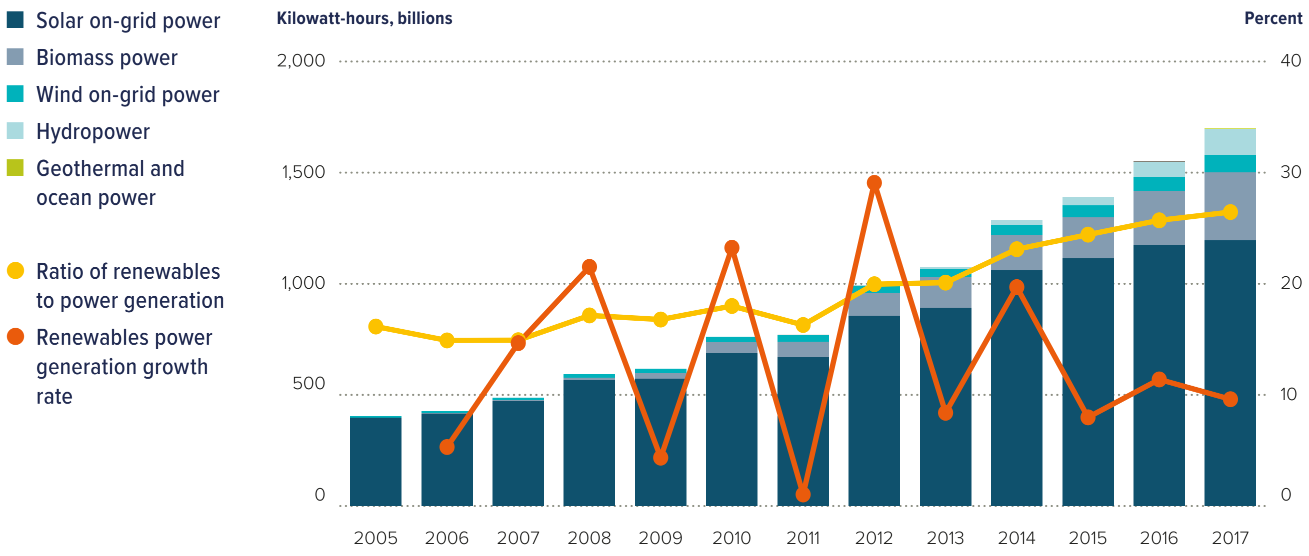
Note: 'Primary energy' is energy that is used directly in its natural form, without any modification. Examples are raw coal, crude oil, natural gas, hydropower, and wind and solar energy, among others. Primary energy is divided into renewable (such as wind and solar) and non-renewable (such as fossil and nuclear) sources. TCE = metric tonnes of coal equivalent.

evolution of its energy structure, resulting in a constantly increasing proportion of non-fossil energy. The total installed capacity of RE power generation grew to 570 million kilowatts (kW) from the 254 million kW of 2010; the proportion of RE electric power generation in total electric power generation rose from 26% in 2010 to 34.6% in 2016. Total renewable electric energy generated in 2016 was over 1.5 trillion kilowatt-hours (kWh), 25% of the national total, compared with 18% of that in 2010. In 2016, China's total energy consumption amounted to 4.36 billion metric tonnes of standard coal equivalent (TCE), with a distribution of 62% coal, 21% oil, 6% natural gas, and 13% non-fossil, of which RE took up 11% of the total.[2] That year, the total RE for commercial use (including all types of electric power and bioliquid fuels) equalled 480 million TCE, approximately 10.8% of the country's total energy consumption.[3] Wind and solar power together provide more than 10% of the total electric power supply in the provinces of Inner Mongolia, Qinghai, and Gansu, providing the greatest share of newly added sources of electric power. Figures 1 and 2 show the history and current status of China's RE source usage and electric generation.

Over the past decade, China has played a significant role in global renewable energy development. In 2008, China ranked 5th worldwide in the amount of wind-generated electric power. In 2011, the country moved up to 2nd place, next only to the U.S., and in 2016, it overtook the U.S. to reach 1st place.[4] Solar photovoltaic (PV) generation also increased quickly from 2014 through 2016, when China replaced the U.S. at the top in this metric. By the end of 2016, China boasted the highest installed capacity of RE sources in the world: it came in 1st globally in the hydropower installed capacity for many years in a row; it was on top in total wind power installations and total solar thermal heat usage for five consecutive years, and it has been number 1 in PV since 2011 with the exception of 2014, when it fell behind.[5]

Figure 2.

China's renewable energy electricity generation, 2005–16



Source: CNREC, 2017b.

Note: There are no available data for the growth rate of renewable power generation for 2005.

As the key force for energy transition, RE is also one of the major instruments used to address climate change. With its commitment to the Paris Agreement, the Chinese government set the goal, with 2005 as the baseline, of reducing its carbon intensity by 45% by 2020 and 60% by 2030. This means that China must make tremendous efforts to reduce carbon emissions. Boosting RE sources would certainly be a critical factor contributing to this goal. Additional goals include investing 41 trillion RMB (US$6.7 trillion) from 2005 to 2030. Of that amount, 10.4 trillion RMB had already been invested from 2005 to 2015. An additional 30 trillion RMB is projected to be invested between 2016 and 2030.[6] All these efforts have established a sound political environment and broad market space to address issues of climate change and sustainable development. To effectively implement its commitment to addressing climate change, China believes that replacing the fossil-fuel dominated energy system with a clean, low-carbon, RE system is a necessity.

For this purpose, China has announced the *Development Plan on Renewable Energy* and set a target of non-fossil energy providing up to 15% of the primary energy demand by 2020, including hydropower (with 340 million kW), wind power (with 210 million kW), solar PV (with 105 million kW), solar thermal power (with 5 million kW), and biomass (with 15 million kW)—together totalling 675 million kW.[7] By 2030, 20% of total primary energy consumption will be from non-fossil energy sources.

Innovation: China's key driver of RE development

Innovation in policy setting stands as the cornerstone of RE and safeguards its development.

Policy innovations

In 2005, based on a thorough investigation of the existing situation and a review of experiences at home and abroad, China promulgated the Renewable Energy Law, which established the legal basis for the country's RE development. The law has put forward a series of innovative provisions, especially the terms of the 'full purchase' and 'feed-in tariff' provisions.[8] With this legal framework, in the RE resource-rich and generation-intensive regions (such as Northeast, Northwest, and North China), high-power direct current transmission networks were erected to realize the West Electricity Supplying East programme, thus providing the necessary infrastructure for the full purchase of renewable energy electricity. The most important determining factor for scaling up the development of RE is its cost. By bidding and other means, China finalized the feed-in tariff for the main RE power generation technologies, such as wind power and solar PV power, so that their costs reflect the characteristic costs of these resources in China. The feed-in tariff has effectively reduced the cost of wind power and solar PV power, driving onshore wind and solar PV power technology to become the first non-hydro RE technologies commercialized in China, and thus contributing to the global effort of cost optimization of wind power and PV power.

The most important determining factor for scaling up the development of RE is its cost.

For many years, China has supported innovative technology in RE development, establishing special funds for it, giving tax exemptions to businesses that use their own funding to invest in innovative technologies, and offering favoured tax status to high-tech and mini and micro businesses.

State-level innovation programmes and pilot projects drive RE technology into scaled-up development and industrialization. The Ministry of Science and Technology has long prioritized RE technology as one of the areas to receive national innovation funding.[9] Notably, programmes that aim to promote the industrialization of these technologies, such as the Solar Leading Runner and the Solar PV Alleviating Poverty programmes, are organized by national energy authorities and local governments. These select and apply advanced technical and market-competitive products through bidding and guide the application of innovative technology, boosting PV industry as a whole.

The scale of the RE industry is expanding, the cost of the technology is decreasing, and policies and measures are being adjusted and modified at appropriate times in the course of RE development. Tariff support for RE electricity has decreased each year since 2015, leaving relevant businesses to face more pressure to make a profit. Under the policy guidance, RE industries have become more motivated to continue technical innovations, develop new products and new technology, and lower costs. These industries have also enhanced their technical capabilities and business management skills. As the governing body for China's RE industry, in 2017 the National Energy Administration proposed establishing a voluntary purchase system for acquiring RE green power certificates and planned to commence power-quota assessment and qualification procedures to mandate the regulation of transactions at the proper time, thus further reducing demand for RE funding support. In the meantime, the policy and regulations also guided enterprises that performed well to obtain a greater market share and helped to secure RE as a stable space for growth.

Technical innovations

Technical innovations are a direct boost to the advancement of China's RE industry. RE technologies, integrated with cross-boundary technologies, preliminarily require technical innovations and adaptive fusions. The field of global RE technology was first explored in Denmark, Germany, and the U.S.; China's RE development began in technology exchanges with Europe and the U.S. As early as the 1980s, China engaged in exchanges with Denmark and Germany over wind turbine technology and human capacity building. With RE industry development, China's innovative capacity for these technologies has consistently improved.

China has carefully prioritized the development of RE technologies with a promising market and rapidly advancing and significant industrial scale-up expansion. For example, the country's wind turbine design technology went through a long process that began with engaging in direct imports, then purchasing licenses, innovating in components, and finally engaging in internal R&D by local producers. Now China has established a complete production chain with the largest production capacity in the world. A set of high-capacity units, such as those with 1.5 to 3 megawatt (MW) unit capacity, is technically a mature batch product. A larger unit with a capacity of 3.6 to 5 MW can also be produced in quantity. Production capacity of most wind turbine components is up to an internationally advanced level and could meet all the requirements of mainstream models. Technology concerned with bearings, inverters, and control systems also has greatly improved.[10]

In 2016, China exported 319 wind turbines, with a total capacity of 550,000 kW. By end of 2016, 28 countries—including Australia, Pakistan, and the U.S.—had imported 1,404 wind turbines from China, with a total capacity of 2,580,000 kW.

China values intellectual property rights protection to encourage RE innovation. The yaw system wind turbine provides an example.[11] Statistics show that, from 2000 to 2007, patent applications for yaw systems in China and Japan witnessed the fastest increase in the world.[12] From 2007 to 2012, there were 1,203 patent applications worldwide related to the yaw system. China had the biggest share, with 318 applications. The rapid growth of patent applications occurred in the fastest-growing period for wind turbines in China.

Innovation suitable to China's national conditions and practical needs is the essential element in its development of RE technology. For example, when China carried out R&D in wind turbines, special attention was paid to meeting the needs created by the country's diverse wind resources, geographic terrains, and market demands. As a result, China has successfully developed turbines that can accommodate various wind-status conditions and terrains in China, including those characterized by low wind speed, high altitude, tidal zones, and coastal areas.

Business and financial model innovations

Innovations in commercial and financial models are instrumental in the RE scale-up, which calls for constant innovation in business models and the participation of both public and private capital. Total investment in China's RE for 2016 amounted to US$78.3 billion. Not counting large hydropower, the Chinese market share was 32% of total RE investment worldwide. In terms of type of investment, the majority—US$72.9 billion—made in 2016 was still asset financing; financing for small and distributed PV projects reached US$3.5 billion,[13] an increase of 32% over 2015. This success demonstrates that China has adopted a two-pronged approach: one prong is securing quick growth by building major PV stations, and the other prong is supporting the development of distributed PV stations with innovative financing models.

Challenges and countermeasures to the development of RE innovation in China

China has made remarkable progress in the development of RE, but it still faces many challenges. The following issues require the attention of policy makers as well as businesses.

