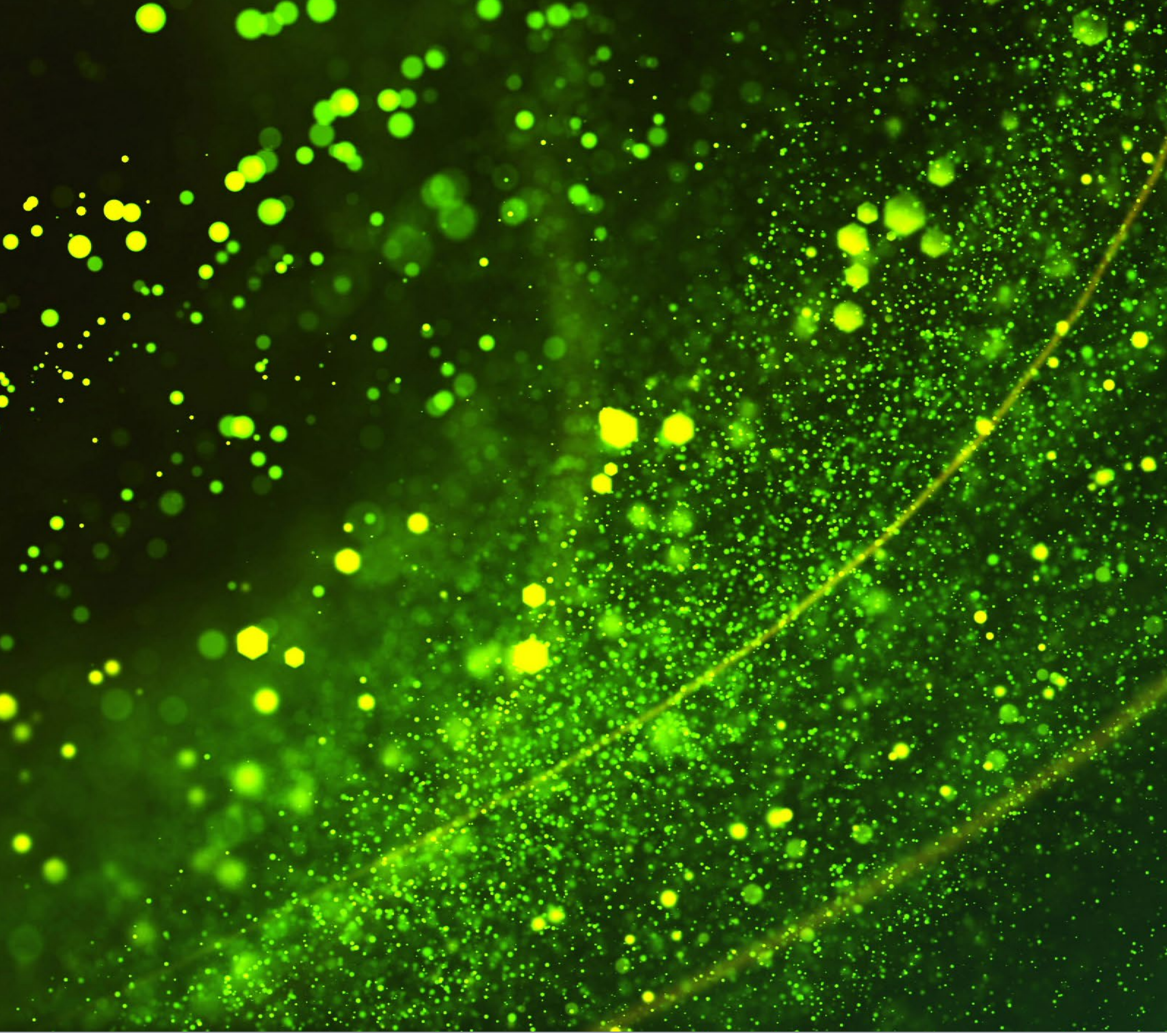
Patents and the energy transition

Global trends in clean energy technology innovation
April 2021



Europäisches Patentamt
European Patent Office
Office européen des brevets

International Energy Agency

Foreword

The energy transition needed to mitigate climate change presents challenges of unparalleled scale and complexity. Many of the technologies needed to cut greenhouse gas emissions are not yet fully mature, whilst the time window available for bringing them to market is closing rapidly. In this context, reliable intelligence on trends in low-carbon energy (LCE) innovation is crucial for supporting sound business and policy decisions.

As the patent office for Europe, the EPO is ideally positioned to first detect and analyse such trends. Because patent applications are typically filed long before products appear on the market, they provide early information on forthcoming technologies. Thanks to our unique access to the world's largest collection of patent and non-patent literature, the EPO is able to exploit that information to produce cutting-edge business intelligence.

Our patent classification scheme for climate change mitigation and adaptation technologies is testament to our commitment to fulfil that role. With millions of patent documents classified across a wide variety of climate change mitigation technologies, it has become a widely-used standard for monitoring progress in green technologies across the world.

Our partnership with the International Energy Agency (IEA) makes it possible to further exploit these resources. By combining the EPO's advanced patent knowledge with the IEA's unparalleled technical and economic expertise in energy, we aim to support decision-making in the public and private sectors with the best possible information on technology trends in this field.

Our new joint study embraces the broad landscape of low-carbon energy technologies. It relies for that purpose on the EPO's dedicated patent classification scheme for such technologies, along with new patent data on fossil fuel technologies that have been developed as a benchmark for this study.

The results reveal encouraging trends and interesting energy transition patterns across countries and industry sectors. However, our report also highlights the need to further accelerate innovation for the technologies – some still emerging – that are poised to play an instrumental role in the energy transition of the next 2-3 decades. By giving decision-makers unparalleled data and analyses about innovative solutions in low-carbon energy, I am confident that this report will help to guide them in driving the vital energy transition.

António Campinos
President, European Patent Office

Foreword

In March of this year top international energy and climate leaders took part in the IEA-COP26 Net Zero Summit, a key milestone in accelerating international collaboration toward clean energy transitions.

Many of the governments present, who represented more than 80% of global GDP and the majority of global energy use and greenhouse gas emissions, highlighted the urgent need to increase the pace and scale of adopting low-carbon technologies, and emphasised that significantly greater private and public investment is needed to quickly harness commercially-available technologies, and to identify and develop breakthrough technologies.

This report examines the landscape of low-carbon energy technologies and covers the past, present and future of clean energy innovation. Recent developments provide welcome grounds for optimism. After a slump in patenting activity during the last decade, we have now seen three years of growth in low-carbon energy (LCE) patenting in many key emerging and cross-cutting technologies.

To provide context to the trends and patterns in low-carbon energy innovation, the report uses new approaches to identify patents related to fossil fuel technologies. The results show fossil fuel patents declining as LCE patents grow. It is clear that to reach our shared objective of net zero emissions, further efforts are urgently required to take this resurgence of clean energy innovation to a new and transformational level. Policy-makers can draw on this report to identify actions that will help bring new technologies to markets and consumers all over the world.

The report's findings are the result of a growing partnership between the IEA and the European Patent Office (EPO) that will help us track progress going forward. It is the second output following our first collaboration which focused on the important area of energy storage.

Dr. Fatih Birol
Executive Director, International Energy Agency

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List of abbreviations

BOS	Balance-of-system
CCUS	Carbon capture, utilisation and storage
CO_2	Carbon dioxide
CSP	Concentrating solar power
EPC	European Patent Convention
EPO	European Patent Office
EV	Electric vehicles
GHG	Greenhouse gas
ICT	Information and communications technology
IEA	International Energy Agency
IPF	International patent families
LCE	Low-carbon energy
LED	Light-emitting diode
Li-ion	Lithium-ion
OCGT	Open-cycle gas turbine
PATSTAT	EPO's worldwide patent statistical database
PEM	Polymer electrolyte membrane
PRO	Public research organisations
PV	Photovoltaics
R&D	Research and development
RTA	Revealed technological advantage
SDS	Sustainable development scenario
SMR	Small modular reactor
TRL	Technology readiness level
Y02	EPO's classification scheme for climate mitigation technologies (see Box 1)

Country codes

AT	Austria
BE	Belgium
CA	Canada
CH	Switzerland
CN	People's Republic of China
DE	Germany
DK	Denmark
ES	Spain
FR	France
IL	Israel*
IN	India
IT	Italy
JP	Japan
KR	Republic of Korea
NL	Netherlands
RU	Russia
SE	Sweden
UK	United Kingdom
US	United States of America

* The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Executive summary

Energy innovation is an inescapable condition of climate change mitigation, occurring against a backdrop of rising policy ambition and a changing technology landscape

Over the last year, many of the planet's largest economies and companies have committed to eliminating their contribution to greenhouse gas emissions by the middle of this century, or soon thereafter. This has focused attention on a planned near-total transformation of the energy system in as little as three decades.

However, the energy sector will only reach net-zero emissions if there is a significant and concerted global push to accelerate innovation (IEA, 2020a). Technologies still currently at the prototype or demonstration phase represent around 35% of the cumulative CO_2 emissions reductions needed to shift to a sustainable path consistent with net-zero emissions by 2070. The successful examples of LEDs or lithium-ion batteries, which took between ten and 30 years to go from the first prototype to the mass market, must set the benchmark for the array of energy technologies needed to achieve net-zero emissions.

Trends in low-carbon energy (LCE) innovation have never been more important to policymaking. Not only do climate change goals demand urgent and informed strategic decisions about innovation, but investment in new technology fields has taken centre stage in proposed recovery plans to combat the impacts of the COVID-19 pandemic (IEA, 2020b).

As described in this report, clean energy transitions are being built using innovations that represent a departure from the types of technologies developed by the energy sector in previous decades. New technologies support a shift to greater reliance on electrical power in a wide range of sectors, with more consumer-oriented solutions and more distributed resources. This is resulting in a focus on smaller unit sizes and a different set of technology customers. These changes are bringing new entrants into the energy systems, increasing the pressure to innovate in product design and raising the role of manufacturing innovations, among other things. As this report describes, the changing dynamics of energy innovation can already be seen in patenting data.

Aimed at decision-makers in both the private and public sectors, this report is a unique source of intelligence on the innovation trends across the energy system, and LCE technologies in particular. Drawing on the EPO's dedicated scheme for patent information on climate change mitigation, the data presented in the report shows the latest trends in high-value inventions for which patents have been filed in more than one office by counting international patent families (IPFs [1]). Highlighting the LCE fields that are gathering momentum and the cross fertilisation taking place provides a guide for policy and business decision-makers to direct resources towards an effective energy transition.

1 Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refer to numbers of IPFs.

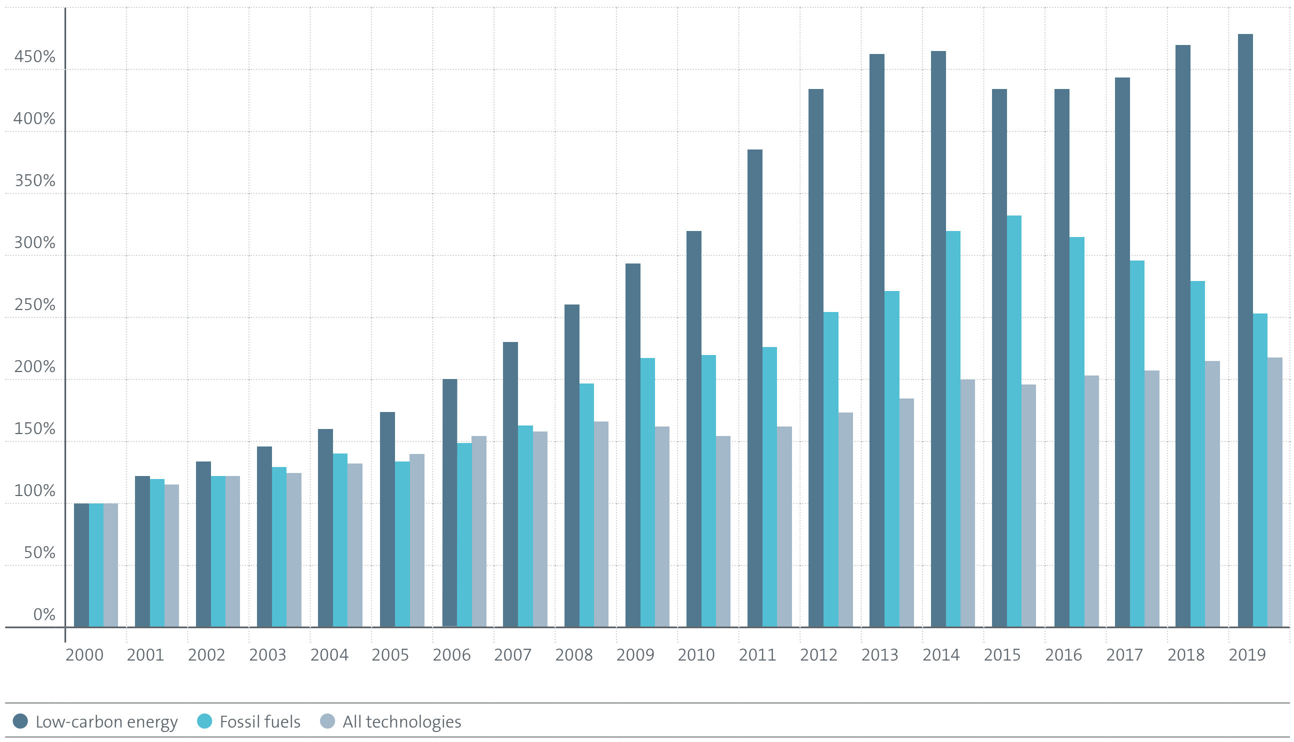
After a rapid rise in the period to 2013, patenting activity in LCE technologies slumped between 2014 and 2016. However, the latest data show three years of growth in LCE, which is a particularly encouraging trend when contrasted with the simultaneous decline of patenting in fossil energy – a four-year decline that is unprecedented since the second World War.

The new drivers are not in energy supply technologies, but rather continued innovation in end-use sectors and rising innovation in cross-cutting technologies such as batteries and hydrogen. Overall, the current growth rate remains below that witnessed before 2013, and an acceleration in activity would be needed to make up for the lost years.