First issue: RE development may grow too quickly, leading to an imbalance between supply and demand. In this case, renewable power generated could not be consumed locally, and could not be integrated into power grids to be transmitted to fulfil long-distance demand, giving rise to problems of curtailed wind or PV electric power. The problem of generating so much renewable power that it exceeds local demand and cannot be integrated into power grids has occurred especially in regions of Western China with abundant RE sources, where more than 20% of the wind or PV power is curtailed. To resolve this problem, the government needs to speed up building infrastructure such as extensive power-transmitting lines. At the same time, enterprises with large power consumption needs should be incentivized to set up production bases in the Western region, where they could benefit from cheaper, more favourable power rates. China should also accelerate the establishment of the power trading market and eliminate institutional obstacles to the development of RE, thus providing a fundamental market guarantee for the development of RE.

Technologically optimal integration of the whole energy system should be consolidated. Thanks to the Internet and other new technologies, RE will become a vital component of the distributed energy system. Power storage technology can play an active role for its flexibility in modulating the supply-demand of power, reducing wind/PV/electric abandonment.

Second issue: There are too many RE enterprises that are too big, especially manufacturers of PV power products such as batteries, panels, and so on, that produce more than can be consumed. These enterprises lead to surplus production and multiple pressures. The government should, on one hand, address this situation by guiding these enterprises to develop new products tailored towards an expansion to different domestic markets; on the other hand, it should encourage these enterprises to take their surplus to the overseas market and bid on international projects.

Third issue: Previous standards and regulations can hardly meet the demands of the fast-growing RE industry; failures have occurred in guaranteeing the quality and expected outcome of certain engineering projects. The government has come up with a solution by issuing the Measures on Encouraging Industrial Associations & Societies to Establish Standards & Regulations. These Measures should be implemented faithfully, thus facilitating the establishment and improvement of RE industry evaluation rules and standards and promoting the healthy and orderly development of the industry.

Fourth issue: There is a global consensus on the need for sustainable development. RE is an important means to achieving this. Because the RE sector has emanated from cooperation and depends on diversified innovation, China should continue to strengthen international cooperation in this sector with a view to achieving a win-win outcome, carrying out exchanges in technology, policy, and management; sharing best practices; and promoting innovation through cooperation and promoting cooperation through innovation.

Conclusions

China's practice demonstrates that innovation is the original driver of energy transformation and sustainable development. Innovation is also a core element of economic growth. China has become the first middle-income country to join the ranks of the world's 25 most innovative economies in 2016, according to the Global Innovation Index. This demonstrates that China has developed quite a robust innovation capacity and exhibits strong performances in many sectors. As one of China's national strategic decisions, the development of RE is an important path leading to eco-environmental improvement, a necessary choice for addressing climate change and an important step towards realizing energy transition and optimizing energy structure. In the future, China is predicted to continue its innovation in the RE sector with better performance, higher efficiency, and larger contributions, thus further promoting the sustainable development of humankind.

Notes

1 'Primary energy' refers to energy that is directly used without change or transformation, such as raw coal, crude oil, natural gas, hydropower, wind energy, solar energy, ocean energy, tidal energy, geothermal energy, natural uranium, and so on. Primary energy is divided into renewable energy and non-renewable energy. The former refers to natural energy that can be generated repeatedly, and includes solar energy, wind energy, tidal energy, and geothermal energy. The latter is mainly composed of fossil fuels and nuclear fuel.

2 CNREC, 2017a, b.

3 CNREC, 2017a, b.

4 REN21, 2017.

5 REN21, 2017.

6 Jiang, 2016.

7 NDRC, 2016.

8 According to the Renewable Energy Law, the 'full purchase system' refers to the power grid companies (including electric power dispatching agencies), which shall fully purchase renewable electric power generated by planned and approved renewable energy projects based on the benchmark price of on-grid electricity and guaranteed utilization hours, combined with market competition mechanisms, through the implementation of priority power generation systems, without disturbance of secure power supply. See the management regulations on the guaranteed full purchase of renewable energy power issued by the NDRC, available at http://www.ndrc.gov.cn/zcfb/zcfbtz/201603/t20160328_796404.html (in Chinese).

According to the same Renewable Energy Law, the 'fee-in tariff system' is regulated by the NDRC and defined by bidding or other means.

9 The two national programmes on innovation, established by the Government of China and implemented by the Ministry of Science and Technology, targeted the basic R&D of strategic and foresighted technologies, especially the high-priority issues faced by the country's economic and social development concerns.

10 CNREC, 2017a, b.

11 The yaw system is responsible for keeping the blades of the turbine oriented toward the wind.

12 Rentian Zhang and Hong Wei, 2017.

13 UNEP and BNEF, 2017.

References

CNREC (China National Renewable Energy Centre). 2017a. *China Renewable Energy Industry Development Report 2017.* Beijing: China Economic Publishing House. (In Chinese.)

——. 2017b. Handbook 2017 of Renewable Energy Data'. Internal document. China National Renewable Energy Centre.

Jiang, T., editor. 2016. 'Xie Zhenhua on China Will Invest 30 trillion RMB to Address Climate Change in the Next 15 years'. *Xinhuanet*. (In Chinese.) Available at http://www.xinhuanet.com/world/2016-04/23/c_128923516.htm.

NDRC (National Development and Reform Commission). 2016. The Notice on Issuing the 13th Five Year Planning for Renewable Energy Development. Beijing: China National Development and Reform Commission. (In Chinese.) Available at http://www.ndrc.gov.cn/zcfb/zcfbtz/201612/t20161216_830264.html.

REN21 (Renewable Energy Policy Network for the 21st Century). 2017. *Renewables 2017 Global Status Report*. Paris: REN21 Secretariat. Available at http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf.

UNEP and BNEF (UN Environment and Bloomberg New Energy Finance). 2017. *Global Trends in Renewable Energy Investment 2017*. Frankfurt am Main: Frankfurt School of Finance and Management. Available at http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

Zhang, R. and H. Wei. 2017. 'Analysis for Yaw System of Wind Turbines'. *Wind Energy* 92: 32.

CHAPTER 13

COMMITMENT AND LEARNING IN INNOVATION

The Case of the First 500 kV Transformer Made in Viet Nam

Hung Vo Nguyen, National Institute for Science and Technology Policy and Strategy Studies (NISTPASS)

In the early 1990s a shortage of electric power generation capacity in the southern provinces of Viet Nam seriously hindered the economic development of the whole country. The long S shape of Viet Nam with its three distinct regions (North, Central, and South), each with its own separate electrical system, made it impossible to match surplus generating capacity in the North with consumer demand in the South. A proposal to construct a 500 kilovolt (kV) transmission line 1,500 kilometres (km) long from the North to the South was considered and approved by the Vietnamese government. The high voltage minimizes the energy lost by transmitting over such a long distance, making the project economically viable. The line was constructed in record time—only two and a half years—and began operation in May 1994. It immediately resolved the problems of electricity shortages in the South. In the following years, the 500 kV transmission network was expanded and now plays a substantial role in harmonizing the supply of electricity in the country.[1]

The strategic importance of 500 kV transformers in Viet Nam

Transformers capable of handling 500 kV step up and step down the voltage at connections between the 500 kV network and the remainder of the network. A malfunction in a 500 kV transformer can lead to power loss for an entire region for a long period. Repair can take several months; replacing the transformer would also take time and money. For these reasons, 500 kV transformers are considered to be critical equipment for the security of the line and for the entire electrical power system.

In Viet Nam, 500 kV transformers from a number of manufacturers have been used. The original 500 kV power line constructed in the 1990s had five transmission stations, each equipped with a 500 kV transformer supplied by a French manufacturer.[2] Since beginning operation in 1994, the 500 kV transmission line has been expanded several times, each time with different vendors and different 500 kV transformers. Because it is a highly sophisticated piece of equipment, only a limited number of countries (including China, France, Germany, the Republic of Korea, the Russian

Federation, and Switzerland) can manufacture 500 kV transformers, and prices are high.[3]

Because 500 kV transformers play a strategic role in the national power system and the demand for them was high, and because imported transformers were very expensive, the Vietnamese government decided to encourage their domestic manufacture. The first of the domestically manufactured 500 kV transformers was a three-phase one with a total capacity of 450 megavolt amps (MVA) (3 × 150 MVA).

Because 500 kV transformers play a strategic role in the national power system and the demand for them was high, and because imported transformers were very expensive, the Vietnamese government decided to encourage their domestic manufacture.

The challenges of designing and manufacturing 500 kV transformers locally

The operation of 500 kV transformers creates super-high-voltage electric fields. These transformers also need to be able to survive voltages up to 1,550 kV in the event of a lightning strike or short circuit, so the equipment must have precisely positioned and engineered electric field shields. The higher the capacity of the 500 kV transformers, the more shields are needed and the more sophisticated the design has to be. Even a small fault in design or manufacture can lead to the failure of the entire system. According to an interview in 2018 with Chief Designer Nguyet, a foreign company with a research and development (R&D) team of eight staff with post-doctoral degrees and 34 engineers failed three times before succeeding on their fourth attempt to design and manufacture a 500 kV transformer.[4] The design of the number of shields, their shape and size, and their arrangement in the structure of the apparatus are all critical: on one hand this allows the transformer to function well and on the other hand it allows the system itself to be easily manufactured. Because the designs of 500 kV transformers are companies' proprietary information, designing the first 500 kV transformer locally was a major challenge. In addition, the capacity of 450 MVA (3 × 150 MVA) of the targeted 500 kV transformer created additional challenges because the required number of electric field shields for this capacity are much higher (21 in this machine compared with only 2 in the transformer in Yali).[5]

Manufacturing presented another challenge. The problem was how to adjust and upgrade existing manufacturing facilities so that such a complex, high-precision 500 kV transformer could be constructed with minimum costs for upgrading the facility.

The process of accumulating knowledge

Dong Anh Electrical Equipment Corporation - Joint Stock Company (EEMC) is a local Vietnamese company that specializes in the manufacture and repair of electric transformers of all kinds. Many of its technical staff members have been trained in top technical universities in Viet Nam and overseas. Some have had experience working in leading research and manufacturing organizations in the Russian Federation, which has given them valuable practical knowledge as well. In Viet Nam, this company's technical staff are considered leading experts in the field.[6]

Having had many opportunities to repair imported transformers made by various manufacturers, and with a good theoretical foundation, gradually EEMC's staff increased their understanding of the functional features of transformers and the theoretical and practical basis for their design and manufacture. In 1994, EEMC successfully developed the first locally made 110 kV transformers. This was a great achievement at that time and helped EEMC win the trust of the top business and government leaders. The firm was then given a contract to develop a 220 kV transformer. Nguyen Thi Nguyet, the project's chief designer, reported that while developing the 220 kV transformer a proposal to spend US$1 million to buy a design from a foreign firm was considered, but that proposal was not approved and EEMC went on to make the 220 kV transformer without foreign assistance.[7] By the early 2000s, EEMC had become a leading local supplier of this equipment.

In 2005 the company encountered a unique learning opportunity when the single-phase 500 kV transformer with a capacity of 72 MVA at the Yaly Hydropower Plant needed repair. The equipment had been manufactured in Ukraine, and it would have taken 16 months to repair if it had been sent back to the original manufacturer. EEMC proposed making the repair in Viet Nam, but it was awarded the contract only after agreeing to complete the repair within three months. EEMC successfully repaired that first transformer and proceeded to repair other low-capacity 500 kV transformers in subsequent years. Experience and knowledge learned while repairing other manufacturers' equipment gave EEMC the confidence to design and manufacture its first 500 kV transformer locally.