Highlight 1: *From 2000 to 2019, patenting activities have been increasing faster in low-carbon energy (LCE) technologies than in fossil fuel technologies. After a significant drop in 2015, the number of international patent families (IPFs) in LCE areas has resumed growth since 2017, while fossil fuel innovation started to decline. However, the average annual growth rate of LCE patents in recent years (3.3% since 2017) has been considerably lower than the 12.5% average growth in the period 2000-2013.*

Figure E1

Global growth of IPFs in low-carbon energy technologies versus all technologies, 2000-2019 (base 100 in 2000)

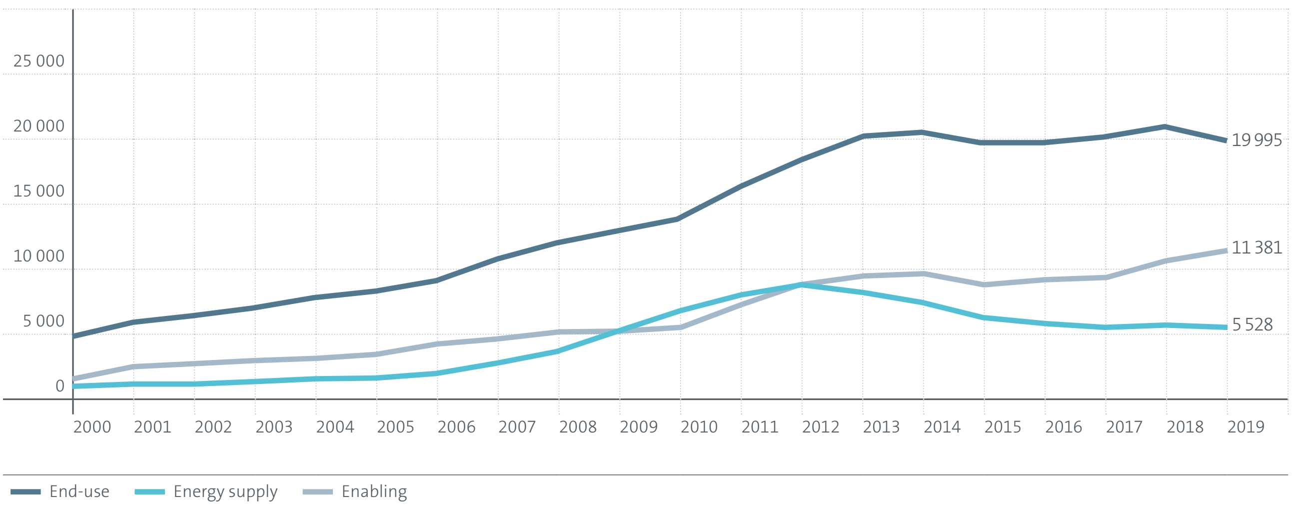


Source: European Patent Office

Highlight 2: *High activity in fuel-switching and energy efficiency technologies in end-use sectors has driven steady LCE patenting since 2012. These areas represent a stable 60% of all LCE patents over the past five years, reflecting the massive challenge of reining in energy demand across the economy. Despite drawing attention, renewables (like wind, solar, geothermal or hydroelectric power) and other LCE supply technologies represented only 17% of all LCE IPFs in 2019. Patenting in these fields has been falling since 2012, in contrast with the fast growth observed in the previous decade. The key driver of LCE growth since 2017 has instead been innovation in cross-cutting technologies such as batteries, hydrogen and smart grids, as well as carbon-capture, utilisation and storage (CCUS), that serve as key enablers of the energy transition. The share of these technologies increased from 27% of all LCE IPFs in 2000 to 34% in 2019.*

Figure E2

Global growth of IPFs in clean energy supply, enabling and end-use technologies, 2000-2019



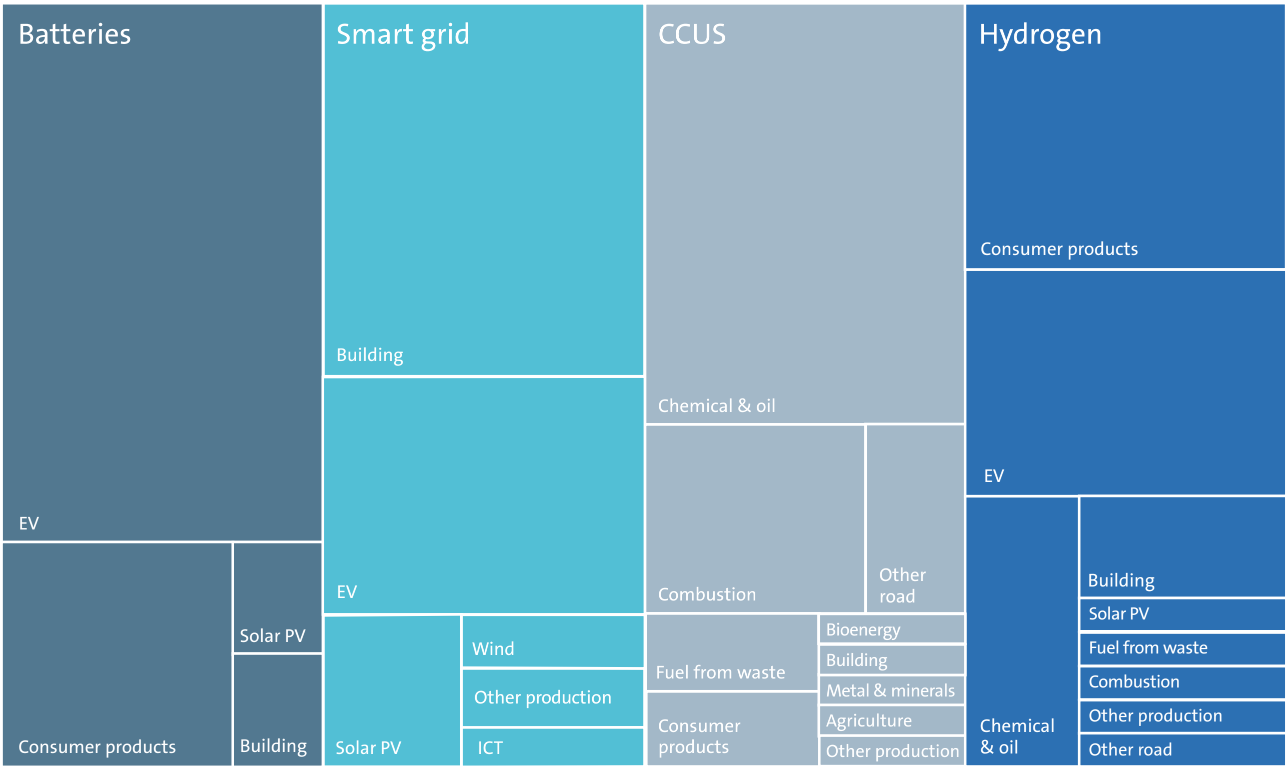
Source: European Patent Office

Highlight 3: *Cross-cutting technologies are playing an increasingly important role as enablers for other LCE technologies. These are helping the energy system to become more flexible and exploit synergies between related sectors. This is illustrated by their increasing overlap with patenting activities in energy supply and end-use technologies. As electricity supply becomes more variable, the flexibility of the power grid and end-use technologies is growing in importance, including their ability to communicate with one another. For example, digital technologies that can adjust the patterns of consumer energy demand to take advantage of energy supplies when they are cheapest are set to become key elements of the overall energy system.*

Today, areas like electricity storage and smart grids are creating market value by supporting higher levels of variable renewable power without compromising electricity network resilience. In future, innovations that help companies offer consumers contracts for the quality of their heating, cooling and vehicle charging – "energy-as-a-service" – while also getting paid by energy suppliers for the demand-side flexibility they can guarantee will further expand these overlaps.

Figure E3

Overlaps of patenting activity in LCE enabling technologies with energy supply and end-use technologies in various sectors, 2000-2019.



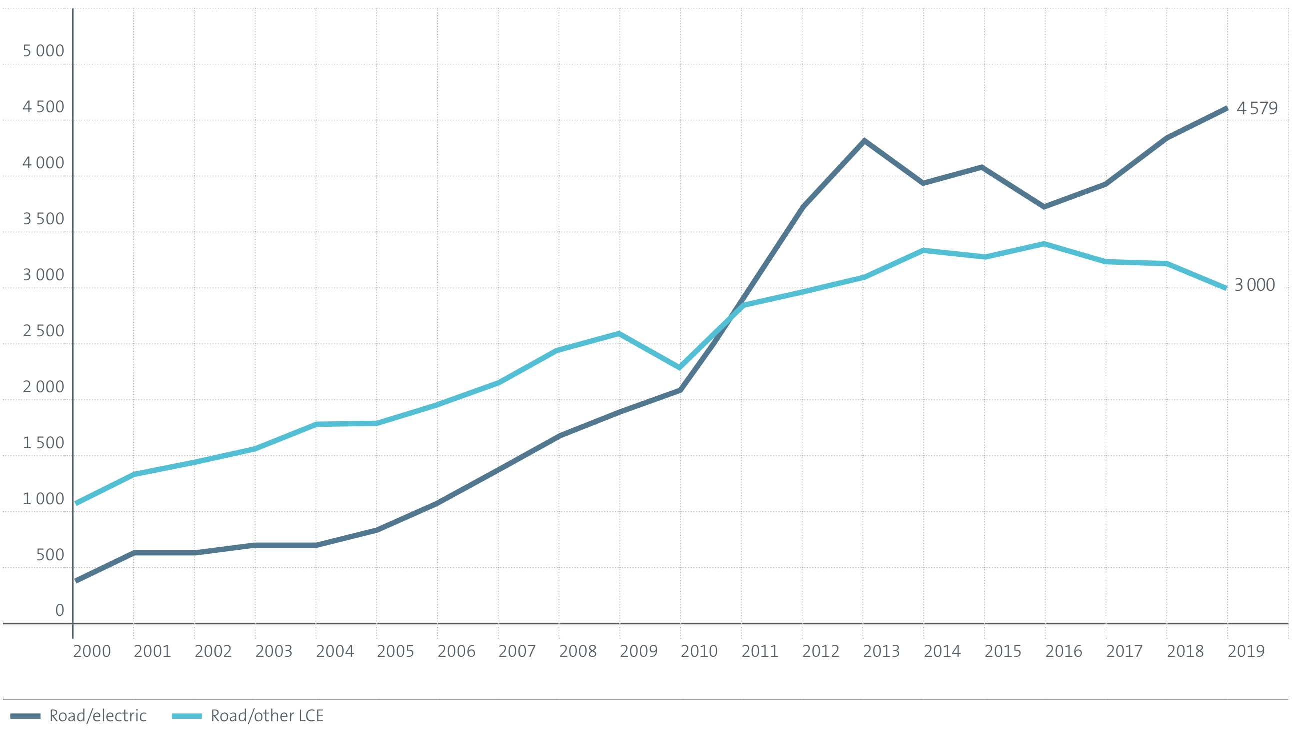
Source: European Patent Office

Electric vehicles are driving the dominance of end-use technologies in low-carbon energy patenting

Highlight 4: *Among the end-use sectors, the fast development of electric vehicles (EVs) and associated infrastructure has been the most powerful driver of innovation in LCE technologies over the past decade. This is visible both in end-use technologies, where the number of IPFs in electric vehicles overtook other clean energy technologies for road vehicles*[2] *as of 2011, and in the fast rise of innovation in batteries as enabling technologies. In addition, there are significant patenting activities in the "hard-to-abate" sectors (e.g. metals), with innovation in both energy efficiency and direct abatement (CCUS).*

Figure E4

Global growth of IPFs in electric vehicles versus other LCE technologies for road transportation, 2000-2019



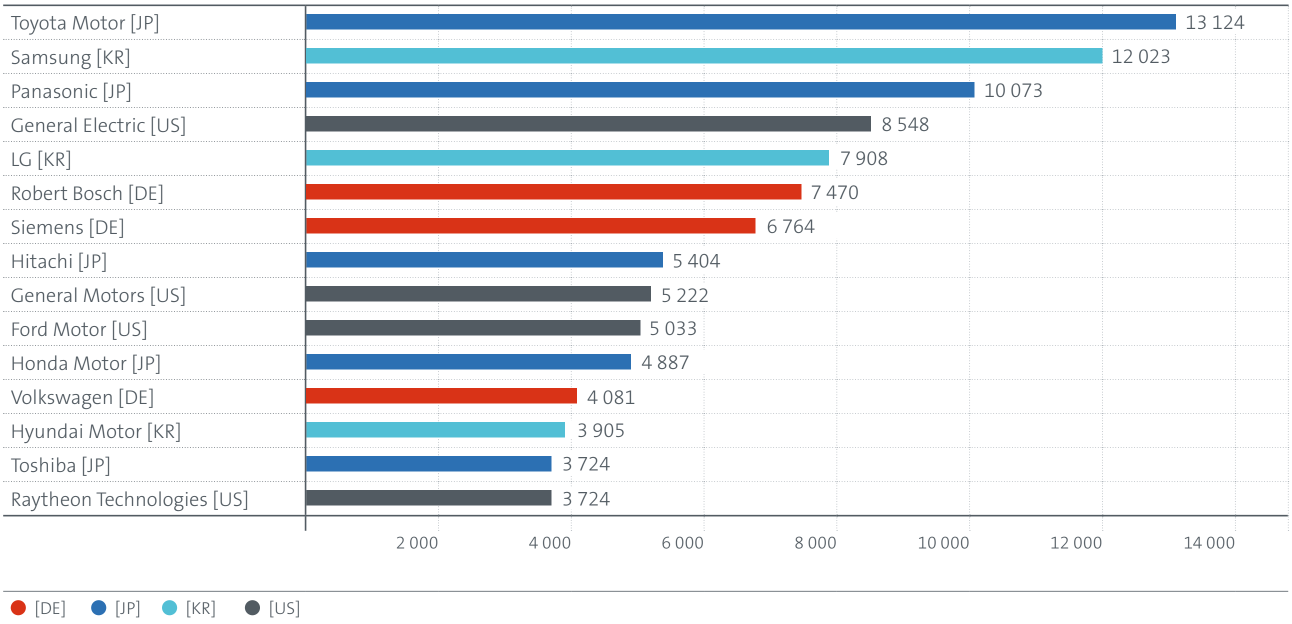
Source: European Patent Office

2 Including technologies aimed at more efficient combustion engines, as well as improved aerodynamics, weight reduction, or more energy-efficient components and subsystems.