The project: To design and manufacture the first 500 kV transformer in Viet Nam

In 2008 EEMC requested, from the Ministry of Industry and Trade and the Ministry of Science and Technology, a 15 billion Vietnamese dong (VND) grant to be matched by its own investment of 62.338 billion VND for the design and manufacture of a 500 kV transformer.[8] Because of the strategic importance of 500 kV transformers in the Vietnamese power system, the grant was approved. In addition, EEMC had access to the national high-voltage laboratory, which has the capability of testing electrical equipment up to 500 kV; the laboratory is located just next to its factory. The project formally began in November 2009 and finished in October 2010. In November 2011, the first locally made 500 kV transformer was installed and began operation in the Nho Quan transmission station in Ninh Binh. The 500 kV transformer strictly followed International Electrotechnical Commission (IEC) 60076:2000 standards for a power transformer.[9] The high-voltage national laboratory in Hanoi and various laboratories of the Quality Assurance and Testing Centre 1 of the Directorate for Standards, Metrology and Quality carried out necessary testing for 19 key specifications of the transformer. The testing verified that the transformer functioned correctly and met the design specifications.[10]

According to the R&D team that designed and manufactured the first locally made 500 kV transformer, the design work was a process of creative problem solving. The team had extensive knowledge of 220 kV transformers and some knowledge of lower-capacity 500 kV transformers from repairing them. However, designing a 500 kV transformer with a higher capacity (one with 3 × 150 MVA) was something new and required a design grounded in first principles. Starting with the basic structure observed in similar equipment in China, the team first developed a design concept with an asymmetric structure, then the physical design, and finally the detailed design.[11]

The team received support during the design process from a Russian consultant whom the chief designer of the team had met at Yali when both EEMC and the original vendor were invited to the site to assess the damage to the broken 500 kV transformer and submit a proposal for its repair. Each time the team came up with a specific design, the consultant reviewed it and suggested improvements. Having more than 40 years of experience in the field and having developed software for calculating various parameters of 500 kV transformers, he proved to be an important resource for the team.[12]

To develop a working physical design of the 500 kV transformer, the team developed a small-scale prototype with similar technical features to test various aspects of the design as well as to collect data for establishing the relationship between key parameters.[13] As mentioned earlier, one of the most difficult issues encountered in designing a 500 kV transformer is the complex and precise arrangement of electric field shields. Another related problem is determining how to design such complex equipment so that it can be manufactured in already-existing production facilities that require the least expensive upgrading and also have low operational costs. For each of these issues, a creative solution was required.

Through the accumulated knowledge of EEMC, the commitment and hard work of the team, and the support of the foreign consultant, the 'learning-by-doing' process and creative problem solving bore fruit. The final EEMC design was considered by the Russian consultant to be very effective and efficient.[14]

In terms of manufacturing, the large size, complex structure, and precise arrangement of 500 kV transformers normally require advanced, sophisticated manufacturing facilities that were too costly for EEMC to acquire. The only available solution was to upgrade the existing 220 kV transformer factory to manufacture the 500 kV unit.

The electric wire used in the 500 kV transformer needs to be wrapped with insulating paper and the process must take place in a perfectly clean environment. EEMC adopted new technology allowing simultaneous wrapping with 21 layers of insulating paper in a closed chamber. After the successful application of the process to 500 kV transformers, the technique was also used to enhance the quality and reliability of the 220 kV transformers with improvements to various design and capacity elements.

Wiring around the huge magnetic cores of the 500 kV transformer also required a new solution. EEMC developed an innovative wiring machine to work with standing magnetic cores. The adjusted machine had a higher capacity than the previous one and was able to wire around magnetic cores that were around 3.5

One of the most difficult issues encountered in designing a 500 kV transformer is the complex and precise arrangement of electric field shields.

metres high. This innovative solution was completely original to EEMC.

The large size of a 500 kV transformer means that a huge quantity of thin magnetic steel plates is required. These plates need to be carefully positioned and rotated without altering their relative placement, among other positioning requirements. Commercially available equipment for this task was very expensive, so EEMC managed to modify the smaller equipment used for manufacturing the 220 kV transformer to enable it to handle the much larger elements used in the magnetic core of the of 500 kV one. This was an important incremental innovation in this project.[15]

Policy recommendations and takeaways

The successful design and manufacture of the first 500 kV transformer raised the confidence of scientists and engineers in Viet Nam in the electrical equipment sector. With this advance, Viet Nam entered the club of the few countries in the world that can design and manufacture such large transformers.[16] In Asia, only Japan, China, the Republic of Korea, India, and now Viet Nam have this capability. With the option of manufacturing locally, Viet Nam has improved its bargaining power in negotiating with international vendors in the 500 kV transformers market. The price of 500 kV transformers has dropped about 20% to 30% of previous prices since 2010.[17] Moreover, the security of the national power system has strategically improved, and the project has been successful in expanding Viet Nam's 500 kV lines over time.[18]

The knowledge acquired in during the course of the project has increased local capacity for maintaining and repairing such sophisticated equipment. The technologies and innovations developed for this project are now used to design and manufacture higher-quality 110kV and 220kV transformers, helping Viet Nam manufacturers to maintain their dominance with this range of products in the local market.

Viet Nam's completion of the project that researched, designed, and manufactured a three-phase 500 kV 3 ×150 MVA transformer was a great technological achievement.[19] The project's success proved that with the right commitment, local scientists and engineers can make extraordinary advances and contribute significantly to the economy. However, its economic success was not so clear, which raises the question of industrial policy related to this project. After the first 500 kV transformer, EEMC found it difficult to win contracts for future ones. So far EEMC has made only three 500 kV transformers. Once EEMC entered the market, foreign vendors—especially those from China—responded with price cuts on their own products. Since 500 kV transformers are usually only one piece of equipment in a larger bidding package, without joining with other vendors EEMC found it difficult to win contracts.

The inconsistency between the policy that supports local R&D efforts to make 500 kV transformers and the bidding policy that works in favour of large and financially powerful international vendors will need to be corrected, otherwise the success of the 500 kV transformer project with all its invaluable knowledge will soon fade away. Many tacit lessons learned and much knowledge generated from this project are in danger of being lost if they are not codified quickly and enhanced further. Knowledge management at both the firm and national level is not currently being sufficiently considered, and some measures must be taken to correct it.

Notes

1 Tran Viet Ngai, 2014.

2 Tran Viet Ngai, 2014.

3 MoST and MoIT, 2010.

4 Nguyet (Chief Designer), interviews, 2018.

5 Nguyet (Chief Designer), interviews, 2018.

6 EEMC management, interviews, 2017 and 2018.

7 Nguyet (Chief Designer), interviews, 2018.

8 Tran Manh Huong (EEMC Technology Department), personal communication, 2018.

9 The International Electrotechnical Commission (IEC) 60076:2000 standards provide technical specifications for power transformers. See https://fenix.tecnico.ulisboa.pt/downloadFile/845043405448082/IEC%20 60076-1%202000.pdf for further information.

10 MoST and MoIT, 2010.

11 Nguyet (Chief Designer), interviews, 2018.

12 Nguyet (Chief Designer), interviews, 2018.

13 EEMC management, interviews, 2017 and 2018.

14 Nguyet (Chief Designer), interviews, 2018.

15 MoST and MoIT, 2010.

16 As of 2011, according to EEMC's Technology Department, the 12 countries capable of manufacturing 500kV transformers were China, France, Germany, India, Italy, Japan, the Republic of Korea, the Russian Federation, Switzerland, Ukraine, the United States of America, and Viet Nam.

17 EEMC management, interviews, 2017 and 2018; Nguyet (Chief Designer), interviews, 2018.

18 MoST and MoIT, 2010.

19 MoST and MoIT, 2010.

References

EEMC management (Tran Manh Huong, Technology Department, and Le Van Diem, Vice-General Director), interviews with NISTPASS (National Institute for Science and Technology Policy and Strategy Studies), 2017 and 2018.

MoST and MoIT (Ministry of Science and Technology and Ministry of Industry and Trade). 2010. *Research, Design and Manufacture of Three Phases 500kV – 3x150MVA: Project Report.* Hanoi: Ministry of Science and Technology – Ministry of Industry and Trade. (In Vietnamese.)

Nguyet, Nguyen Thi (Chief Designer), interviews with NISTPASS (National Institute for Science and Technology Policy and Strategy Studies), 2018.

Tran Viet Ngai, President of Viet Nam Energy Association. 2014. *North – South 500 kV Transmission Line: A Bright Historical Milestone.* (In Vietnamese.) Available at http://nangluongvietnam.vn/news/vn/dien-luc-viet-nam/duong-day-sieu-cao-ap-500kV-bac-nam-mot-moc-son-lich-su.html.

SPECIAL SECTION

SPECIAL SECTION

IDENTIFYING AND RANKING THE WORLD'S LARGEST SCIENCE AND TECHNOLOGY CLUSTERS

Kyle Bergquist, Carsten Fink, and Julio Raffo, World Intellectual Property Organization (WIPO)

For the first time, the 2017 edition of the Global Innovation Index (GII) presented a ranking of the world's largest clusters of inventive activity.[1] Last year's effort was motivated by the recognition that innovation activities tend to geographically concentrate in specific clusters. Adopting this cluster perspective opens the door to better understanding the determinants of innovation performance that operate at the sub-national level.

The 2017 ranking offered insights on the spatial agglomeration of innovative activity, relying on a globally harmonized set of criteria. It was based on the geocoded addresses of inventors listed in patent filings under WIPO's Patent Cooperation Treaty (PCT). It then measured the size of the identified clusters by the number of PCT applications associated with the inventors present in a given cluster.

As acknowledged in GII's special section last year, patent data are an imperfect metric for inventive activity and an even less perfect metric for innovation activity more broadly. For this year's ranking, we took the first step towards widening the range of innovation metrics included in our research. In particular, we used the data on scientific publications compiled by Clarivate to enlarge the geospatial dataset we use and thus identify and measure broader science and technology clusters.

This chapter reports the results of our enriched analysis. We first briefly describe the scientific publication data and explain how we geocoded our data. We then discuss how we applied the DBSCAN algorithm and measured the size of clusters. We finally present this year's top 100 clusters and discuss key features of those clusters, and end with a few concluding remarks.

For additional background on the patent data we use and the choice of clustering methodology, we refer interested readers to the Special Section on Clusters published in last year's GII report.

Comments and suggestions from Hao Zhou and the participants of the Geography of Innovation Conference are gratefully acknowledged. The views expressed here are those of the authors and do not necessarily reflect those of WIPO or its member states.

Table 1: Summary of geocoding results

Country	Scientific publications: Number of addresses	Scientific publications: City-level address accuracy (%)	PCT applications: Number of addresses	PCT applications: Block-level address accuracy (%)	PCT applications: Sub-City-level address accuracy (%)	PCT applications: City-level address accuracy (%)	PCT applications: Total address accuracy (%)
United States of America	5,339,705	98.18	803,058	94.61	4.94	0.19	99.73
China	2,444,482	99.10	305,311	2.32	0.27	96.81	99.40
Japan	1,046,116	96.20	505,270	39.22	31.79	27.91	98.91
Germany	1,144,157	97.32	254,843	97.37	0.46	1.58	99.41
United Kingdom	1,135,996	96.53	75,484	78.83	5.59	12.81	97.22
France	977,704	92.78	103,013	85.16	1.35	7.10	93.62
Italy	883,205	95.48	39,345	85.86	4.76	7.67	98.28
Republic of Korea	661,015	93.10	185,861	0.17	0.76	82.20	83.12
Canada	724,727	98.63	41,091	96.66	2.27	0.60	99.53
Spain	668,199	96.59	26,791	66.58	8.30	23.50	98.39
Australia	641,940	86.27	19,410	92.42	5.10	1.16	98.69
India	526,411	96.18	35,147	32.79	39.18	22.28	94.25
Brazil	499,076	98.77	8,526	77.73	13.02	7.49	98.24
Netherlands	433,044	97.30	48,506	91.01	0.68	7.67	99.36
Turkey	341,875	96.66	9,024	27.26	50.8	17.00	95.06
Switzerland	261,694	90.86	34,227	86.90	6.54	5.30	98.74
Russian Federation	279,909	99.09	15,347	81.02	5.34	11.08	97.44
Sweden	244,009	97.58	37,491	94.45	0.89	3.92	99.26
Poland	238,847	98.84	5,779	95.09	2.54	1.54	99.17
Belgium	206,156	94.10	16,680	92.13	1.18	5.12	98.42

Notes: This list includes the top 20 countries that account for the highest combined shares of patents and scientific articles. PCT inventor addresses were geocoded to highest level of detail. Due to the much larger volume, scientific author addresses were geocoded to the city level only.