Highlight 5: *The list of the top 15 applicants in LCE technologies provides a striking illustration of the expectations for continued growth in EV deployment and the commercial pressure that is driving major manufacturers to compete for a position in this changing landscape for transport. The ranking includes six automotive companies (Toyota, GM, Ford, Honda, VW, Hyundai) and six of their main battery suppliers (Samsung, Panasonic, LG, Robert Bosch, Hitachi, Toshiba). The remaining three top applicants are GE and Siemens – two conglomerates directly involved in the energy sector – and US company Raytheon, which shows a strong specialisation in LCE for aviation.*

Figure E5

Top 15 applicants in LCE technologies, 2000-2019



Source: European Patent Office

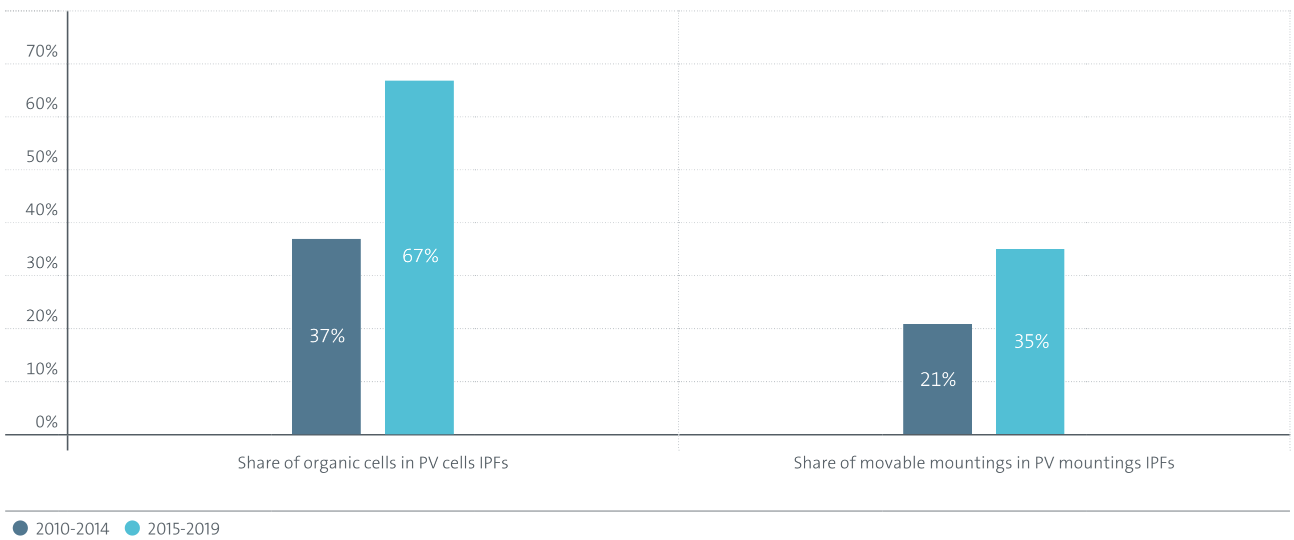
Innovation in energy supply technologies such as solar PV has shifted downstream as deployment has ramped up, but hydrogen – cultivated by research institutions – is still waiting to hit the big time

Highlight 6: *Changes in patenting activity reveal how innovation shifts when technologies pass through the key phases of their development. Since 2010, commercial solar PV panel technologies have largely consolidated around a couple of dominant designs for crystalline silicon cells. Inventive activity shifted to optimising manufacturing and scale-up to push down production costs. This reduced the ability for other designs to reach sufficient scale to compete and decreased the incentive to invent new cell designs, as illustrated by the patent data. Solar power technologies continue to rule the roost among LCE supply technologies.*

However, two notable trends have emerged: a move towards other types of solar PV designs and a focus on technologies for more cost-effective installation and operation. In cell designs, there has been a marked shift in patenting from inorganic to a new generation of organic PV cells. This is paving the way to very low-cost manufacturing and integration as an energy source into many more applications, including windows, wearables and connected objects. And, as prices have fallen for cells and modules, there has been an increase in the value of cost-cutting in installation technologies such as mobile mounting and technologies that increase output such as smart tracking technologies. This has led to a rapid growth in patenting for technologies that raise the performance and local value of solar PV installations, especially in regions that deploy mostly imported solar PV modules.

Figure E6

Emerging technologies in PV cells and mountings, 2015-2019

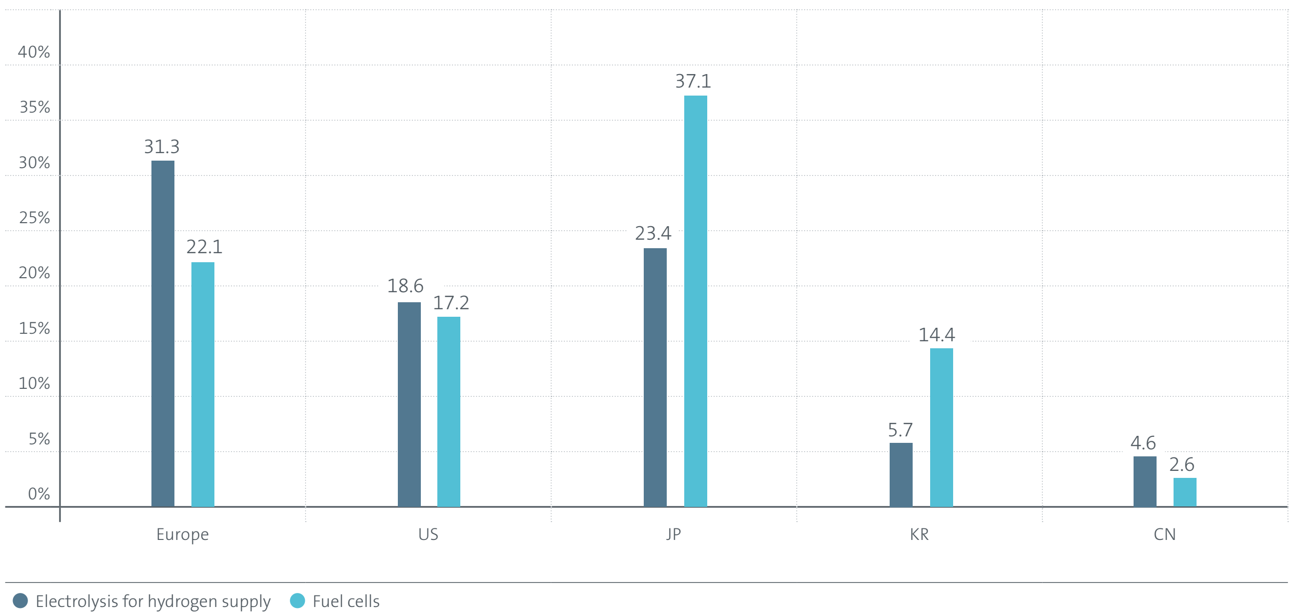


Source: European Patent Office

Highlight 7: *Despite waning attention between 2010 and 2015 and a recent surge in interest in hydrogen, related patenting activities have remained relatively stable. This reflects sustained research funding that has ensured a steady flow of invention and the lack of a market for hydrogen supply or use to generate significant competition and scale-up. Japan clearly dominates research in fuel cells, while Europe is in a leading position in the development of technologies with the potential to supply and store low-carbon hydrogen, including electrolysers. Patenting activities in hydrogen supply and storage have been increasing rapidly between 2010 and 2019 but remain below those for fuel cells. Germany alone accounts for nearly half of Europe's contribution in IPFs related to storage and a third in IPFs related to low-carbon hydrogen supply.*

Figure E7

Share of IPFs in fuel cells and low-carbon hydrogen production, 2010-2019

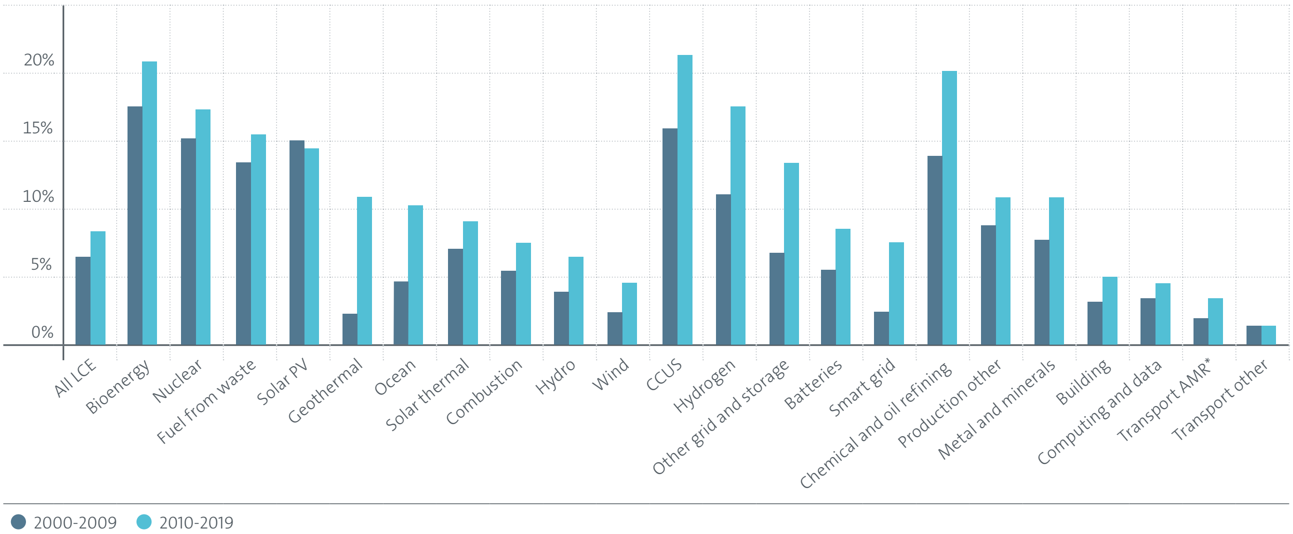


Source: European Patent Office

Highlight 8: *Overall, the share of IPFs in LCE technologies generated by research institutions (universities and public research organisations) has been increasing over the past twenty years, from 6.6% between 2000 and 2009 to about 8.5% between 2010 and 2019. LCE end-use technologies dominate patenting activity for LCEs as a whole, and research institutions are especially active in LCE supply technologies (alternative fuels, nuclear energy and some renewable energies) and emerging enabling technologies such as CCUS and hydrogen. End-use technologies show a lower share of IPFs from universities and public research organisations, with the notable exception of chemical and refining.*

Figure E8

Share of IPFs originating from universities and PROs in LCE technology fields, 2000-2019



Source: European Patent Office

*Notes: AMR = Aerospace, maritime, rail

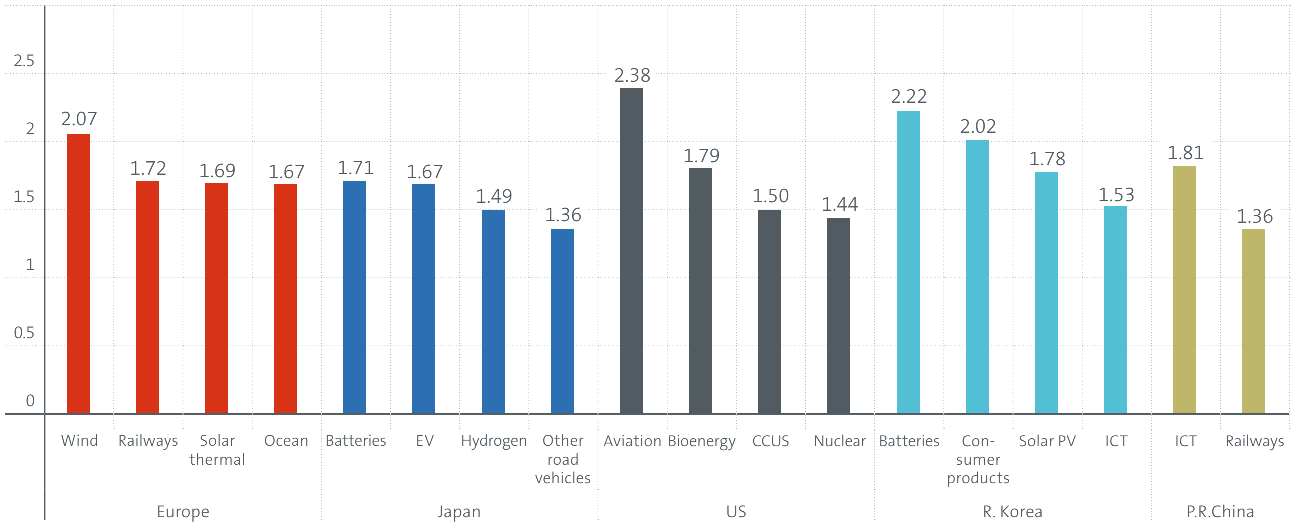
Countries are specialising nationally and collaborating internationally to foster local technology advantages

Highlight 9: *Since 2000, Europe has consistently led patenting activities in LCE, and generated 28% of all IPFs in the period 2010-2019 (with 11.6% for Germany alone). It ranks first in most renewable energy fields and performs well in some end-use sectors such as railways. With 25% of all IPFs since 2010, Japan remained closely behind Europe during the period of analysis, followed at some distance by the US in third position (with 20% of all IPFs).*

Japan is a world leader in batteries and hydrogen, which translates into an advantage in EVs. As well as a strong specialisation in fossil fuel technologies, the US shows a technology advantage in low-carbon combustion (alternative fuels, efficient combustion, nuclear as well as CCUS) and related end-use sectors such as aviation. R. Korea (10% of all IPFs) and P.R. China (8% of all IPFs) remain modest innovation centres in LCE technologies but showed a sustained increase in patenting activities in the past decade. Korea's main strengths lie in batteries, solar PV technology, energy efficiency in production and ICT – the latter also being true for China.

Figure E9

Main revealed technology advantages of global innovation centres



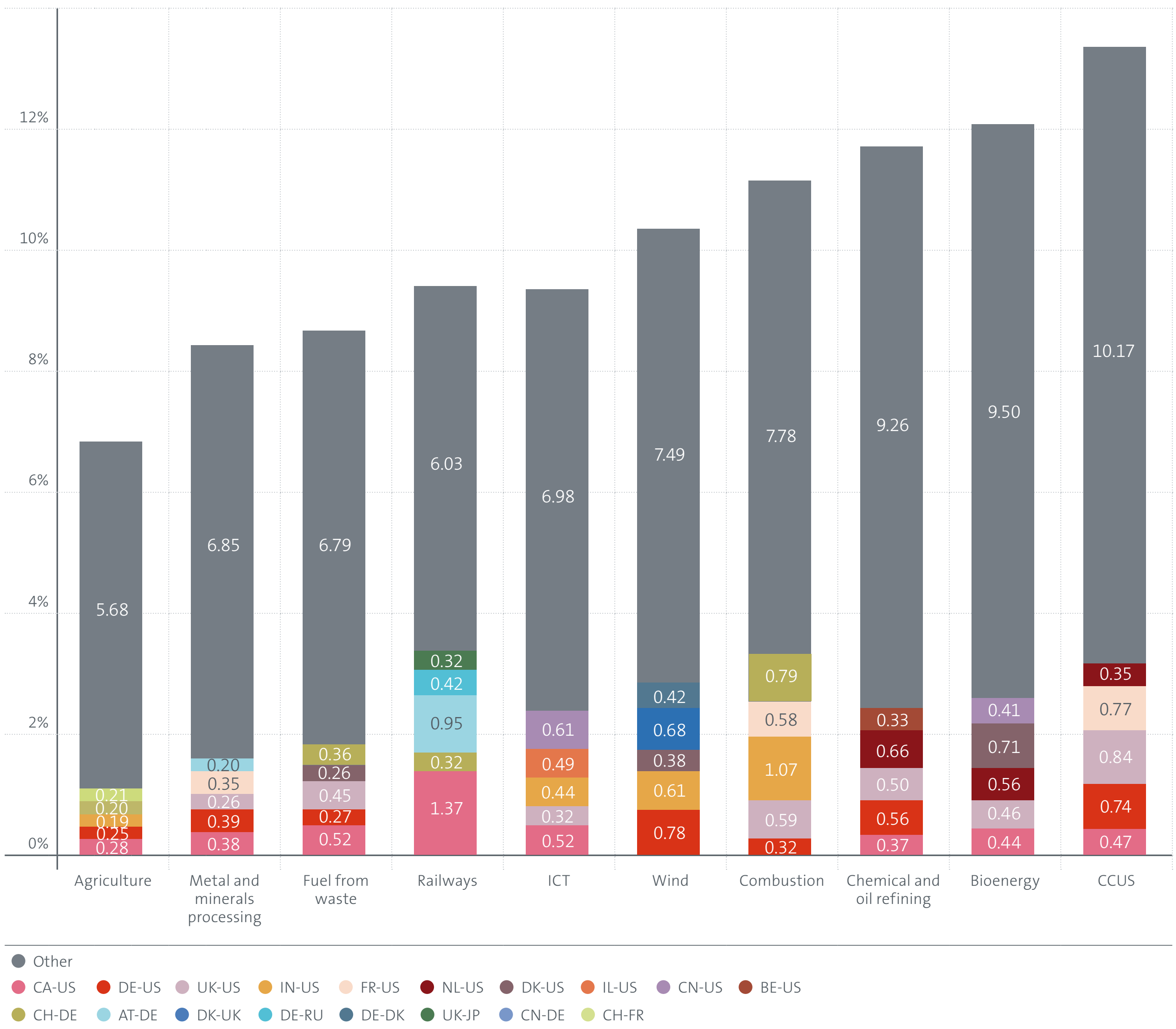
Source: European Patent Office

Notes: The revealed technology advantage (RTA) index indicates a country's specialisation in terms of LCE technology innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology. Only the highest RTAs (approximately 1.5 or more) are reported in the chart.

Highlight 10: *International collaboration for the development of LCE technologies provides a basis to further accelerate R&D efforts by fostering international knowledge diffusion. Collaboration networks typically involve the US and European countries. The US in particular plays a major role in the organisation and technological orientation of those networks. They show a technology advantage in seven of the ten most collaborative fields and are a partner in nearly all of the main bilateral collaborations, with railways being a noticeable exception.*

Figure E10

Top 10 fields for share of IPFs stemming from international collaboration (with top 5 pairs of collaborating countries highlighted in each field), 2000-2019.



Source: European Patent Office

A broadly promising picture of global LCE innovation, with much work still to do

The evidence is promising. Inventive activity has increased in some areas such as batteries and smart grids giving us greater confidence that they can enable clean energy transitions. In addition, end-use technologies occupy a dominant position in LCE inventive activity, reflecting the bigger role they will need to play in the future energy system. In addition, the sources of LCE invention have become broader. Meanwhile, there is an increase in institutional and international research collaboration in fields central to the clean energy transition (CET).

These reported trends are expected to underpin future trends and inform successful clean energy policies. Part of energy innovation still depends on capital-intensive large-scale technologies. However, the broadening of the scope of energy innovation and the entry of new participants is in line with the expansive nature of the clean energy challenge. This is particularly true of the stronger competition between a wider range of energy sources and options for integrating them into resilient systems. If innovators continue to focus on technologies that can be standardised, modular and tailored to consumer preferences, costs of LCE technologies will hopefully continue to fall.

However, the current stagnation in clean energy patenting activity should concern governments and citizens alike. There is no guarantee that ambitious long-term climate change targets will re-energise LCE technology innovation without the right policies to back them up. The threat of COVID-19 to constrain investments in R&D, start-ups and demonstration projects has arrived at precisely the wrong time. Addressing the climate challenge, including keeping the pipeline of improved LCE technologies flowing, requires joined-up government thinking. While the roles of climate and innovation policies are primordial, other policy levers play an important role in encouraging the development and diffusion of LCE technologies. As the kinds of technologies required to bring about the CET become more deeply entrenched in the economy, well-designed competition, consumer, trade and investment policies will complement environmental and innovation policies.

1. Introduction

1. Introduction

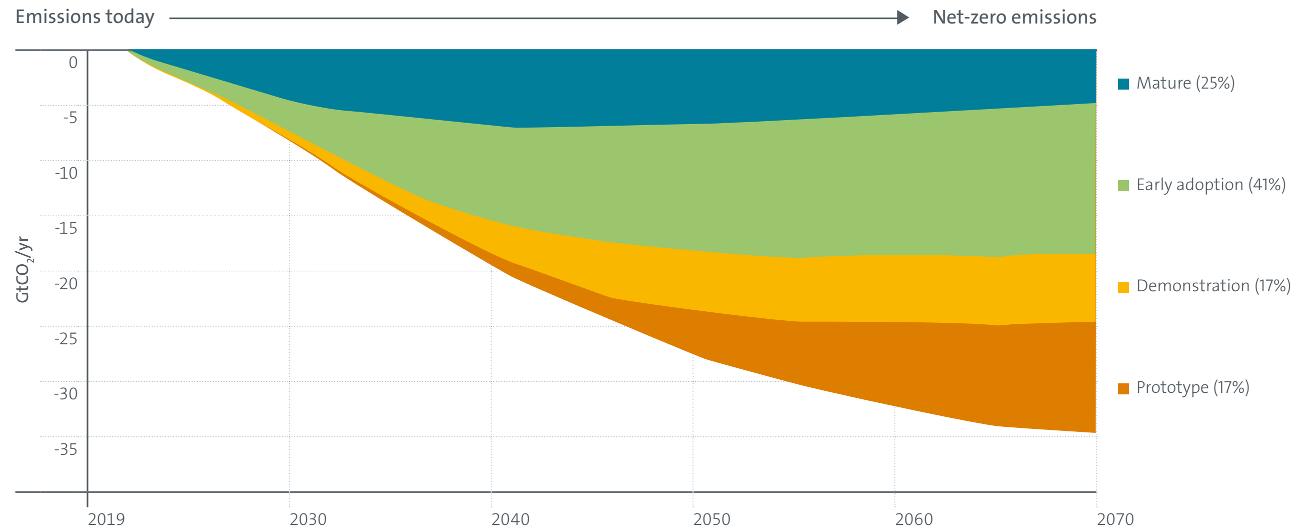
The climate challenge is largely an energy challenge, with three-quarters of global greenhouse gas emissions arising from energy supply and use. In the last year, many of the planet's largest economies and companies have announced that they aim to bring down their emissions to net zero by the middle of this century, or soon thereafter. Net-zero pledges from countries represent more than half of the global economy and around half of the CO_2 emissions from fossil fuel use. This has focused attention on a planned near-total transformation of the energy system in as little as three decades.

However, analysis from the IEA shows that the energy sector will only reach net-zero emissions if there is a significant and concerted global push to accelerate innovation (IEA, 2020a). Technologies still currently at the prototype or demonstration phase represent around 35% of the cumulative CO_2 emissions reductions needed to shift to a sustainable path consistent with net-zero emissions by 2070. For today's early-stage technologies to dominate their sectors by mid-century, we would require more rapid innovation cycles than in recent energy technology history.

The fastest energy-related examples in recent decades include consumer products such as LEDs and lithium-ion batteries, which took ten to 30 years to go from the first prototype to the mass market. These examples must provide the benchmarks for building the array of energy technologies to reach net-zero emissions. According to IEA scenarios, meeting net-zero emissions by 2050 would require robust market deployment right after the completion of only one single commercial-scale demonstration, which is not common practice.

Figure 1.1

Global energy sector CO_2 emissions reductions by current technology readiness category in the IEA Sustainable Development Scenario relative to the Stated Policies Scenario



Notes: the IEA Sustainable Development Scenario maps out a way to meet the key energy-related goals of the United Nations Sustainable Development Agenda, including by mitigating climate change in line with the Paris Agreement. The trajectory for emissions in the Sustainable Development Scenario is consistent with reaching global "net-zero" CO_2 emissions by around 2070. The Stated Policies Scenario assesses the evolution of the global energy system on the assumption that government policies that have already been adopted or announced with respect to energy and the environment, including commitments made in the nationally determined contributions under the Paris Agreement, are implemented. Percentages refer to cumulative emissions reductions by 2070 between the Sustainable Development Scenario and the Stated Policies Scenario enabled by technologies at a given level of maturity.
Source: IEA 2020a: ETP Special Report on Clean Energy Innovation

1.1 Aim of the study

Aimed at decision-makers in both the private and public sectors, this report is a unique source of intelligence on the innovation trends across the energy system, in particular low-carbon energy (LCE) technologies. It draws on the latest information available in patent documents and the combined expertise of IEA analysts and EPO examiners. It is based on an updated international classification of low-carbon innovation that provides a widely used standard for consistent and robust analysis of patents for technologies contributing to climate change mitigation (Box 1).

Trends in LCE innovation have never been more important to policymaking. Not only do climate change goals demand urgent and informed strategic decisions about innovation, but investment in new technology fields has taken centre stage in proposed recovery plans to combat the impacts of the COVID-19 pandemic (IEA, 2020b). In addition, concerns about the demands future clean energy technologies might place upon critical mineral supplies have assumed strategic global importance. Patent data can help inform governments about their comparative advantage at different stages of a technology's value chain and shed light on innovative companies and institutions that may be in a position to contribute to economic recovery and long-term sustainable growth.

The data presented in this report show trends in high-value inventions for which patents have been filed in more than one office.[3] Patent information provides robust statistical evidence of technical progress. Companies and inventors make use of the temporary exclusivity conferred by patent rights to market their innovations and recoup their research and development (R&D) investments. The data highlight the LCE fields that are gathering momentum and the cross-fertilisation taking place. In this way, it also provides a guide for policy and business decision-makers to direct resources towards value creation in energy transition.

BOX 1

Tracking LCE technologies in patent data

As one of the world's main providers of patent information, the EPO is uniquely placed to observe the early emergence of LCE technologies and to track and document their development. The study builds on the EPO's dedicated classification scheme for climate mitigation technologies. The scheme consists of more than 3 million documents and 372 cross-sectional classes that have been designed to cover areas related to specific clean energy technologies (Y02E), smart grids (Y04S), carbon capture and storage (Y02C), and energy-efficient technologies in end-use sectors such as transportation (Y02T), building (Y02B) or industrial production (Y02P).

The Y02/Y04S scheme is an integral part of the Cooperative Patent Classification and freely available in the EPO's patent information products such as Espacenet, the Global Patent Index or the PATSTAT database. The first version of the scheme (Veefkind et al., 2012), developed in the early 2010s, has become the global benchmark for empirical studies related to innovation in climate change mitigation, with hundreds of articles published in peer-reviewed journals.

This study presents data based on a new version of the scheme. It draws upon the combined expertise of the IEA and the EPO to exploit this data to track technical progress in LCE technologies. It also introduces a new fossil fuel technology patent tagging scheme, which is used as a counterfactual benchmark in this report. In the context of clean energy transitions, any change in the rate of invention in LCE technologies should be assessed relative to trends in other energy technologies. To this end, the EPO and the IEA have collaborated to develop a systematic search strategy for analysing patenting for fossil fuel technologies. The scope of the search strategy includes technological developments have the effect of reducing the costs or improving the attractiveness of using fossil fuels. It covers the supply, transformation and distribution of fossil fuels and fossil fuel-based energy products. Technologies that are designed to reduce greenhouse gas emissions from fossil fuel use are included among the LCE end-use technologies, including e.g., efficiency improvements of internal combustion engines.

Throughout the report, focus technology areas – such as solar PV, hydrogen, EVs or industrial processes – are highlighted to illustrate detail behind the high-level trends. Given this report's focus on the aggregate insights from the Y02 classes, it has not been possible to present all of the fascinating technology stories revealed by this analysis, but the authors plan to explore many more of them in future.

3 Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refer to numbers of IPFs. See Annex 3 for further explanations on the methodology.

1.2 Structure of the report

Chapter 2 outlines the technology roadmap towards a decarbonised energy and the way in which patent data can be mapped to LCE technologies. The main trends in LCE patenting in the three categories of (i) energy supply, (ii) enabling technologies, and (iii) end-use technologies are presented in chapter 3. This chapter highlights the critical role of enabling technologies in connecting diverse clean energy solutions. Chapter 4 examines in more detail the nature of the applicants, and chapter 5 highlights the main innovation trends by geography, revealing the evolving technological strengths and advantages of different regions.

About the European Patent Office

The European Patent Office was created in 1977. As the executive arm of the European Patent Organisation, it is responsible for examining European patent applications and granting European patents, which can be validated in up to 44 countries in Europe and beyond. As the patent office for Europe, the EPO is committed to supporting innovation, competitiveness and economic growth across Europe by delivering high-quality products and services and playing a leading role in international co-operation on patent matters. The EPO is also one of the world's main providers of patent information. As such it is uniquely placed to observe the early emergence of technologies and to follow their development over time. The analyses presented in this study are a result of this monitoring.

About the International Energy Agency

The International Energy Agency provides authoritative data, analysis and recommendations across all fuels and all technologies, and helps governments develop policies for a secure and sustainable future for all. The IEA was created in 1974 and examines the full spectrum of issues, including energy security, clean energy transitions and energy efficiency. It is a global leader in understanding pathways to meeting climate goals, reducing air pollution and achieving universal energy access, in line with the United Nations Sustainable Development Goals. Its work on energy technology innovation spans the collection of national data on public energy R&D budgets, regular technology trend analysis and policy guidance for governments. The IEA family of countries accounts for 75% of global energy consumption and includes 30 member countries and eight association countries – Brazil, P.R. China, India, Indonesia, Morocco, Singapore, South Africa and Thailand.

2. Technology roadmap to a decarbonised economy

2. Technology roadmap to a decarbonised economy

Since the turn of the century, patenting activities have been growing faster in low-carbon energy (LCE) technologies than in fossil fuel technologies. The gap further widened after 2015 due to a decline in innovation in fossil fuel supply, including processing and distribution. However, policymakers around the world should be concerned that the rapid growth in LCE patenting between 2000 and 2013 has not been sustained. After a significant drop in 2015, the average annual growth rate of LCE patents since 2017 has been only 3.3%, more than three times lower than the impressive 12.5% average growth sustained by LCE innovation between 2000 and 2013 (Figure 2.1). A boost in inventive activity is needed to accelerate the availability, diversity and cost declines of these technologies.