Description of scientific publication data

Since its systematic compilation in 1960, bibliographic information contained in scientific articles has been used to measure the scientific performance of individual scholars, academic institutions, and countries as a whole. Indeed, scientific publishing activity is a longstanding variable in the GII.[2]

For several decades, the Science Citation Index (SCI) created by the Institute for Scientific Information was the only comprehensive source of such scientific information.[3] Today there are several databases available on scientific publication activity. The two main ones with global coverage are the Web of Science's SCI Expanded (SCIE), published by Clarivate; and SCOPUS, published by Elsevier.[4]

These databases differ in their coverage of journals and languages. In a nutshell, the SCIE offers better language coverage at the expense of somewhat reduced journal coverage compared to SCOPUS.[5] To promote the international comparability of scientific activity—especially with Asian countries—we opted to use the SCIE. In particular, our analysis is based on scientific articles in the SCIE for the last available five years (2012–16). We limit ourselves to the broad field of science and technology, disregarding scientific articles in the fields of social sciences and humanities.

In total, our SCIE extract includes 8.5 million articles from across 113 scientific fields.

Geocoding addresses of inventors and scientific authors

Our analysis focuses on patents and scientific articles published in the 2012–16 period. In the case of patents, our population consists of approximately 1 million patents filed under the PCT, which list 2.8 million inventors that account for close to 1 million unique addresses. In the case of scientific articles, our population consists of 8.5 million articles, which list 22.5 million authors that account for an additional 7.4 million unique addresses.

We geocoded these addresses as follows. First, we used the ArcGIS service of Esri to geocode inventor addresses for all countries, except China, Japan, and the Republic of Korea. For the latter three countries, the address matches of ArcGIS proved insufficiently accurate. We therefore adopted an alternative approach for these countries whereby we identified the city name in the address string by matching address records with the city-level data from GeoNames' gazetteer database.[6] This latter database also provides the geocodes of each city. Finally, using an equivalent approach, we relied on the GeoNames database to geocode scientific author addresses at the city level.

Overall, we were able to geocode 97% of inventor addresses at the city or a more accurate level, and 96% of scientific author addresses at the city level. Table 1 provides an overview of the geocoding results for the top 20 countries that account for most of the inventor and scientific author addresses. As can be seen in the table, the coverage of geocoded addresses is above 95% in most cases and falls below 90% only once.

Figures 1 and 2 in the 'Clusters by Patent and Scientific Publishing Performance and Cluster Rankings' annex at the end of this section (the Annex) visualize the geocoded locations of inventors and scientific authors, respectively, by depicting the density of geocoded addresses per 100 square kilometres. The two figures highlight how certain regions—notably parts of South America, Africa, and the Middle East—display relatively more activity in scientific publishing than patenting.

Identifying clusters and measuring their size

As in our 2017 analysis, we rely on the density-based algorithm for discovering clusters originally proposed in Ester et al. (1996), also known as the 'DBSCAN algorithm'. In applying the algorithm, we treated multiple listings of the same address—for example, the same inventor/author being listed in multiple patents/articles—as separate data points.

In addition, we gave equal weight to inventors and authors by expressing data points as a share of total inventor and author addresses, respectively. Given that the number of scientific articles far exceeds the number of patents, cluster identification on the basis of the raw data points would have resulted in cluster shapes heavily dominated by the scientific author landscape. Of course, our equal weighting approach is somewhat arbitrary. However, as will be shown later, patenting and scientific publishing activity correlates positively and, in any case, most clusters reflect patterns of overall economic agglomeration, so the identity of most clusters would probably have stayed the same if we had opted for different weights.[7]

Compared with our patent-based 2017 analysis, the inclusion of scientific articles helped to disambiguate the shape of clusters. In particular, the identification of clusters in certain densely populated areas—notably Frankfurt–Mannheim in Germany and New York in the United States of America (U.S.)—was highly sensitive to the chosen density parameters when focusing only on inventors. With both inventors and scientific authors included, the shape of the clusters was comparatively less sensitive to the chosen input parameters.

In the end, we settled on baseline input parameters of 15 kilometres (radius) and 4,500 density (minimum number of data points). These parameters effectively replicate last year's density while accounting for the substantially higher number of observations in this year's dataset. The DBSCAN algorithm then identified 198 clusters worldwide. Notwithstanding the reduced ambiguity in cluster identity, there were still a number of contiguous clusters. As last year, we applied co-inventor relationships to decide whether to combine two clusters into one. This led us to merge clusters in six cases, reducing the final list to 192 clusters covering 43 economies.[8]

The greater number of clusters compared with last year largely reflects the inclusion of geographical areas seeing substantial scientific publishing activity but comparatively less patenting activity, especially in middle-income economies, as illustrated in Figures 1 and 2 in the Annex.

Finally, we ranked the 192 clusters by counting the number of patents and scientific articles accounted for by the inventors and authors present in a given cluster. In doing so, we adopted a fractional counting approach, whereby counts reflect the share of a patent's inventors and an article's authors present in a particular cluster. In addition, mirroring our equal weighting approach described above, we express counts relative to the total numbers of patents and scientific articles.

The top 100 science and technology clusters

Annex Table 1 presents our top 100 cluster rankings. Although there are some notable changes, the inclusion of scientific publications did not dramatically alter the identity and size of clusters. Notably, nine of the top 10 clusters included in last year's rankings are still among the top 10 in the new rankings. Tokyo–Yokohoma still comes out on top and continues to have a wide margin over 2nd ranked Shenzhen–Hong Kong. Beijing—the cluster showing the greatest scientific publishing activity—rose in the rankings; San Diego, in turn, fell, reflecting its relatively weaker publishing performance. The New York cluster rose to 8th place; this largely reflects and expansion of the cluster to include the Princeton, NJ area.

Annex Table 2 presents the rankings for patent and scientific publishing performance separately, and Figure 3 in the Annex compares the two indicators for the top 100 clusters. The figure shows a strong positive correlation. Clusters that excel in scientific activity generally also account for more patent filings. Notably, top-ranked Tokyo–Yokohama is the top-performing patenting cluster and the 2nd ranked scientific publishing cluster.

However, some clusters show notably stronger performance for one of the two measures of science and technology activity. At one extreme, Eindhoven—the home of Philips Electronics— shows a relatively strong patenting performance far out of line with its relatively weak scientific publishing performance. At the other extreme, Tehran excels in scientific publishing activity, but shows relatively weak patenting output. Similarly, Figure 3 in the Annex points to other clusters located in middle-income countries that, albeit less extremely, also show comparatively stronger scientific publishing performance and that did not feature in last year's top 100. These include, for example, Ankara, Changchun, Delhi, Harbin, Hefei, Istanbul, São Paulo, and Xi'an.

The top 100 features clusters from 28 economies. The U.S., with 26 clusters, accounts for the highest number, followed by China (16), Germany (8), the United Kingdom (4), and Canada (4). Interestingly, there are only three Japanese clusters in the top 100, even if those three are the top-ranked Tokyo–Yokohama cluster and the highly ranked Osaka–Kobe-Kyoto and Nagoya clusters. In addition to China, there are clusters from five middle-income countries— Brazil, India, the Islamic Republic of Iran, the Russian Federation, and Turkey—in the top 100. Annex Figures 4, 5, and 6 offer zoomed-in visualizations of the East Asian, European, and North American clusters featuring in the top 100.

Annex Table 1 presents key characteristics of the top 100 clusters. In particular, it shows the top field of scientific publishing, the top organizations with which scientific authors are affiliated, the top patenting field, and the top patent applicant. Many patterns are the same we reported on last year: the largest patent applicant is typically a company; several companies constitute the top applicant for more than one cluster; and the share of patents accounted for by the top applicant differs substantially across clusters.[9]

Compared with last year, there is a shift in the distribution of top patenting fields. In particular, pharmaceuticals is now the most frequent top patenting field; it features as the top field in 22 clusters. Because pharmaceutical research and development (R&D) relies heavily on scientific input, the incorporation of scientific publications has led to the inclusion of clusters with vibrant scientific activity in this field. Pharmaceuticals is followed by digital communications and medical technology, which were the top two patenting fields last year; this year they each feature in 16 clusters.

Looking at the top fields of scientific publishing, the prominence of the life sciences is even more pronounced. Chemistry features as the top field in 36 clusters, even if not all chemistry research necessarily relates to the life sciences. In addition, the top science field in another 34 clusters relates to either medical research or pharmaceuticals. Engineering and physics are the remaining top technology fields, with 15 and 12 clusters each, respectively.

There is some correspondence between the top science field and the top patenting field. For example, both Shenzhen–Hong Kong and Seoul feature engineering as the top science field and digital communication as the top patenting field. Similarly, for Washington, DC–Baltimore, MD, oncology as the top science field relates to pharmaceuticals as the top patenting field. However, there are many cases for which the two fields do not seem to correspond. More generally, the top science field accounts for less than 10% of all scientific publications in most clusters, and the shares of the top science fields are typically below those of the top patenting fields. This suggests that clusters' scientific activities are more diverse than their patenting activities.[10]

Concluding remarks

This chapter has presented a new ranking of the world's top science and technology 100 clusters showing the greatest agglomeration of inventors and scientific authors. Building on last year's analysis, which focused solely on international patent filings, we incorporated scientific publication data into the identification and measurement of clusters. This has enriched the measurement approach and broadened the analysis to science and technology activity at large.

With an equal weight assigned to patenting and scientific publication activity, the resulting top 100 list looks in many ways similar to last year's list. This is especially the case for the top 10, which hardly changed. It arguably reflects underlying patterns of urbanization in the—mostly developed—countries that account for most innovative activity. However, the revised top 100 list includes clusters not present in last year's rankings. Among them are a number of clusters from middle-income countries that show substantial publishing activity but do not exhibit strong patenting output.

Many of the caveats outlined in last year's chapter continue to apply.[11] In addition, we acknowledge that the weighting of patenting and scientific publishing activity is arbitrary. While different weights would not lead to dramatic changes in the top half of the rankings, it would lead to noticeable changes in the lower half. From this viewpoint, we again caution that the current ranks should be best interpreted as orders of magnitude, with clusters moving up and down a few ranks depending on different weighting schemes and cluster parameter choices.

For the future, we aim to improve and broaden our analysis in at least two ways. First, we will continue to be on the lookout for other measures of innovative activity that could be included in the analysis. Second, we will strive to provide greater insight into the knowledge networks that are behind the spatial clusters we identify through our density-based approach. The richness of the patenting and scientific publication datasets—which include many variables not yet explored in our analysis—offers promising avenues to pursue this research.

Notes

1 Bergquist et al., 2017.

2 See GII model variables 6.1.4 and 6.1.5, which cover the number and quality of publications by country.

3 Garfield, 1970, 1972.

4 For further information, see https://clarivate.com/products/web-of-science and https://www.elsevier.com/solutions/scopus, respectively.