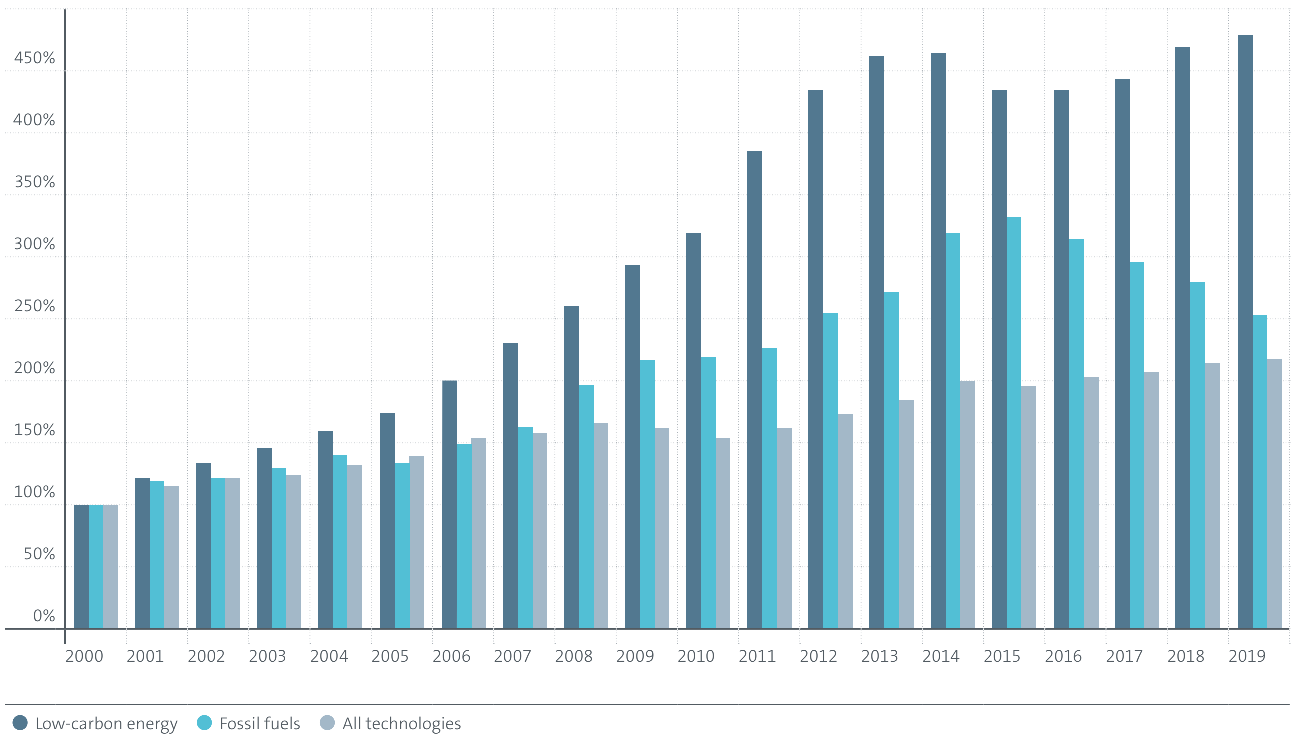
2.1 Beyond the headline trend: capturing the diverse dynamics of energy innovation in the data

The landscape of LCE technologies is diverse and policy insights derive from a more granular analysis of the underlying trends. This study groups a selection of the patent classes related to low-carbon energy to shed light on some of the most pertinent distinctions between technologies. There is a notable distinction between those technologies that generate and supply low-carbon energy and those that facilitate more efficient use of energy in end-use applications or more use of low-carbon electricity in energy end uses, including transport.

A third category of LCE technologies, which cut across supply and end use or enhance infrastructure to accommodate higher levels of clean energy, is classified separately (Table 2.1). Details of the methodology used to identify relevant patent applications and map them to the cartography fields can be found in Annex 1. Each of the categories shown is further subdivided to ensure that the cartography is comprehensive and to enable an analysis at the most granular level possible. A global perspective on the respective impact of these technologies on CO_2 emission mitigation is provided in Box 2.

Figure 2.1

Global growth of IPFs in low-carbon energy technologies versus all technologies, 2000-2019



Source: European Patent Office

Table 2.1

Overview of the cartography and how it maps to key technology gaps

Grouping	Technology area		Examples of innovation priorities to maximise technology potential and their current TRL level
Energy supply technologies	Wind		Floating offshore wind (TRL 8)
	Solar	Solar PV	Concentrated PV (TRL 9) Organic printable thin-film PV (TRL 6)
		Solar thermal	Linear Fresnel reflectors (TRL 7)
		Other solar	Mass production of solar thermal heating (TRL 9)
	Other renewables	Geothermal energy	Kalina cycle low temperature geothermal (TRL 6)
		Hydro	Further standardisation and environmental protection (TRL 9)
		Ocean power	Ocean thermal energy conversion (TRL 4) Wave energy converters (TRL 4) Salinity gradient (TRL 3)
	Fuel of non-fossil origin	Bioenergy	Lignocellulosic ethanol via enzymatic fermentation (TRL 8)
		Fuel from waste	Waste gasification and syngas fermentation (TRL 7)
		Other	Liquid fuels from hydrogen and CO_2 (TRL 6)
	Combustion technologies with mitigation potential		Waste heat recovery systems using phase change materials (TRL 8) Integrated gasification combined cycle to enable CO_2 capture (TRL 7)
	Energy generation of nuclear origin (electricity)		Light water reactor-based small modular reactor (TRL 6) Fusion (TRL 3)
Enabling technologies	CCUS		CO_2 storage in a saline formation (TRL 9) Direct air capture (TRL 6)
	Batteries		Redox flow (TRL 8) Solid state lithium metal battery for vehicles (TRL 5)
	Hydrogen and fuel cells		Salt cavern hydrogen storage (TRL 9) Polymer electrolyte membrane (TRL 8) Solid oxide electrolyser cell (TRL 7)
	Other		Compressed air energy storage (TRL 8) Virtual inertia for fast frequency response (TRL 6)
	Smart grids		Smart inverter (TRL 8) Transactive energy (TRL 4) Gamification of demand response (TRL 8) Level 4+ automated and connected vehicles (TRL 6)
End-use technologies	Buildings		Organic and polymer LED (TRL 9) Highly insulating window (TRL 8) Direct current building, direct current microgrid system (TRL 7) Water heating heat pump (TRL 7)
	Production/chemical and oil refining		BTX from methanol or lignin (TRL 6) Oxy fluid catalytic cracking (TRL 5) Steam cracker electrification (TRL 3)
	Production/metal and minerals processing		CCUS on DRI steel production (TRL 9) DRI steel based on 100% hydrogen (TRL 5) Cement kiln oxy fuelling with CCUS (TRL 6)
	Production/ other	Agriculture Consumer products Other production	Electromagnetic heating for large-scale industrial processes (TRL 5) Folding shearing (TRL 3)
	Transportation/ electric vehicles and EV infrastructure	EV and infrastructure	Electric heavy-duty trucks (TRL 9) Conductive electric road systems (TRL 8)
		Fuel cells for road vehicles	Fuel cell truck (TRL 7) Low-platinum intensity PEM fuel cell (TRL 7)
	Transportation/other road technologies		(Bio)gas internal combustion engine vehicles (TRL 9)
	Other transportation	Aviation	Ultra-high bypass ratio engine (TRL 9) Electric taxiing (TRL 6) Battery and hydrogen planes (TRL 4)
		Maritime and waterways	Rotor sail or kite (TRL 9) Battery electric ship (TRL 8) Solid oxide ammonia fuel cell ship (TRL 4)
		Railways	Hydrogen fuel cell train (TRL 8) Gas hybrid train (TRL 7)
	Computing and communication		Power efficient CPUs and GPUs

Notes: colour coding indicates the status of the technology areas in comparison with the deployment levels in the Sustainable Development Scenario and as assessed in the IEA's 2020 Tracking Clean Energy Progress report (IEA, 2020c). Green indicates "on track". Orange indicates "more efforts needed". Red indicates "not on track". The examples of innovation priorities are from the IEA ETP Clean Technology Guide, which contains explanations of technology readiness levels (TRL) as an indicator of technology maturity (IEA, 2020d). The highest achieved TRL is shown for a given technology, which may not correspond to its competitiveness in the marketplace or to the TRL level of the most promising design of that technology today.

BOX 2

IEA scenarios reveal the scale of the challenge

The IEA World Energy Outlook and Energy Technology Perspectives scenarios project how the global energy system might evolve over the coming decades. The Sustainable Development Scenario (SDS) sets out an ambitious and pragmatic vision of how the global energy sector can evolve in order to achieve the critical energy-related sustainable development goals (SDGs): achieving universal access to energy (SDG 7), reducing severe health impacts caused by air pollution (part of SDG 3) and tackling climate change (SDG 13). The IEA starts by looking at the SDG target and then works backwards to set out what is needed to deliver these goals in a realistic and cost-effective way.

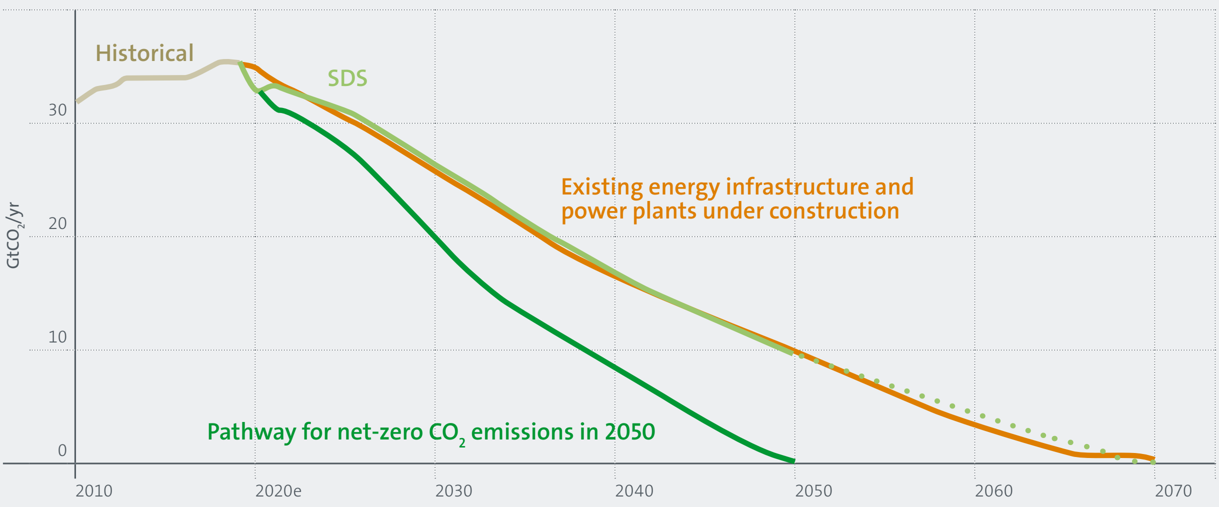
The SDS incorporates the most ambitious climate objectives and targets being considered by governments around the world and relies on their full implementation, alongside rapid and wholesale changes in all other parts of the energy system. As a result, many of the advanced economies will reach net-zero emissions by 2050, or earlier in some cases, and global emissions are on course to reach net zero by 2070. This puts the world firmly on track to limit the temperature rise to well below 2°C. It limits the temperature rise to 1.5°C in 2100 on the assumption that negative emissions technologies are deployed in the second half of the century (at levels towards the lower end of the range seen in scenarios assessed by the Intergovernmental Panel on Climate Change).

We require a wide array of technological changes as well as changes in investment patterns and other behaviours to shift the world to the SDS from the trajectory it would follow under existing government policies today. This challenge has three main components. Firstly, new demand for energy services, especially in emerging and developing economies, must be met in a sustainable way. Secondly, existing assets at the ends of their lives must be replaced in the most energy-efficient or low-carbon manner. Finally, in some cases, expected future emissions from recently installed assets must be reduced by capturing the emissions, or using them less. The scale of the latter is often little appreciated – CO_2 emissions from the continued use of existing energy infrastructure and power plants under construction would on their own lead to a global average temperature rise of around 1.65°C by 2070 (Figure 2.2). To reach net-zero emissions by 2050, many of these plants would need to be retrofitted, closed or operated far less.

Against the backdrop of the SDS, the IEA tracks the overall progress made in developing and deploying LCE technologies in its annual Tracking Clean Energy Progress report, as well as the policy framework conditions surrounding all key technologies needed to achieve the energy transition. The IEA is currently developing a global roadmap for the energy sector to reach net-zero emissions by 2050, to be published in mid-2021.

Figure 2.2

Historical and projected CO_2 emissions from existing energy infrastructure and emissions pathways in IEA climate change mitigation scenarios



Source: World Energy Outlook 2020, IEA 2020e

2.2 The rising importance of end-use and enabling technologies for clean energy

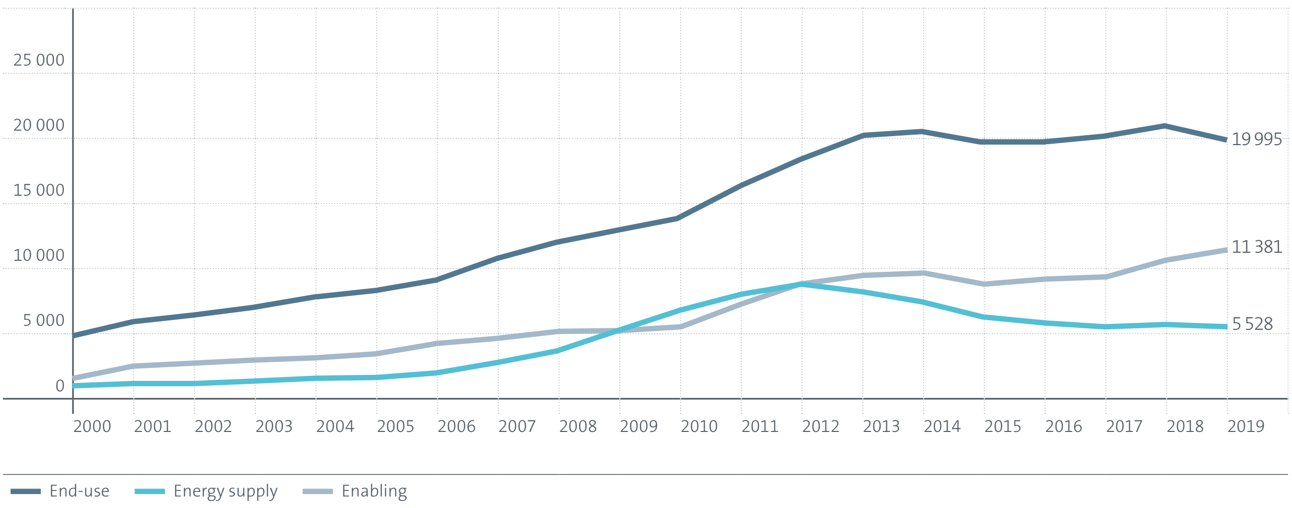
As indicated in Figure 2.3, most of the patenting activity for LCE technologies is related to end-use technologies, and not the supply of low-carbon energy. In 2019, end-use technologies represented more than 60% of LCE technology patenting. While patenting in the area of low-carbon energy supply has declined to 17% since 2013, patenting in end-use technologies has remained relatively stable.

At the same time, there has been a rise in patenting in enabling technology areas such as electricity storage and smart grids, which now have clear market value for the resilient operation of electricity networks with higher levels of variable renewable power. Patenting activity for enabling technologies has risen from 27% of all LCE IPFs in 2000 to 34% in 2019. As electricity supply becomes more variable, the flexibility of the power grid and end-use technologies, including their ability to communicate with one another, is growing in importance. For example, as end uses become more electrified, digital technologies that can adjust the patterns of consumers' energy demand to take advantage of energy supplies when they are cheapest (known as "demand-side response") will become key in managing the overall energy system.

Patenting in LCE supply technologies peaked in 2012, and has recently been declining in line with patenting in fossil fuel supply (chapter 3). Meanwhile, patenting for end-use and enabling technologies has maintained an overall stable trend. However, there is still a need for innovation in LCE supply technologies, despite the market forces propelling wind and solar PV in all regions. The dip seen in the period from 2012 needs to be an aberration.

Figure 2.3

Global growth of IPFs in LCE supply, enabling and end-use technologies, 2000-2019



Source: European Patent Office

2.3 End-use and enabling technologies are accelerating new types of innovation

Innovation in energy technologies transformed the twentieth century, as gas turbines, nuclear power and electricity networks revolutionised the availability of high-quality energy. The pace of change needed for today's energy transitions need only replicate the fastest speeds of technology development in recent history. However, changes in the characteristics of energy technologies have introduced new dynamics in energy innovation that help explain some of the patenting trends over the past two decades. These changes will underpin future trends and provide information for successful clean energy policies.

Much of past energy innovation arose from large companies that benefitted from high levels of market power. These companies, mostly in energy supply sectors but also in industry and transport sectors, operated sizeable research facilities and controlled extensive infrastructure and markets for deploying new technologies. This model was often a good fit with the economies of scale and precision engineering inherent in nuclear energy, fuel processing and combustion. However, the scope of energy innovation has broadened out with the widespread introduction of more energy sources and associated energy system challenges.

Two main ways in which many LCE technologies differ include:

Economies of scale in different places in the value chain. Traditional fuel power plants and refineries typically have large economies of scale in plant-level capital and fuel costs. The benefits of building a relatively small number of large facilities often outweighs the benefits of highly standardised designs and mass production of the major components. In contrast, LCE technologies often have limited economies of scale at plant level, but larger economies of scale in equipment manufacturing and network effects. This is primarily for three reasons:

- Efficiency does not generally increase with the size of photoelectric, electrochemical, electrical or digital units.
- Renewable energy has a diffuse resource base, and costs are not significantly lower when wind, solar, bioenergy or ocean energy plants are geographically concentrated.
- Plant size is more likely to be limited by the needs and capital resources of consumers, who own a higher share of energy supply and enabling technologies, as well as critical end-use technologies with a more active role in clean energy systems.

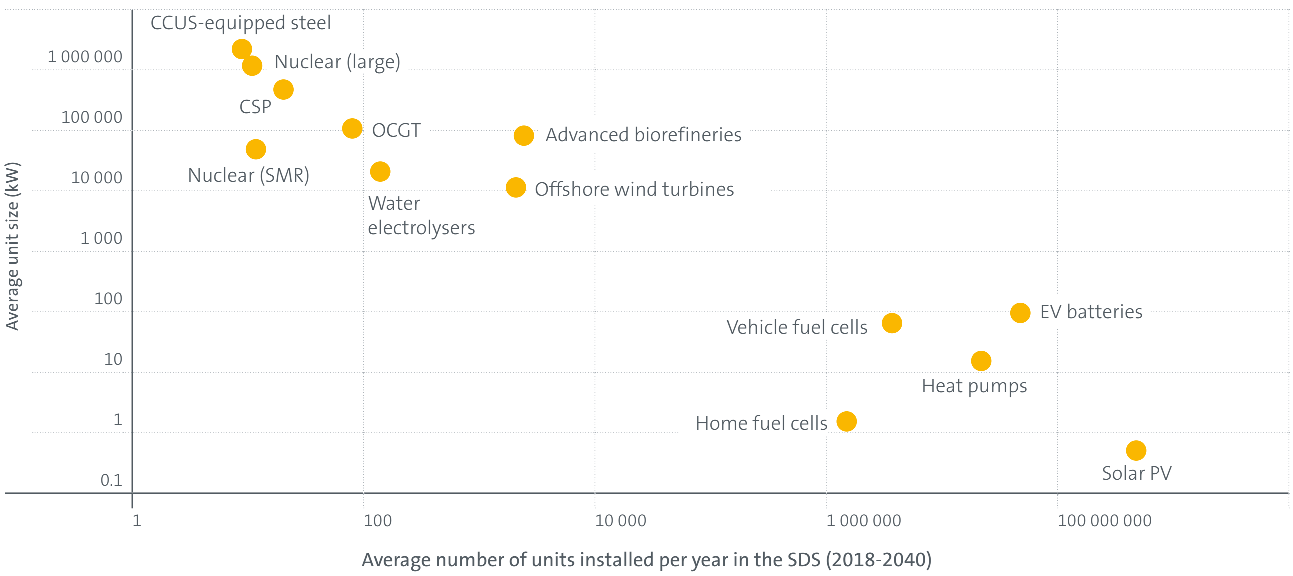
Higher penetration of variable renewable energy and more use of electricity for end uses. This places more importance on the demand profile of end-user technologies and increases the market value of flexible enabling technologies. For example, innovations that help charging vehicles to be more responsive to minute-by-minute changes in external factors are more valuable in resilient systems.

These two differences (new dynamics of economies of scale and more value for flexibility) have fundamental impacts on innovation, relating to technology sizes, users, owners and producers.

In terms of **size**, the lower incentives for plants to reach large economies of scale favours smaller units. Fuel cell, battery and solar PV units are designed for energy throughput of up to 0.1 kW to 100 kW. They are deployed at rates of 100 000 to more than 400 million units per year worldwide in the IEA Sustainable Development Scenario. New nuclear designs, CCUS and low-carbon industrial processes are similar in many ways to the types of technologies that have dominated energy supply over the past century (each unit is designed for 50 MW to 2 GW of energy throughput) (Figure 2.4). For smaller units with many buyers, new products with improved features can hit the market every few years and there can be rapid progression through multiple generations of technology for every gigawatt or terawatt of capacity installed. This has been observed in the early days of solar PV and the deployment of lithium-ion batteries.

Figure 2.4

Low-carbon technologies by unit size and average annual installations in the Sustainable Development Scenario



Source: World Energy Outlook 2019, IEA 2019a.

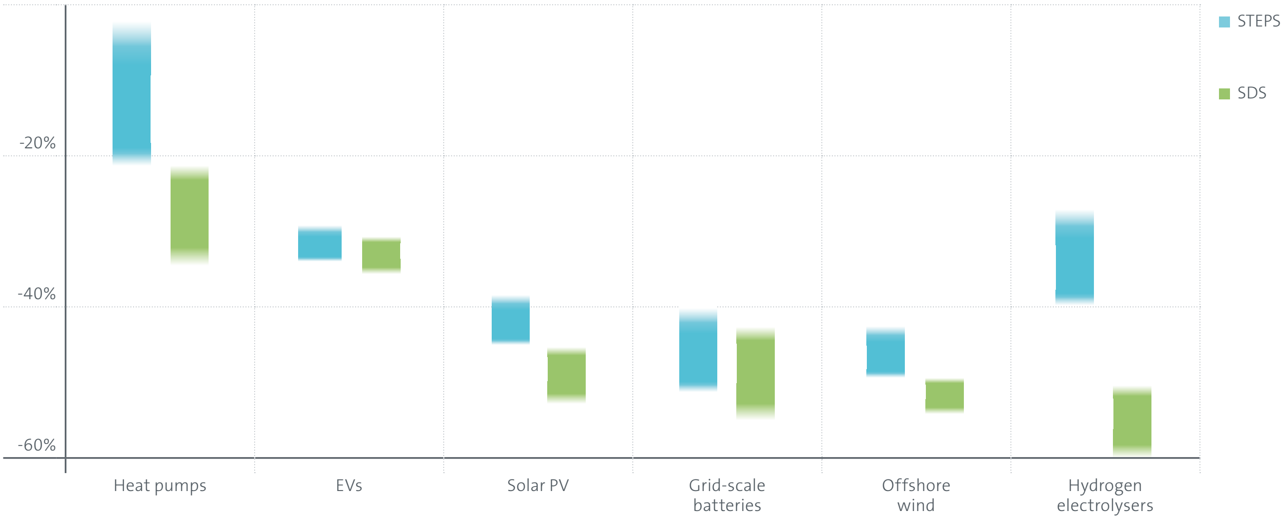
Notes: CCUS = carbon capture, utilisation and storage; CSP = concentrating solar power; SMR = small modular reactor; EV = electric vehicles; OCGT = open-cycle gas turbine; PV = photovoltaics; SDS = Sustainable Development Scenario. Capacities refer to rated maximum energy output. For technologies that do not have output rated in energy terms, energy throughput for the relevant technology component is used.

There is more opportunity for **product differentiation**. This is because citizens are more involved as buyers and owners of critical assets in clean and resilient energy systems. Many important end-user technologies are consumer goods such as EVs, appliances, heat pumps and even energy efficient homes. Consumers of these products value multiple attributes, not just reliability and cost, and often prefer personal ownership to communal solutions. Innovators have wide scope to develop solutions at different price points to meet consumer wishes. This can be especially useful at market entry if there are early adopters willing to pay for the low-carbon option. It can also drive competition between multiple suppliers who can compete across numerous dimensions, including cost, design, comfort, convenience, size and speed.

Standardisation, modularity and mass production are more important for smaller products with no fuel costs. For these technologies, the benefits of economies of scale in manufacturing can outweigh any disadvantages brought by a lack of tailored solutions for each application or size of project. Competition on the basis of the cost of standardised products leads to more invention in manufacturing processes and cost reductions that closely follow the level of cumulative production – so-called learning rates (Figure 2.5). Furthermore, if a technology can improve the productivity of many applications, then there are more opportunities to innovate, improve and dominate (the most widespread examples are called "general purpose technologies"). This has already been seen with solar PV, batteries and LEDs, and it is expected for electrolysers, fuel cells, and even modular options for capturing CO_2 directly from the air.

Figure 2.5

Capital costs for selected energy technologies in 2040 relative to 2019



Source: World Energy Outlook 2020, IEA 2020e

Less vertical corporate integration along the supply chain is likely to be a more efficient means of providing energy services when assets are smaller, distributed and connected. Enabling technologies – including smart meters, bidirectional networks and variable load regulators – facilitate further unbundling of the different elements of energy services. A far wider variety of entities can compete to provide services in separate markets for peak power supply, demand response and frequency control. This disaggregation of the market, coupled with technologies that have low operational costs, reduces barriers to entry for businesses with new technologies, thereby fostering competitive innovation.

In addition, **lower scope for horizontal monopoly behaviour** is expected in an energy system with lower plant-level economies of scale. With lower barriers to entry for smaller asset owners or so called virtual power plants with no physical asset ownership, the incentives for technological innovation are likely to be higher. Connected end-use technologies as well as geothermal energy, onshore wind and mini-grid systems are expected to benefit, and there are emerging examples of innovative ways to pair renewable energy projects with energy storage or provide pay-as-you-go energy to remote locations. A further result of lower barriers to market entry is more involvement of venture capital investors in innovative energy-related technologies, with higher investor confidence that start-ups can follow in the footsteps of Tesla, Northvolt and Array Technologies. In 2020, clean energy start-ups in fields such as smart grids, electric vehicles and end-use energy efficiency were the most successful at attracting investment (IEA, 2021). This dynamic can provide a higher incentive to patent, as patenting can attract early-stage equity investment (Hall, 2019).

However, these dynamics are not relevant to all clean energy transitions. Several major challenges for emissions reduction are expected to need large-scale solutions with plant-level economies of scale. These include large process technologies for materials production and the large engines of ships and aircraft. In other areas, such as the hydrogen economy, convenient drop-in solutions for end users could be provided, but rely on system-wide developments, including large infrastructure developments. While venture capital investors show increased confidence in the growth potential of clean energy, they often focus on incremental improvements to parts of the energy system already in transition. These include digital optimisation technologies. Key large-scale technologies for industry and transport are generally less mature and likely to need more government support at all stages of the innovation process. Government policies for net-zero emissions need to increase the incentives for inventors to tackle these more uncertain and costly challenges.

3. Main technology trends

3. Main technology trends

Using the cartography of LCE technologies described in chapter 2, we identified a total of 421 537 IPFs, each corresponding to an LCE invention patented in two or more jurisdictions or in a regional patent office globally between 2000 and 2019. This chapter looks at the main trends in these inventions over the last two decades and across different technology fields and sectors.

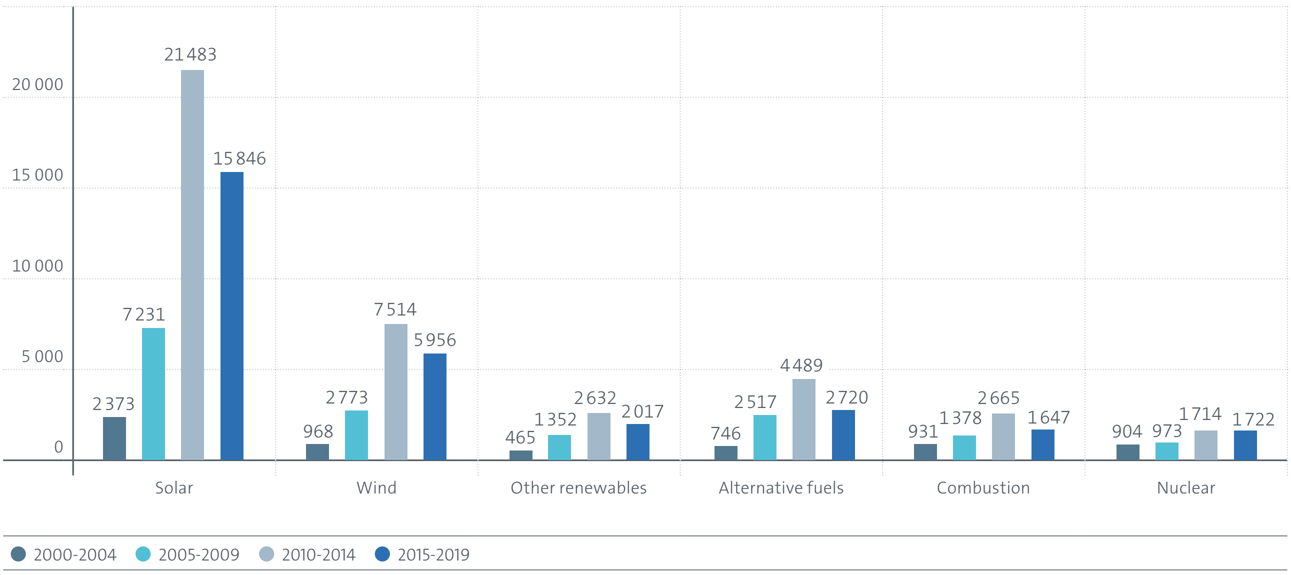
3.1 Trends in energy supply technologies

LCE supply technologies supporting the energy transition include renewable energy technologies (e.g. wind, solar, marine, hydro and geothermal energy), alternative fuels (e.g. biofuels and fuels from waste) as well as nuclear energy and efficient combustion technologies with potential to save GHG emissions. Among them, technologies related to solar energy – and in particular solar photovoltaic energy (Box 2) – generated by far the largest volume of patenting activities (with 46 500 IPFs between 2000 and 2019), followed by those related to wind energy (17 000 IPFs) [4] and alternative fuels (10 000 IPFs). In comparison, other renewable energies, nuclear and efficient combustion technologies show relatively low levels of patenting during the same period (respectively 2 000, 5 000 and 6 600 IPFs between 2000 and 2019).