5 Falagas et al., 2008; Harzing and Alakangas, 2016.

6 The GeoNames database is available at http://geonames.org/.

7 See also Chapter 1, Annex 1, on the equal weighting approach adopted in the GII.

8 In particular, we calculated the share of a cluster's co-inventors belonging to all the other clusters as well as to two noise categories—namely, co-inventors located within 80 kilometres of the cluster midpoint not belonging to any other cluster and co-inventors beyond 80 kilometres not belonging to any other cluster We then merged two clusters if two conditions were met for at least one of the clusters: first, the minimum distance between any two points of the two clusters was less than 5 kilometres; and second, the neighbouring cluster accounted for the largest share of co-inventors among all clusters plus the two noise categories. This procedure led us to merge Long Beach with Los Angeles, Rotterdam with Amsterdam, Kaohsiung with Tainan, Jerusalem with Tel Aviv, Baltimore, MD with Washington, DC, and Matsudo with Tokyo.

9 See Bergquist et al. (2017) for further discussion.

10 An important caveat here is that the categorizations of science fields and patenting fields are structured differently and the shares are thus not directly comparable.

11 Bergquist et al., 2017.

References

Bergquist, K., J. Raffo, and C. Fink. 2017. 'Identifying and Ranking the World's Largest Clusters of Inventive Activity'. In *The Global Innovation Index 2017: Innovation Feeding the World.* Special Section, eds. S. Dutta, B. Lanvin, and S. Wunsch-Vincent. Ithaca, Fontainebleau, and Geneva: Cornell, INSEAD, and WIPO. 161–76.

Ester, M., H.-P. Kriegel, J. Sander, and X. Xu. 1996. 'A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise'. Proceedings of the 2nd International Conference on Knowledge Discovery and Data Mining, 226–31. Available at https://www.aaai.org/Papers/KDD/1996/KDD96-037.pdf.

Falagas, M.E., E.I. Pitsouni, G.A. Malietzis, and G. Pappas. 2007. 'Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and Weaknesses'. *The FASEB Journal* 22 (2): 338–42. Available at https://doi.org/10.1096/fj.07-9492LSF.

Garfield, E. 1970. 'Citation Indexing for Studying Science'. *Nature* 227 (5259): 669–71.

———. 1972. 'Citation Analysis as a Tool in Journal Evaluation'. *Science* 178 (4060): 471–79.

Harzing, A.-W., and S. Alakangas. 2016. 'Google Scholar, Scopus and the Web of Science: A Longitudinal and Cross-Disciplinary Comparison'. *Scientometrics*106 (2): 787–804. Available at https://doi.org/10.1007/s11192-015-1798-9.

SPECIAL SECTION ANNEX

CLUSTERS BY PATENT AND SCIENTIFIC PUBLISHING PERFORMANCE AND CLUSTER RANKINGS

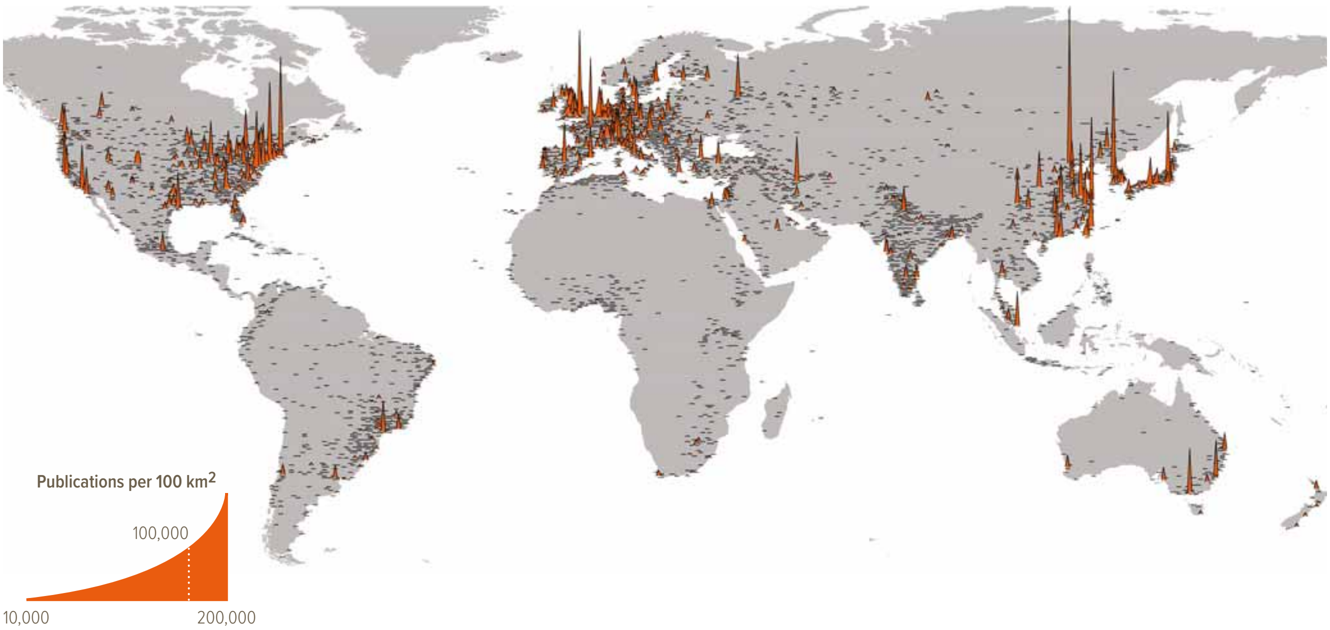
Figure 1.

PCT patent density per 100 square kilometres

Source: WIPO Statistics Database, March 2018.
Note: Patent filing counts refer to the 2012–16 period and are based on fractional counts, as explained in the text.

Figure 2.

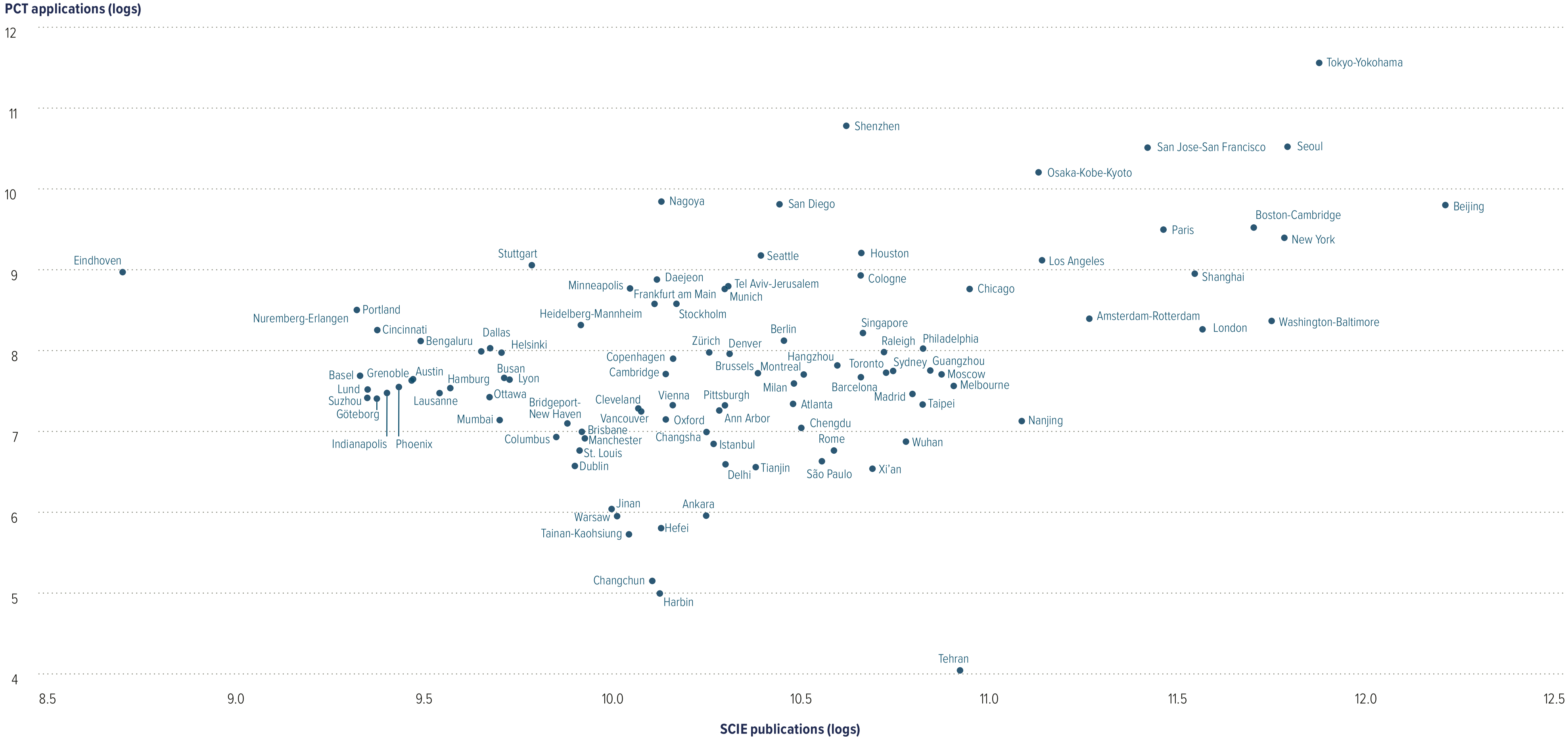
SCIE publication density per 100 square kilometres



Source: WIPO IP Statistics Database, March 2018.
Note: Publication counts refer to the 2012–16 period and are based on fractional counts, as explained in the text.

Figure 3.

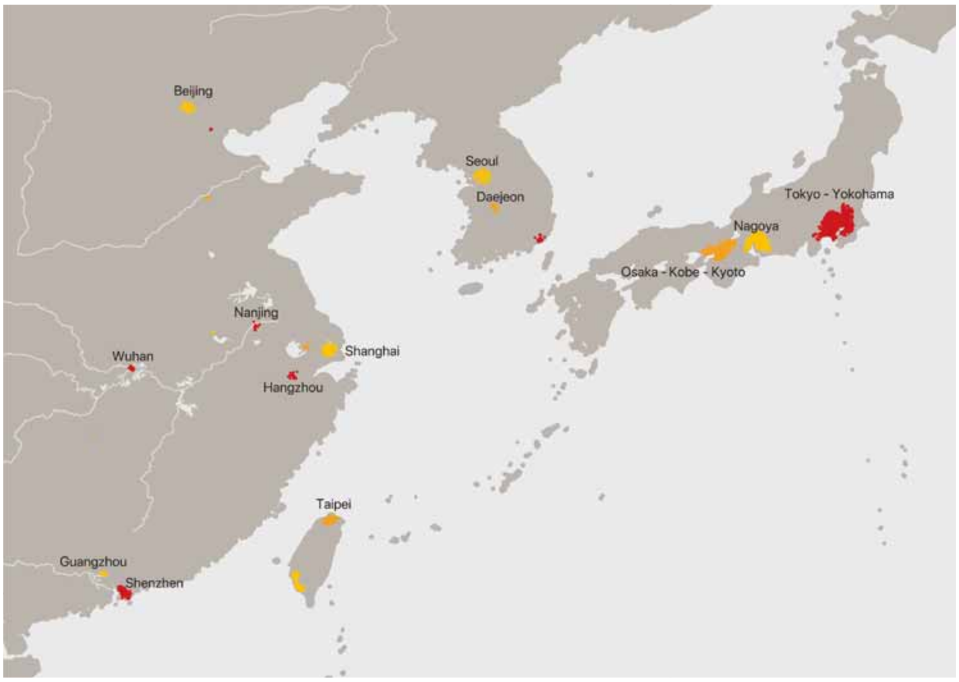
Patenting versus scientific publishing activity for the top 100 clusters



Note: Patent filing and scientific publication shares refer to the 2012–16 period and are based on fractional counts, as explained in the text.

Figure 4.