However, between 2015 and 2019, all technologies related to LCE supply show a similar decrease in patenting activities, after experiencing a long period of sustained growth from 2000 to the beginning of the 2010s (Figure 3.1). Given that a similar decline can be observed in the case of fossil fuel exploration and extraction technologies, it is possible that innovation directed to the supply side of energy underwent a general decline in recent years. LCE supply technologies fared no better, despite policy action to favour them, including allocating 80% of public energy R&D funding to low-carbon energy (IEA, 2020f).

Figure 3.1

Growth of IPFs in energy supply technologies, 2000-2019



Source: European Patent Office

4 The proportion of IPFs focused on offshore versus onshore wind energy has remained stable over the whole period of analysis, with approximately two IPFs related to onshore wind for every IPF related to offshore wind. However, given the considerable overlap between these two areas, onshore wind IPFs likely include many developments that are applicable to both onshore wind and offshore wind.

BOX 3

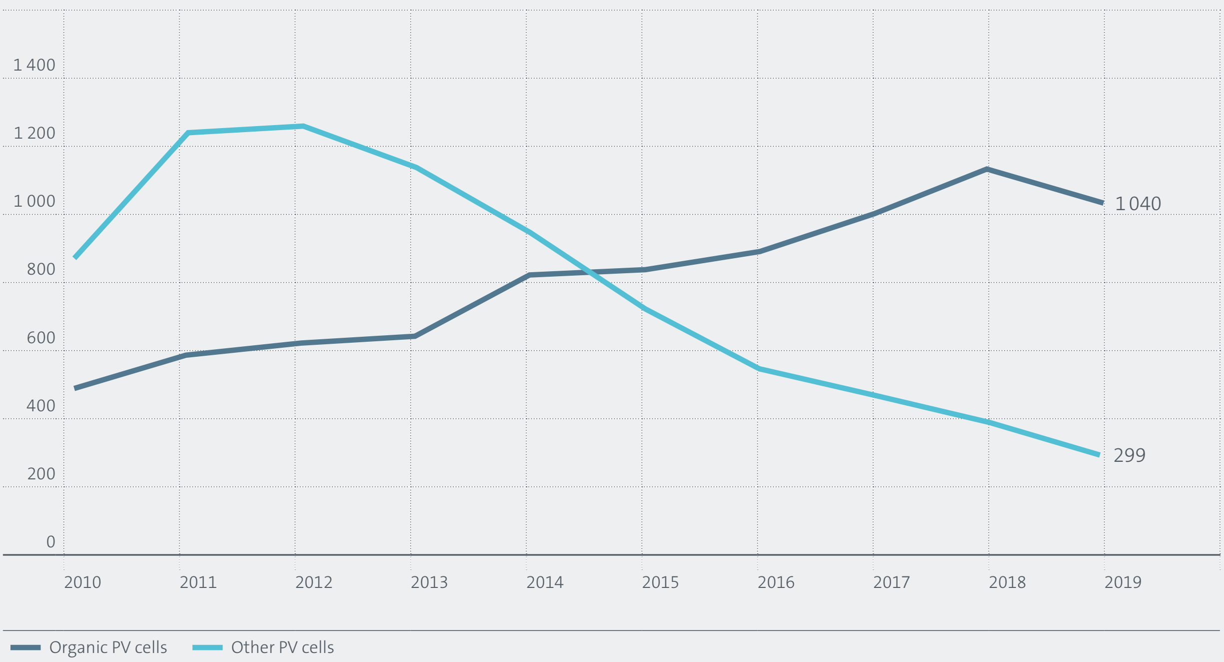
Latest trends in solar PV technologies (2010-2019)

Over the past decade, the market for solar PV has expanded dramatically, shifting the focus of inventive activity. Between 2010 and 2020, annual global installations of solar PV rose more than six-fold, from 17 GW to over 100 GW per year, more than any other electricity source. At the time, annual investment in these installations was relatively flat, reaching nearly USD 140bn in 2019 before the start of the COVID-19 pandemic, just 13% higher than in 2010. To achieve these two trends in parallel, the solar PV industry rapidly scaled up mass manufacturing of cells packed into modules that could be shipped worldwide in standardised formats. In technology terms, there was market consolidation around types of cells that could compete in a highly competitive price environment. In addition, there was intensive effort to innovate new manufacturing processes that could minimise waste and shave costs in a low-margin industry. Alongside these innovations, there were equally impressive cost reductions in "balance-of-system" (BOS) costs that include inverters, racking, mounting and installation. The share of BOS costs in total costs for utility-scale solar PV has been relatively stable over the past decade. For example, it has remained around 50% in Italy.

Solar PV cells are still the most technology-intensive element and continued to generate the largest proportion of solar PV patenting activities (48% in the period 2010-2019). However, the industry's transition to a cutthroat manufacturing business meant there were few opportunities for new entrants to gain a foothold against the major crystalline silicon makers. This caused a decline in invention in crystalline and thin-film cells, which had been tussling for market leadership. In their place, there has been a steady rise in patenting activity in a new competitor field, namely organic PV cells. Organic cells are a more recent generation of PV cells, based on conductive organic polymers or small organic molecules. Compared with silicon-based devices, they are lighter, more flexible and more customisable on the molecular level, and allow for new applications as an energy source on supports such as windows, wearables and connected objects. However, they are significantly less efficient than other cells on the market and not yet fully competitive. Japan and Korea lead with PV cells. China has replaced the US, which specialises in non-organic PV cells, in the domain of organic cells.

Figure 3.2

IPFs in organic PV cells versus other types of PV cells, 2010-2019



Source: European Patent Office

The increasing reliance on standardised module imports, especially from China, means that much competition, and therefore profitability, has been around BOS costs. Power conversion systems and mountings and tracking have been dynamic BOS innovations, which have helped to reduce the total costs of power generation from solar PV (Figure 3.3). Europe and the US are clearly dominant in mounting and tracking technologies, which are increasingly focused on smart, flexible applications allowing for solar tracking. Japan and China show some specialisation in power conversion systems, despite trailing Europe in terms of share of global IPFs in this field. Concentrator photovoltaics, a specific technology using lenses or curved mirrors to focus sunlight onto solar cells, is no longer a major priority area, after generating important patenting activities in the early 2010s.

Table 3.1

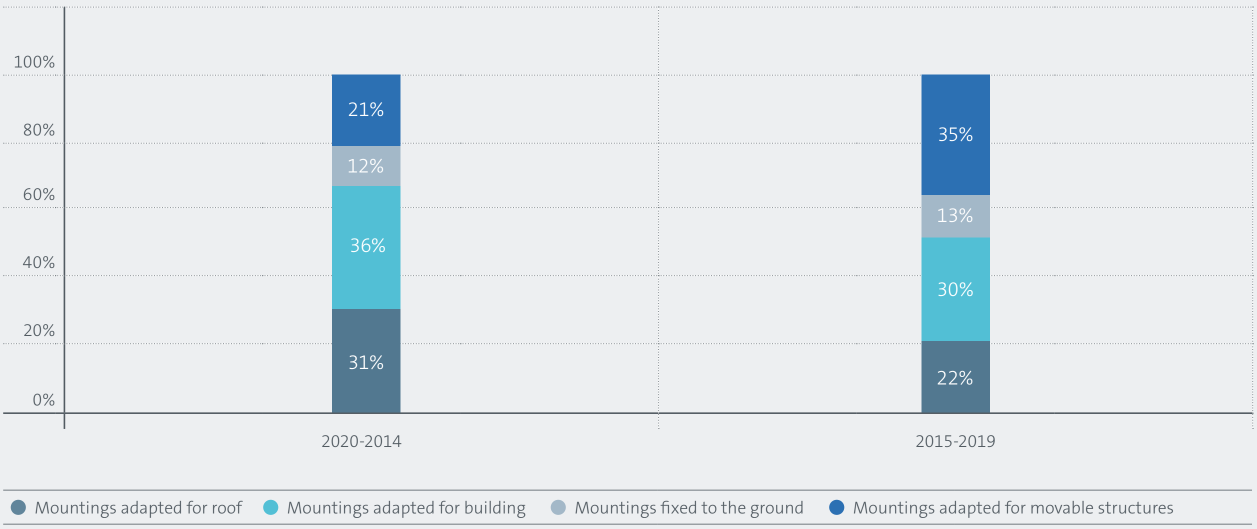
Distribution of global IPFs in PV technology between the world main regions, 2010-2019

	No. of IPFs, 2010-2019	Growth 2010-2019	EPC share	US share	JP share	KR share	CN share
PV cells, organic	8 052	111%	20.3%	9.0%	25.0%	**26.0%**	13.5%
PV cells, other	7 908	-54%	17.3%	20.8%	31.0%	**16.7%**	4.1%
Mounting or tracking	3 326	11%	33.9%	25.0%	11.3%	8.3%	9.7%
Power conversion	3 312	33%	26.7%	20.4%	24.2%	7.0%	11.4%
Concentrator PV systems	3 316	-46%	24.0%	23.9%	22.1%	9.7%	5.9%

Note: the colour codes indicate the RTA, calculated with respect to a region's share in all types of technologies. Highlighted ranges (from lightest to darkest blue) are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

Figure 3.3

Innovation trends in mounting and tracking



3.2 Trends in end-use technologies

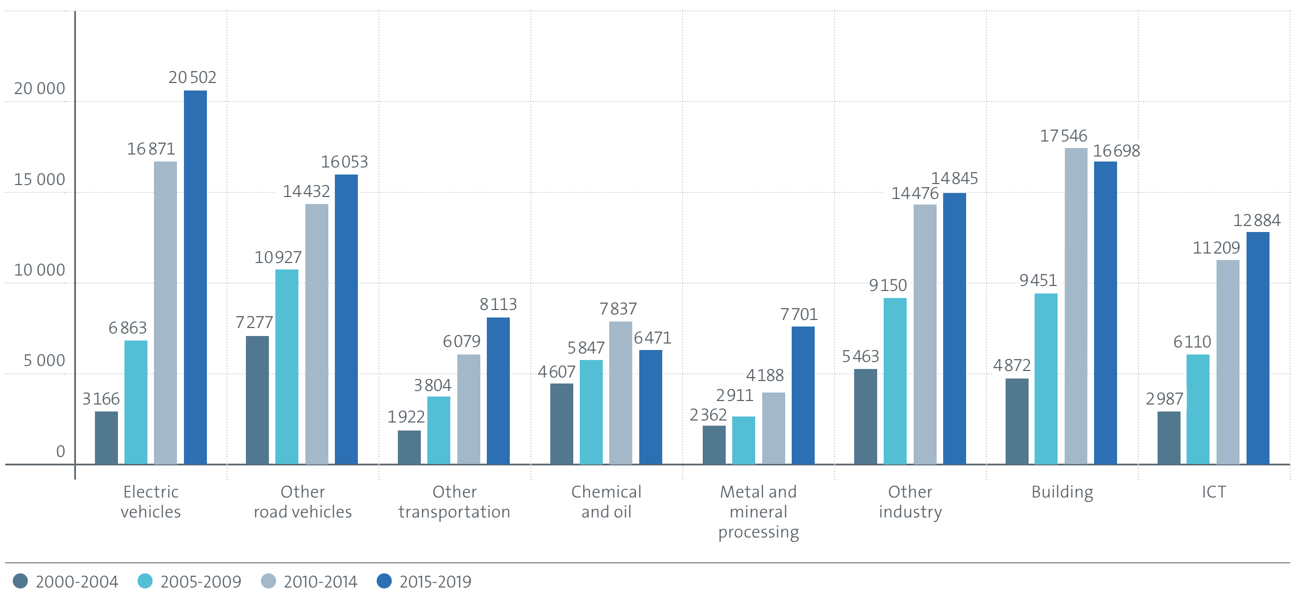
Transportation shows the highest level of patenting activity among the different types of LCE technologies in end-use sectors. More than 40% of the IPFs related to end-use technologies from 2000 to 2019, including about 35% for road transportation alone. To illustrate the importance of EVs within road transport, EV IPFs (including fuel cells and electric charging technologies) have been separated from other technologies that could reduce the carbon footprint of combustion engine-based vehicles (Figure 3.4). Both categories generated relatively similar levels of patenting activities (respectively 47 000 and 49 000 IPFs) and continuous growth between 2000 and 2019. However, the number of IPFs in EVs has been growing significantly faster. In 2011, EVs overtook other LCE technologies for road vehicles (Box 5). Besides road transport, there were about 20 000 IPFs for aviation, rail, marine and inland waterway transportation between 2000 and 2019. Patenting activity for this group grew steadily at an annual rate of 9% on average.

Reducing the emissions and energy intensity of industrial production is another major area of innovation, accounting for nearly a third (30%) of all the IPFs recorded in end-use technologies between 2000 and 2019. Heavy industries such as the chemical and oil sector and metal and mineral processing generated respectively 24 700 and 17 200 IPFs during the period. Innovation in more energy-efficient technologies for metal and mineral processing has been particularly dynamic in recent years, with an average annual growth rate of nearly 12% from 2010 to 2019. In contrast, the number of new IPFs related to clean energy in the chemical and oil processing sectors significantly decreased after 2015, despite steady growth since 2000. Other sectors of industrial production generated 44 000 IPFs related to clean energy between 2000 and 2019, which represents 16% of all IPFs in end-use technologies during that period. They include innovation in the production of consumer goods, as well as clean technologies for agriculture.

The last two categories of end-use technologies relate to buildings (including efficient lighting, heating, air-conditioning and home appliances, as well as construction) and information and communication technologies (ICT). Energy saving in buildings is a significant area of innovation, accounting for 17.7% of IPFs related to end-use technologies from 2000 to 2019. However, after a sharp increase from 2000 to 2013, patenting activities in this sector has declined, with a 10% drop between 2010-2014 and 2015-2019. Clean energy IPFs in the ICT sector grew at an impressive average annual rate of 10% between 2000 and 2019. This reflects the acute need for energy saving in computing and communication technologies, with the continual and rapid increase of digital communication and big data.