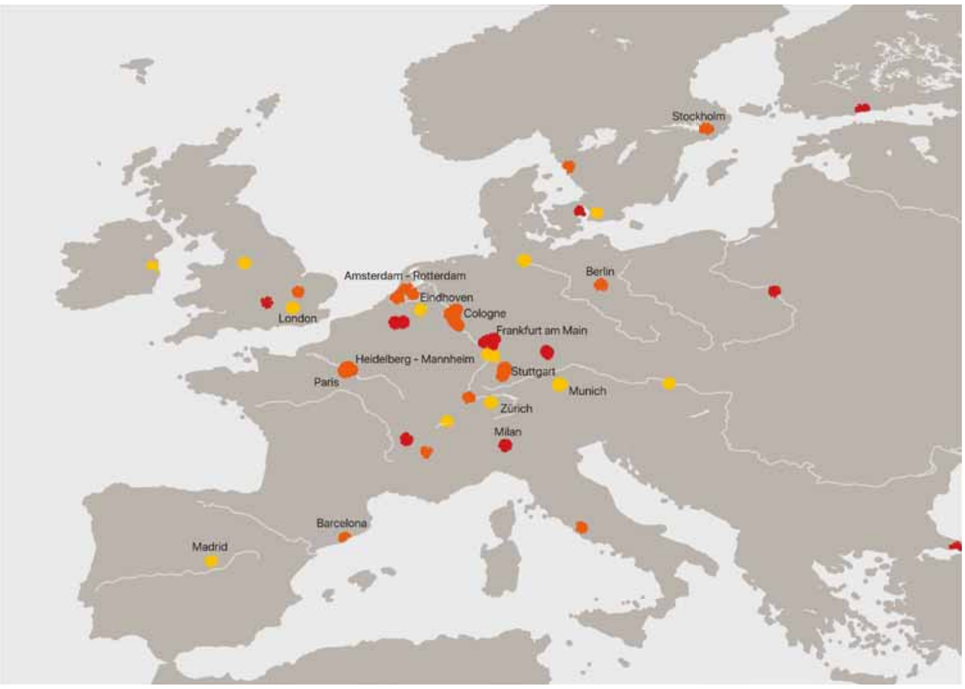
Regional clusters: Asia



Source: WIPO Statistics Database, March 2018.
Note: Colours have been assigned based on the colour of the nearest neighbours (in order to make clear the distinction between any two clusters).

Figure 5.

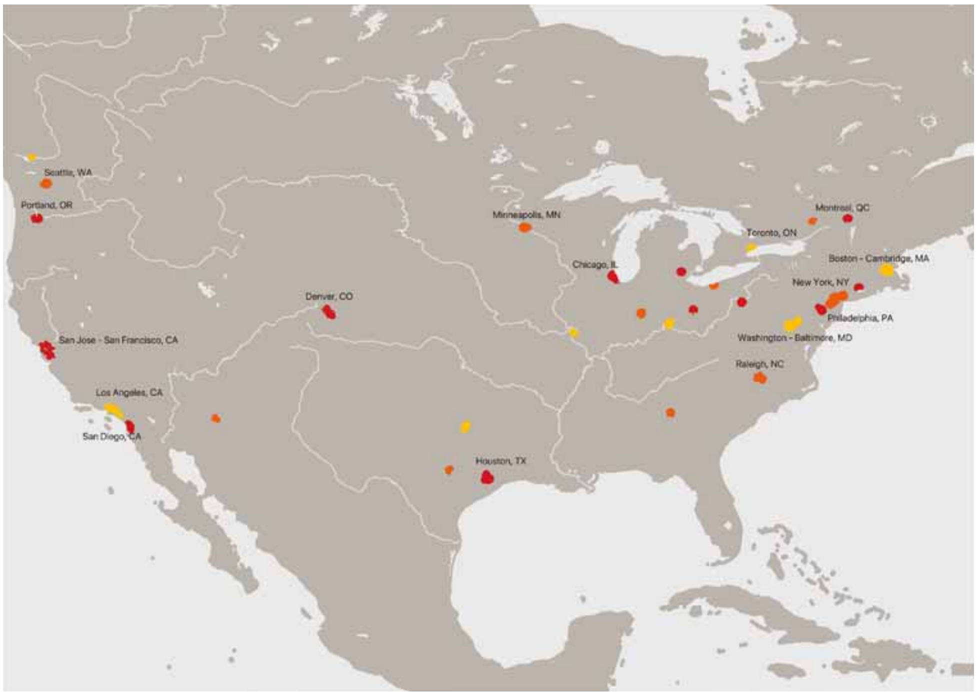
Regional clusters: Europe



Source: WIPO Statistics Database, March 2018.
Note: Colours have been assigned based on the colour of the nearest neighbours (in order to make clear the distinction between any two clusters).

Figure 6.

Regional clusters: Northern America



Source: WIPO Statistics Database, March 2018.

Note: Colours have been assigned based on the colour of the nearest neighbours (in order to make clear the distinction between any two clusters).

Table 1: Top 100 cluster rankings

Rank	Cluster name	Economies	Share of total PCT filings, %	Share of total pubs., %	Total	Scientific publishing performance: Top science field	Share, %	Top scientific organization	Share, %	Patent performance: Top patenting field	Share, %	Top applicant	Share, %
1	Tokyo–Yokohama	JP	11.00	1.77	12.77	Physics	9.43	University of Tokyo	13.95	Electrical machinery	9.83	Mitsubishi Electric	6.78
2	Shenzhen–Hong Kong	CN/HK	5.05	0.51	5.56	Engineering	10.71	University of Hong Kong	18.40	Digital communication	42.33	ZTE Corp.	30.41
3	Seoul	KR	3.90	1.63	5.53	Engineering	7.55	Seoul National University	16.27	Digital communication	15.77	LG Electronics	17.43
4	San Jose–San Francisco, CA	US	3.86	1.13	4.98	Chemistry	6.63	University of California	38.23	Computer technology	22.92	Google	7.18
5	Beijing	CN	1.90	2.46	4.36	Chemistry	10.65	Chinese Academy of Sciences	23.46	Digital communication	25.49	BOE Technology Group	21.09
6	Osaka–Kobe–Kyoto	JP	2.84	0.85	3.69	Chemistry	10.23	Kyoto University	22.05	Electrical machinery	14.05	Murata Manufacturing	10.26
7	Boston–Cambridge, MA	US	1.43	1.49	2.92	Oncology	5.88	Harvard University	53.77	Pharmaceuticals	16.90	M.I.T	6.45
8	New York, NY	US	1.26	1.61	2.88	Gen. & internal med.	5.97	Columbia University	13.29	Pharmaceuticals	14.38	Honeywell	4.69
9	Paris	FR	1.40	1.17	2.57	Physics	7.65	CNRS	22.16	Transport	11.63	L'Oréal	7.97
10	San Diego, CA	US	1.91	0.43	2.34	Chemistry	6.61	University of California	51.38	Digital communication	30.00	Qualcomm	57.30
11	Nagoya	JP	1.98	0.31	2.29	Physics	9.70	Nagoya University	33.86	Electrical machinery	17.62	Toyota	32.28
12	Shanghai	CN	0.81	1.27	2.09	Chemistry	13.67	Shanghai Jiao Tong University	22.96	Digital communication	10.62	Alcatel-Lucent	4.13
13	Washington, DC–Baltimore, MD	US	0.45	1.56	2.01	Oncology	5.24	Johns Hopkins University	22.37	Pharmaceuticals	17.60	Johns Hopkins University	14.53
14	Los Angeles, CA	US	0.96	0.85	1.81	Chemistry	5.69	University of California	44.21	Medical technology	18.10	University of California	5.78
15	London	GB	0.41	1.30	1.71	Gen. & internal med.	7.02	University of London	49.79	Digital communication	11.47	British Telecom	7.54
16	Houston, TX	US	1.05	0.53	1.58	Oncology	14.27	UTMD Anderson Cancer Center	29.54	Civil engineering	35.18	Halliburton	16.96
17	Amsterdam–Rotterdam	NL	0.46	0.97	1.43	Cardio. & cardiology	6.34	University of Utrecht	16.32	Civil engineering	6.24	Shell	8.94
18	Seattle, WA	US	1.02	0.41	1.42	Oncology	5.05	University of Washington	65.90	Computer technology	41.97	Microsoft Corp.	31.33
19	Chicago, IL	US	0.67	0.71	1.38	Chemistry	6.06	Northwestern University	27.02	Digital communication	8.38	Illinois Tool Works	15.01
20	Cologne	DE	0.79	0.53	1.32	Chemistry	6.89	University of Bonn	16.39	Basic materials chemistry	9.94	Henkel	8.62
21	Stuttgart	DE	0.90	0.22	1.12	Chemistry	7.33	University of Tubingen	44.53	Engines, pumps, turbines	14.05	Robert Bosch Corp.	47.99
22	Tel Aviv–Jerusalem	IL	0.69	0.37	1.07	Neurosciences	6.76	Tel Aviv University	33.98	Computer technology	17.12	Intel Corp.	4.46
23	Daejeon	KR	0.75	0.31	1.06	Engineering	13.49	KAIST	25.59	Electrical machinery	19.45	LG Chem	35.29
24	Munich	DE	0.67	0.37	1.04	Physics	8.11	University of Munich	55.04	Transport	11.49	BMW	13.57
25	Minneapolis, MN	US	0.68	0.29	0.97	Chemistry	6.06	University of Minnesota	74.37	Medical technology	29.69	3M Innovative Properties	35.12
26	Philadelphia, PA	US	0.32	0.62	0.95	Oncology	6.14	University of Pennsylvania	49.38	Pharmaceuticals	21.60	University of Pennsylvania	10.01
27	Nanjing	CN	0.13	0.81	0.94	Chemistry	12.97	Nanjing University	18.98	Digital communication	10.94	Southeast University	8.81
28	Singapore	SG	0.39	0.53	0.92	Chemistry	10.77	National Univ. of Singapore	38.24	Computer technology	7.71	A*Star	17.81
29	Eindhoven	BE/NL	0.83	0.08	0.90	Engineering	14.91	Eindhoven Univ. of Technology	61.67	Medical technology	25.57	Philips Electronics	81.76
30	Moscow	RU	0.23	0.66	0.89	Physics	17.56	Russian Academy of Sciences	38.16	Computer technology	10.44	Yandex Europe	3.30

(Continued on next page)

Table 1: Top 100 cluster rankings *(continued)*

						Scientific publishing performance				Patent performance			
Rank	Cluster name	Economies	Share of total PCT filings, %	Share of total pubs., %	Total	Top science field	Share, %	Top scientific organization	Share, %	Top patenting field	Share, %	Top applicant	Share, %
31	Stockholm	SE	0.56	0.33	0.89	Chemistry	5.35	Karolinska Institutet	49.66	Digital communication	38.88	Ericsson	46.17
32	Guangzhou	CN	0.24	0.64	0.88	Chemistry	10.67	Sun Yat Sen University	29.39	Medical technology	8.25	South China U. of Tech.	6.60
33	Melbourne	AU	0.20	0.68	0.88	Gen. & internal med.	5.69	University of Melbourne	25.63	Pharmaceuticals	9.12	Monash University	4.98
34	Raleigh, NC	US	0.31	0.56	0.87	Oncology	4.88	University of North Carolina	50.66	Pharmaceuticals	12.10	Cree	9.31
35	Frankfurt am Main	DE	0.56	0.31	0.87	Physics	9.31	Goethe University Frankfurt	24.10	Medical technology	11.61	Merck Patent GmbH	9.56
36	Sydney	AU	0.24	0.58	0.82	Gen. & internal med.	5.82	University of Sydney	40.29	Medical technology	11.95	Cochlear	4.73
37	Toronto, ON	CA	0.24	0.57	0.81	Neurosciences	7.10	University of Toronto	80.99	Computer technology	12.48	Synaptive Medical	3.52
38	Madrid	ES	0.18	0.61	0.79	Chemistry	5.93	CSIC	15.90	Digital communication	14.74	Telefonica	10.85
39	Berlin	DE	0.35	0.43	0.79	Chemistry	7.40	Free University of Berlin	37.59	Electrical machinery	11.03	Siemens	11.98
40	Taipei	TW	0.16	0.62	0.78	Engineering	8.41	National Taiwan University	28.29	Pharmaceuticals	10.66	MediaTek	9.21
41	Hangzhou	CN	0.26	0.50	0.76	Chemistry	12.99	Zhejiang University	59.88	Computer technology	26.99	Alibaba Group	42.83
42	Barcelona	ES	0.23	0.53	0.76	Chemistry	5.39	University of Barcelona	29.10	Pharmaceuticals	10.94	Hewlett-Packard	13.55
43	Wuhan	CN	0.10	0.60	0.70	Chemistry	10.72	Huazhong Univ. of Sci. & Tech.	30.54	Optics	10.59	Huazhong Univ. of Sci. & Tech.	11.10
44	Tehran	IR	0.01	0.69	0.69	Engineering	15.65	Tehran Univ. of Med. Sciences	11.80	Medical technology	10.52	Gharooni, Milad	5.26
45	Milan	IT	0.23	0.46	0.69	Neurosciences	8.07	University of Milan	24.79	Pharmaceuticals	7.62	Pirelli Tyre S.p.A.	7.20
46	Heidelberg–Mannheim	DE	0.43	0.25	0.68	Oncology	9.18	University Heidelberg	61.08	Basic materials chemistry	12.74	BASF	42.27
47	Denver, CO	US	0.30	0.38	0.68	Meteor. & atmos. sci.	5.07	University of Colorado	56.38	Medical technology	13.74	University of Colorado	6.61
48	Zurich	CH/DE	0.31	0.36	0.66	Chemistry	8.28	ETH Zurich	40.20	Medical technology	8.31	Sika Technology AG	5.08
49	Portland, OR	US	0.52	0.14	0.66	Neurosciences	6.99	Oregon University	67.29	Computer technology	24.29	Intel Corp.	50.37
50	Montreal, QC	CA	0.21	0.44	0.65	Engineering	7.02	McGill University	42.72	Digital communication	17.12	Ericsson	9.48
51	Brussels	BE	0.24	0.40	0.64	Physics	4.75	KU Leuven	41.71	Pharmaceuticals	7.47	Procter & Gamble Company	4.93
52	Xian	CN	0.07	0.55	0.62	Engineering	13.54	Xi'an Jiaotong University	29.37	Digital communication	16.29	Xian Jiaotong University	11.97
53	Copenhagen	DK	0.28	0.32	0.61	Neurosciences	5.18	University of Copenhagen	73.02	Biotechnology	15.95	Novozymes	11.07
54	Atlanta, GA	US	0.16	0.44	0.61	Public health	6.08	Emory University	36.75	Medical technology	14.83	Georgia Tech Research	8.90
55	Rome	IT	0.09	0.49	0.59	Neurosciences	6.57	Sapienza University Rome	31.81	Pharmaceuticals	10.93	Bridgestone Corp.	7.07
56	Chengdu	CN	0.12	0.45	0.57	Chemistry	11.03	Sichuan University	44.52	Pharmaceuticals	12.12	Huawei	6.22
57	São Paulo	BR	0.08	0.48	0.56	Neurosciences	4.18	Universidade de Sao Paulo	46.91	Medical technology	8.44	Mahle Metal Leve	3.37
58	Nuremberg–Erlangen	DE	0.40	0.15	0.55	Chemistry	8.04	Univ. of Erlangen Nuremberg	67.34	Electrical machinery	16.35	Siemens	41.38
59	Cambridge	GB	0.23	0.32	0.55	Other science and tech.	6.98	University of Cambridge	73.39	Computer technology	13.08	ARM IP Limited	5.80
60	Pittsburgh, PA	US	0.16	0.37	0.53	Neurosciences	5.63	(PCSHE)	66.74	Medical technology	12.55	University of Pittsburgh	11.92
61	Dallas, TX	US	0.32	0.20	0.52	Cardio. & cardiology	6.12	U of Texas SW Medical Center	50.46	Civil engineering	17.60	Halliburton	16.61

(Continued on next page)

Table 1: Top 100 cluster rankings *(continued)*

						Scientific publishing performance				Patent performance			
Rank	Cluster name	Economies	Share of total PCT filings, %	Share of total pubs., %	Total	Top science field	Share, %	Top scientific organization	Share, %	Top patenting field	Share, %	Top applicant	Share, %
62	Cincinnati, OH	US	0.35	0.17	0.52	Pediatrics	6.15	University of Cincinnati	46.92	Medical technology	30.07	Procter & Gamble Company	44.54
63	Ann Arbor, MI	US	0.15	0.37	0.52	Chemistry	5.29	University of Michigan	89.57	Transport	9.61	University of Michigan	25.07
64	Helsinki	FI	0.31	0.21	0.51	Neurosciences	4.49	University of Helsinki	57.08	Digital communication	31.32	Nokia Corp.	16.15
65	Bengaluru	IN	0.31	0.20	0.51	Chemistry	12.99	Indian Institute of Science	30.63	Computer technology	24.05	Hewlett-Packard	11.11
66	Vienna	AT	0.16	0.32	0.48	Physics	4.87	Medical University of Vienna	28.61	Pharmaceuticals	9.35	Siemens	3.95
67	Tianjin	CN	0.07	0.40	0.48	Chemistry	18.89	Tianjin University	29.16	Pharmaceuticals	10.95	Tianjin University	10.54
68	Changsha	CN	0.11	0.35	0.47	Chemistry	10.97	Central South University	42.30	Civil engineering	17.60	Zoomlion	36.38
69	Istanbul	TR	0.10	0.36	0.46	Engineering	6.59	Istanbul University	21.08	Pharmaceuticals	29.06	Bilgic, Mahmut	12.56
70	Oxford	GB	0.13	0.32	0.45	Physics	7.47	University of Oxford	78.64	Pharmaceuticals	10.01	Isis Innovation Limited	23.74
71	Cleveland, OH	US	0.15	0.30	0.45	Cardio. & cardiology	7.98	Cleveland Clinic Foundation	47.59	Medical technology	15.13	Cleveland Clinic	10.91
72	Delhi	IN	0.08	0.37	0.45	Chemistry	7.37	All India Inst. of Med. Sciences	14.50	Pharmaceuticals	15.25	Ranbaxy Laboratories	9.08
73	Vancouver, BC	CA	0.15	0.30	0.45	Neurosciences	4.70	Univ. of British Columbia	70.40	Medical technology	8.91	Univ. of British Columbia	7.12
74	Lyon	FR	0.22	0.21	0.43	Chemistry	7.46	CNRS	30.14	Organic fine chemistry	10.92	IFP Energies nouvelles	10.15
75	Busan	KR	0.22	0.21	0.43	Engineering	9.61	Pusan National University	39.27	Electrical machinery	7.71	Pusan National University	4.51
76	Ankara	TR	0.04	0.35	0.39	Cardio. & cardiology	5.51	Hacettepe University	17.01	Computer technology	12.40	Aselsan	23.46
77	Austin, TX	US	0.22	0.16	0.38	Chemistry	11.73	University of Texas Austin	83.72	Computer technology	23.39	University of Texas System	11.68
78	Grenoble	FR	0.22	0.16	0.38	Physics	18.03	CNRS	42.04	Electrical machinery	14.50	CEA	42.37
79	Hamburg	DE	0.20	0.18	0.38	Physics	8.11	University of Hamburg	57.70	Organic fine chemistry	17.84	Henkel	10.01
80	Ottawa, ON	CA	0.18	0.20	0.38	Engineering	6.31	University of Ottawa	56.78	Digital communication	42.42	Huawei	26.70
81	Bridgeport–New Haven, CT	US	0.13	0.25	0.37	Neurosciences	6.19	Yale University	86.33	Pharmaceuticals	15.09	Bristol-Myers Squibb	12.95
82	Basel	CH/DE/FR	0.23	0.14	0.37	Pharma. & pharmacy	7.66	University of Basel	61.33	Pharmaceuticals	19.06	F. Hoffmann-La Roche AG	12.51
83	Brisbane	AU	0.11	0.26	0.37	Engineering	5.31	University of Queensland	49.90	Civil engineering	13.41	University of Queensland	9.77
84	Manchester	GB	0.11	0.26	0.36	Chemistry	6.63	University of Manchester	65.09	Electrical machinery	15.68	MicroMass	14.50
85	Lausanne	CH/FR	0.19	0.18	0.36	Chemistry	8.20	EPFL	47.70	Food chemistry	9.86	NESTEC	27.79
86	Phoenix, AZ	US	0.20	0.16	0.36	Neurosciences	6.87	Arizona State University	50.84	Computer technology	13.67	Intel Corp.	16.63
87	Tainan–Kaohsiung	TW	0.03	0.31	0.35	Engineering	11.47	National Cheng Kung Univ.	32.09	Pharmaceuticals	14.89	MediaTek	7.55
88	Columbus, OH	US	0.11	0.24	0.35	Oncology	5.70	Ohio State University	89.80	Pharmaceuticals	13.20	Abbott Laboratories	14.98
89	St. Louis, MO	US	0.09	0.25	0.34	Neurosciences	6.72	Washington University	69.64	Biotechnology	16.35	Monsanto Technology	14.95
90	Lund	SE	0.19	0.15	0.34	Other science and tech.	5.12	Lund University	87.00	Digital communication	20.08	Ericsson	20.18
91	Indianapolis, IN	US	0.19	0.15	0.34	Oncology	5.48	Indiana University	67.90	Basic materials chemistry	11.33	Dow AgroSciences	21.55
92	Mumbai	IN	0.13	0.21	0.34	Chemistry	16.22	Bhabha Atomic Research Center	24.16	Organic fine chemistry	19.48	Piramal Enterprises	6.17

(Continued on next page)

Table 1: Top 100 cluster rankings *(continued)*

Rank	Cluster name	Economies	Share of total PCT filings, %	Share of total pubs., %	Total	Scientific publishing performance: Top science field	Share, %	Top scientific organization	Share, %	Patent performance: Top patenting field	Share, %	Top applicant	Share, %
93	Harbin	CN	0.02	0.31	0.33	Engineering	11.39	Harbin Institute of Tech.	43.69	Measurement	14.46	Harbin Institute of Tech.	42.64
94	Dublin	IE	0.08	0.25	0.33	Gen. & internal med.	17.10	Trinity College Dublin	30.49	Computer technology	11.36	Alcatel-Lucent	8.41
95	Changchun	CN	0.02	0.31	0.32	Chemistry	25.64	Jilin University	57.03	Measurement	11.36	Changchun Railway Vehicles	16.23
96	Gothenburg	SE	0.17	0.15	0.32	Engineering	7.28	University of Gothenburg	45.54	Digital communication	12.40	Ericsson	21.53
97	Hefei	CN	0.03	0.29	0.32	Physics	16.12	Univ. of Science & Technology	42.30	Electrical machinery	13.34	Anhui Jianghuai Automobile	12.05
98	Warsaw	PL	0.04	0.28	0.32	Chemistry	9.37	Polish Academy of Sciences	19.34	Pharmaceuticals	8.87	IBB Pan	3.71
99	Jinan	CN	0.04	0.28	0.32	Chemistry	14.57	Shandong University	60.58	Electrical machinery	10.38	Shandong University	10.04
100	Suzhou	CN	0.17	0.15	0.32	Chemistry	17.86	Suzhou University	69.82	Electrical machinery	9.88	Ecovacs Robotics	5.06

Notes: Patent filing and scientific publication shares refer to the 2012–16 period and are based on fractional counts, as explained in the text. We use the location of inventors to associate patent applicants to clusters; note that addresses of applicants may well be outside the cluster(s) to which they are associated. The identification of technology fields relies on the WIPO technology concordance table linking International Patent Classification (IPC) symbols with 35 fields of technology (available at http://www.wipo.int/ipstats/en/). The top scientific field is based on SCIE's Extended Ascatype subject field. An article can be assigned to more than one subject field. Fractional counting was used when more than one subject was assigned to an article. Codes refer to the ISO-2 codes. See page 37 for a full list, with the following addition: TW = Taiwan, Province of China. CEA = Commissariat a l'Energie Atomique; CNSR = Centre National de la Recherche Scientifique; IBB Pan = Instytut Bio Chemii I Biofizki Pan; PCSHE = Pennsylvania Commonwealth System of Higher Education.

Table 2: Cluster rankings by patent and publishing performance

Top 100 clusters ranked by patents

Patent rank	Cluster name	Economies	Number of patents
1	Tokyo–Yokohama	JP	104,746
2	Shenzhen–Hong Kong	CN/HK	48,084
3	Seoul	KR	37,118
4	San Jose–San Francisco, CA	US	36,715
5	Osaka–Kobe–Kyoto	JP	27,046
6	Nagoya	JP	18,837
7	San Diego, CA	US	18,217
8	Beijing	CN	18,041
9	Boston–Cambridge, MA	US	13,659
10	Paris	FR	13,318
11	New York, NY	US	12,032
12	Houston, TX	US	9,972
13	Seattle, WA	US	9,668
14	Los Angeles	US	9,113
15	Stuttgart	DE	8,574
16	Eindhoven	BE/NL	7,868
17	Shanghai	CN	7,718
18	Cologne	DE	7,554
19	Daejeon	KR	7,181
20	Tel Aviv–Jerusalem	IL	6,610
21	Minneapolis, MN	US	6,432
22	Munich	DE	6,389
23	Chicago, IL	US	6,385
24	Stockholm	SE	5,318
25	Frankfurt am Main	DE	5,312
26	Portland, OR	US	4,928
27	Amsterdam–Rotterdam	NL	4,423
28	Washington, DC–Baltimore, MD	US	4,302
29	Heidelberg–Mannheim	DE	4,089
30	London	GB	3,878
31	Nuremberg–Erlangen	DE	3,842
32	Singapore	SG	3,706
33	Berlin	DE	3,371
34	Cincinnati, OH	US	3,356
35	Dallas, TX	US	3,070
36	Philadelphia, PA	US	3,056
37	Bengaluru	IN	2,952
38	Raleigh, NC	US	2,926
39	Zürich	CH/DE	2,914
40	Helsinki	FI	2,906
41	Denver, CO	US	2,863
42	Copenhagen	DK	2,697
43	Hangzhou	CN	2,482
44	Guangzhou	CN	2,330
45	Sydney	AU	2,317
46	Toronto, ON	CA	2,268
47	Brussels	BE	2,254
48	Cambridge	GB	2,231
49	Moscow	RU	2,221
50	Milan	IT	2,218

Top 100 clusters ranked by scientific publications

Publication rank	Cluster name	Economies	Number of publications
1	Beijing	CN	197,175
2	Tokyo–Yokohama	JP	141,584
3	Seoul	KR	130,290
4	New York, NY	US	129,214
5	Washington–Baltimore, MD	US	124,968
6	Boston–Cambridge, MA	US	119,240
7	London	GB	104,238
8	Shanghai	CN	102,132
9	Paris	FR	94,073
10	San Jose–San Francisco, CA	US	90,238
11	Amsterdam–Rotterdam	NL	77,445
12	Los Angeles	US	68,404
13	Osaka–Kobe–Kyoto	JP	67,781
14	Nanjing	CN	64,856
15	Chicago, IL	US	56,564
16	Tehran	IR	55,156
17	Melbourne	AU	54,251
18	Moscow	RU	52,549
19	Guangzhou	CN	51,013
20	Philadelphia, PA	US	50,056
21	Taipei	TW	50,002
22	Madrid	ES	48,682
23	Wuhan	CN	47,857
24	Sydney	AU	46,272
25	Toronto, ON	CA	45,426
26	Raleigh, NC	US	45,176
27	Xi'an	CN	43,830
28	Singapore	SG	42,747
29	Houston, TX	US	42,568
30	Barcelona	ES	42,518
31	Cologne	DE	42,497
32	Shenzhen–Hong Kong	CN/HK	40,920
33	Hangzhou	CN	39,968
34	Rome	IT	39,615
35	São Paulo	BR	38,381
36	Milan	IT	36,596
37	Chengdu	CN	36,362
38	Montreal, QC	CA	35,666
39	Atlanta, GA	US	35,583
40	Berlin	DE	34,743
41	San Diego, CA	US	34,340
42	Seattle, WA	US	32,705
43	Brussels	BE	32,449
44	Tianjin	CN	32,261
45	Denver, CO	US	30,124
46	Tel Aviv–Jerusalem	IL	30,017
47	Delhi	IN	29,802
48	Pittsburgh, PA	US	29,758
49	Munich	DE	29,740
50	Ann Arbor, MI	US	29,317

(Continued on next page)

Table 2: Cluster rankings by patent and publishing performance *(continued)*

Top 100 clusters ranked by patents				Top 100 clusters ranked by scientific publications			
Patent rank	Cluster name	Economies	Number of patents	Publication rank	Cluster name	Economies	Number of publications
51	Basel	CH/DE/FR	2,184	51	Istanbul	TR	28,886
52	Barcelona	ES	2,145	52	Zürich	CH/DE	28,554
53	Lyon	FR	2,127	53	Changsha	CN	28,351
54	Austin, TX	US	2,093	54	Ankara	TR	28,327
55	Busan	KR	2,081	55	Stockholm	SE	26,200
56	Grenoble	FR	2,059	56	Copenhagen	DK	25,972
57	Montreal, QC	CA	1,984	57	Vienna	AT	25,949
58	Melbourne	AU	1,925	58	Oxford	GB	25,478
59	Phoenix, AZ	US	1,900	59	Cambridge	GB	25,475
60	Hamburg	DE	1,874	60	Nagoya	JP	25,186
61	Lund	SE	1,842	61	Tainan–Kaohsiung	TW	25,168
62	Indianapolis, IN	US	1,765	62	Harbin	CN	25,081
63	Lausanne	CH/FR	1,762	63	Daejeon	KR	24,891
64	Madrid	ES	1,743	64	Frankfurt am Main	DE	24,736
65	Ottawa, ON	CA	1,676	65	Changchun	CN	24,591
66	Suzhou	CN	1,661	66	Vancouver, BC	CA	23,885
67	Gothenburg	SE	1,645	67	Cleveland, OH	US	23,705
68	Atlanta, GA	US	1,542	68	Minneapolis, MN	US	23,195
69	Taipei	TW	1,530	69	Hefei	CN	23,130
70	Vienna	AT	1,518	70	Warsaw	PL	22,422
71	Pittsburgh, PA	US	1,514	71	Jinan	CN	22,101
72	Cleveland, OH	US	1,457	72	Manchester	GB	20,601
73	Ann Arbor, MI	US	1,421	73	Brisbane	AU	20,441
74	Vancouver, BC	CA	1,404	74	Heidelberg–Mannheim	DE	20,386
75	Oxford	GB	1,272	75	St. Louis, MO	US	20,318
76	Mumbai	IN	1,262	76	Dublin	IE	20,068
77	Nanjing	CN	1,246	77	Bridgeport–New Haven, CT	US	19,679
78	Bridgeport–New Haven, CT	US	1,211	78	Columbus, OH	US	19,113
79	Chengdu	CN	1,146	79	Stuttgart	DE	17,924
80	Brisbane	AU	1,092	80	Busan	KR	16,908
81	Changsha	CN	1,089	81	Lyon	FR	16,670
82	Columbus, OH	US	1,023	82	Helsinki	FI	16,555
83	Manchester	GB	1,006	83	Mumbai	IN	16,475
84	Wuhan	CN	967	84	Dallas, TX	US	16,068
85	Istanbul	TR	940	85	Ottawa, ON	CA	16,042
86	Rome	IT	866	86	Bengaluru	IN	15,696
87	St. Louis, MO	US	866	87	Hamburg	DE	14,471
88	São Paulo	BR	758	88	Lausanne	CH/FR	14,069
89	Delhi	IN	730	89	Cincinnati, OH	US	13,389
90	Dublin	IE	715	90	Austin, TX	US	13,124
91	Tianjin	CN	705	91	Grenoble	FR	13,076
92	Xi’an	CN	691	92	Phoenix, AZ	US	12,644
93	Jinan	CN	420	93	Indianapolis, IN	US	12,256
94	Ankara	TR	387	94	Nuremberg–Erlangen	DE	11,948
95	Warsaw	PL	384	95	Gothenburg	SE	11,934
96	Tainan–Kaohsiung	TW	331	96	Lund	SE	11,649
97	Hefei	CN	307	97	Suzhou	CN	11,638
98	Changchun	CN	173	98	Basel	CH/DE/FR	11,420
99	Harbin	CN	148	99	Portland, OR	US	11,323
100	Tehran	IR	57	100	Eindhoven	BE/NL	6,124

Notes: Patent filing and scientific publication counts refer to the 2012–16 period and are based on fractional counts, as explained in the text. Codes refer to the ISO-2 codes. See page 37 for a full list with the following addition: TW = Taiwan, Province of China.

Innovation is now widely recognized as a central driver of economic growth and development. The Global Innovation Index (GII) aims to capture the multi-dimensional facets of innovation by providing a rich database of detailed metrics for 126 economies, which represent 90.8% of the world's population and 96.3% of global GDP. Today a wide range of high-, medium-, and low-income countries are using the GII as a tool for action to improve innovation performance—often at the prime ministerial and ministerial level, and often with specific cross-ministerial task forces comprising a large variety of relevant innovation stakeholders.

The GII 2018 marks the 11th edition of the GII, and the beginning of its second decade providing data and insights gathered from tracking innovation across the globe. The GII work contributes on two important fronts: By collecting innovation metrics, it assists countries to better assess their innovation performance; and by identifying strengths and challenges, it helps empower countries to improve their innovation policies by leveraging strengths and overcoming challenges. By pursuing these two objectives, the GII has helped to shape the innovation measurement and the innovation policy agenda of the countries it analyses.

This year's edition, *The Global Innovation Index 2018: Energizing the World with Innovation*, is dedicated to the theme of energy innovation. The GII 2018 analyses the energy innovation landscape of the next decade and identifies possible breakthroughs in fields such as energy production, storage, distribution, and consumption. It also looks at how breakthrough innovation occurs at the grassroots level and describes how small-scale renewable systems are on the rise.

The GII is co-published by Cornell University, INSEAD, and the World Intellectual Property Organization (WIPO), a specialized agency of the United Nations. The 2018 edition of the GII draws on the expertise of its Knowledge Partners: the Confederation of Indian Industry (CII), PwC's Strategy&, and the National Confederation of Industry (CNI) and Serviço Brasileiro de Apoio às Micro e Pequenas Empresas (Sebrae), as well as an Advisory Board of eminent international experts. For the eighth consecutive year, the Joint Research Centre (JRC) of the European Commission audited the GII calculations.

The GII is concerned primarily with improving the journey towards a better way to measure and understand innovation and with identifying targeted policies and good practices that foster innovation.

The full report and the GII Android and iOS mobile apps can be downloaded at **www.globalinnovationindex.org.**

ISBN 9791095870098

9 791095 870098