Figure 3.4

Growth of IPFs in end-use technologies, 2000-2019



Source: European Patent Office

3.3 Trends in enabling technologies

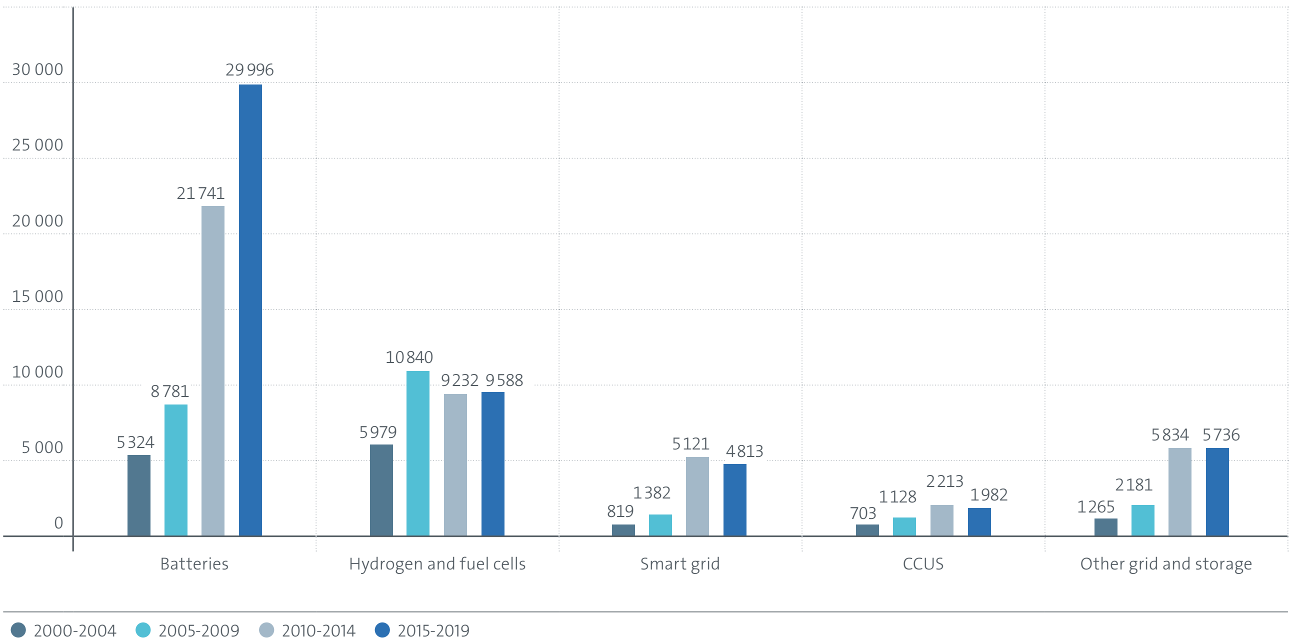
Cross-cutting technologies such as batteries, hydrogen, smart grids and CCUS are set to play a pivotal role in energy transitions. These will enable the deployment of clean energy sources on the supply side, while facilitating the integration of those sources (in particular electricity from renewables) in end-use sectors. Technical progress in enabling technologies is therefore a powerful driver of innovation in energy supply and end use, which are increasingly intertwined. Indeed, up to a third of the IPFs related to enabling technologies produced since 2010 (representing more than 10% of all clean energy IPFs) also qualify as LCE supply and/or end-use technologies (Table 3.2).

The positive aggregate trend in patenting activity in LCE enabling technologies has been chiefly driven by innovation in battery technologies, which alone generated 57% of the IPFs in 2010-2019, with an average annual growth rate of 13% (Figure 3.5). This reflects the increasing use of batteries in an ever-expanding array of personal devices and tools, and in particular the rapid development and industrialisation of lithium-ion battery technologies for electric mobility (EPO & IEA, 2020). For EVs, lithium-ion battery prices have decreased by almost 90% since 2010, while for stationary applications, including electricity grid management, they have dropped by around two-thirds over the same period. These cost reductions are partly due to new types of chemistries mostly adjustments to the composition of the battery cathode, as well as manufacturing economies of scale.

Enabling technologies such as batteries have many links with LCE supply and end-use technologies, for which they facilitate integration or emissions reduction. However, the links with LCE end-use technologies are much more significant than those on the supply side, further reinforcing the rising importance of end-use applications as integral parts of the transforming energy system (Table 3.2). Patent data reveals a strong synergy between battery innovation and EVs. There is a strong overlap between patents in the the two areas, compared with the overlap between batteries and, for example, industrial production. Innovation in EVs appears to also drive technical progress in other enabling technologies, including smart grids, hydrogen, and other grid and storage technologies.

Figure 3.5

Growth of IPFs in enabling technologies, 2000-2019



Source: European Patent Office

Compared with batteries, the data show more synergies between fuel cells and hydrogen and a wide range of end-use sectors, including chemicals and other industrial sectors, as well as buildings and road transportation. However, while hydrogen and fuel cell patenting nearly doubled from 2000-2004 to 2005-2009 and continued to generate a significant volume of patenting activities during the period of analysis (about 19 000 IPFs since 2010), it has lost momentum during the past decade. This is largely explained by stagnation of innovation in fuel cells and their applications, which generate the largest share of patenting activities related to hydrogen. In contrast, new technologies for the clean production and storage of hydrogen have been developing at a rapid pace in the past decade, albeit from a relatively low initial level (Box 4). It remains to be seen whether the recent enthusiasm for hydrogen as a potential cornerstone of low-carbon energy systems is yet translating into an increase in inventive activity.

With a stable average of about 1 000 IPFs per year during 2010-2019, there was significantly less patenting activity in smart grids than in batteries or hydrogen-related technologies. However, smart-grid patenting is a more recent phenomenon, with only low numbers reported in 2000-2009 (about 200 IPFs every year on average). Further growth is widely expected, supported by the unrelenting and disruptive introduction of new digital platforms, including the Internet of Things, 5G communication networks, cloud computing and artificial intelligence (EPO, 2020). Substantial synergies with renewable energy, energy efficiency gains in buildings and industrial production, as well EV charging are already evident in the data. In addition, many inventions in the "other enabling technologies" category also relate to the storage (e.g. capacitors and thermal storage), transmission and distribution of electric power. Together they generated a volume of patenting activities comparable to that of smart grids.

CCUS (a set of technologies for capturing CO_2 and preventing it from contributing to climate change) accounted for less than 5% of patenting activity related to LCE enabling technologies between 2000 and 2019. CCUS patenting grew up to 2014, which coincided with several major research and demonstration programmes in Australia, Europe and North America, but has since declined. This pattern is more in line with LCE and fossil fuel supply technologies than other enabling technologies. Nonetheless, its cross-cutting nature is visible in the data on synergies with LCE end uses, including chemicals and oil, which account for 28% of IPFs in CCUS.

Table 3.2

Share of IPFs in enabling technologies overlapping with other fields, 2010-2019

	Batteries	Hydrogen and fuel cells	Smart grid	Other grid and storage	CCUS
Number of IPFs	51 737	18 820	9 934	10 147	4 195
LCE supply					
Wind	0%	0%	4%	11%	0%
Solar PV	1%	1%	8%	10%	0%
Solar thermal	0%	0%	0%	3%	0%
Other solar	0%	0%	0%	0%	0%
Geothermal	0%	0%	0%	1%	0%
Hydro	0%	0%	0%	3%	0%
Ocean	0%	0%	0%	1%	0%
Bioenergy	0%	0%	0%	0%	1%
Fuel from waste	0%	1%	0%	0%	3%
Combustion	0%	1%	0%	1%	9%
Nuclear	0%	0%	0%	0%	0%
End-use					
Building	1%	3%	42%	15%	1%
Chemical and oil	0%	5%	0%	1%	28%
Metal and minerals	0%	0%	0%	0%	1%
Agriculture	0%	0%	0%	0%	1%
Consumer products	5%	14%	0%	2%	3%
Other production	0%	1%	4%	5%	1%
EV and infrastructure	17%	12%	26%	18%	0%
Road vehicles - other	0%	1%	0%	1%	4%
Other transportation	0%	0%	0%	0%	0%
ICT	0%	0%	2%	0%	0%

BOX 4

Trends in hydrogen and fuel cells

Although current consumption for energy purposes is relatively low, hydrogen receives a great deal of attention and its production for a variety of clean energy applications is widely expected to rapidly expand. Hydrogen is a versatile energy carrier that can be produced from fossil fuels or electricity via water electrolysis.

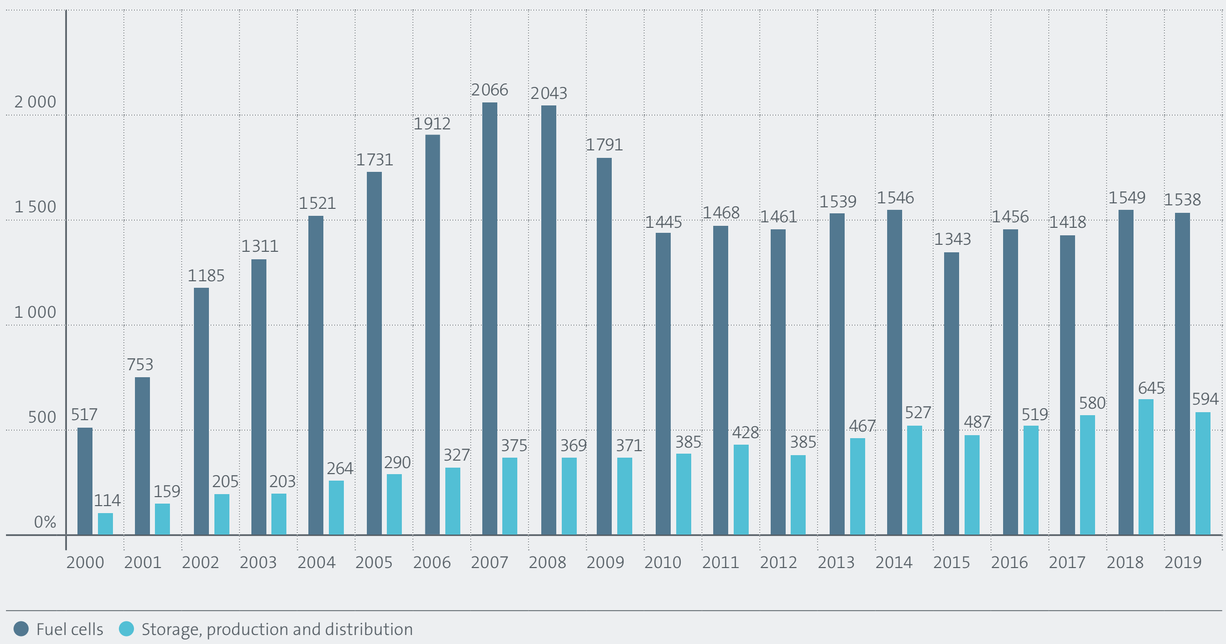
A more resilient energy sector could make use of low-carbon hydrogen in a variety of applications, e.g. iron and steel and fertiliser production, transport (directly in road vehicles and trains, or as synthetic fuels in airplanes and ships) and buildings (for heating) (IEA, 2019b). It could also be used to store electricity over weeks or months and to generate clean, on-demand power generation to help balance power systems. Not all applications for low-carbon hydrogen use fuel cells. However, many end uses in the transport and power sectors take advantage of the pairing of hydrogen and fuel cells for converting the chemical energy in hydrogen into electricity (and heat), with relatively high efficiency.

The flexibility of hydrogen, combined with its anticipated importance in tackling emissions in the hard-to-abate sectors, underpins the current efforts in many countries to develop effective policy support for low-carbon hydrogen.

Despite recent efforts, patenting activity has not risen sharply in recent years and remains much higher in fuel cells than in other aspects of the hydrogen value chain. This reflects sustained research funding that has ensured a steady flow of invention, but an absence of a market for hydrogen supply or use to generate significant competition and scale-up. Without market growth, there have been few incentives for associated innovations to optimise real-world performance, installation, safety and manufacturing of technologies such as electrolysers or hydrogen storage. Fuel cells, on the other hand, have found niche markets such as providing back-up power or powering forklift trucks that run on natural gas or hydrogen produced from fossil fuels without CCUS.

Figure 3.6

IPFs in hydrogen-related technologies, 2000-2019



Source: European Patent Office

There is good reason to expect this situation to change in the coming years. Investments in low-carbon hydrogen production and hydrogen-related companies are increasing, triggering scale-up in manufacturing, in Europe and China in particular. Many governments have published ambitious hydrogen strategies, and several have signalled their intention to invest economic stimulus funds in this area. Capacity additions of electrolysers to produce hydrogen have expanded rapidly, from 2 MW_e in 2010 to 25 MW_e in 2019, representing capital expenditure of around USD 40 million (IEA, 2020g). They have grown in scale, from below 0.5 MW_e on average in 2010 to 6 MW_e in 2019, with a 20 MW_e polymer electrolyte membrane (PEM) facility commissioned in France in 2021. Quoted costs for newer designs such as PEM have halved, but expectations for future plant sizes and costs far exceed this pace of change. Several plants of 1 GW size are now proposed for operation before 2030, and their future competitiveness likely relies on equipment prices that have not yet been realised.

Japan dominates research in fuel cells. However, Europe leads the development of new technologies for hydrogen production from non-carbon containing sources and hydrogen storage. Patenting activities in this area increased rapidly from 2010 to 2018. Germany alone accounts for nearly half of Europe's contribution in IPFs related to storage and a third of the IPFs related to low-carbon hydrogen production.

Table 3.3

Distribution of global IPFs in hydrogen between the world main regions, 2010-2019

	No. of IPFs, 2010-2019	Growth 2010-2019	EPC share	US share	JP share	KR share	CN share
Storage	1 859	25.2%	40.2%	19.2%	26.7%	5.3%	1.5%
Production	3 308	69.9%	31.3%	18.6%	23.4%	5.7%	4.6%
Fuel cells	14 763	6.4%	22.1%	17.2%	37.1%	14.4%	2.6%

Note: the colour codes indicate the RTA, calculated with respect to a region's share in all types of technologies. Highlighted ranges (from lightest to darkest blue) are: 1-1.25; 1.25-1.5; 1.5-1.75.

4. Profile of applicants in LCE technologies

4. Profile of applicants in LCE technologies

Further innovation in a wide range of LCE technologies is required to achieve the clean energy ambitions of the Paris Agreement and other major policy goals. Some of these technologies are already exploited on an industrial scale, while others are still at an early stage of development or deployment. This diversity translates into different forms of R&D activities: progress in some fields remains strongly reliant on fundamental research carried out in universities and public research organisations, while it is chiefly driven by applied corporate R&D in more mature areas of LCE technology. This chapter draws on information on patent applicants. Documenting the profile and technology specialisation of the main actors of LCE innovation highlights these differences.

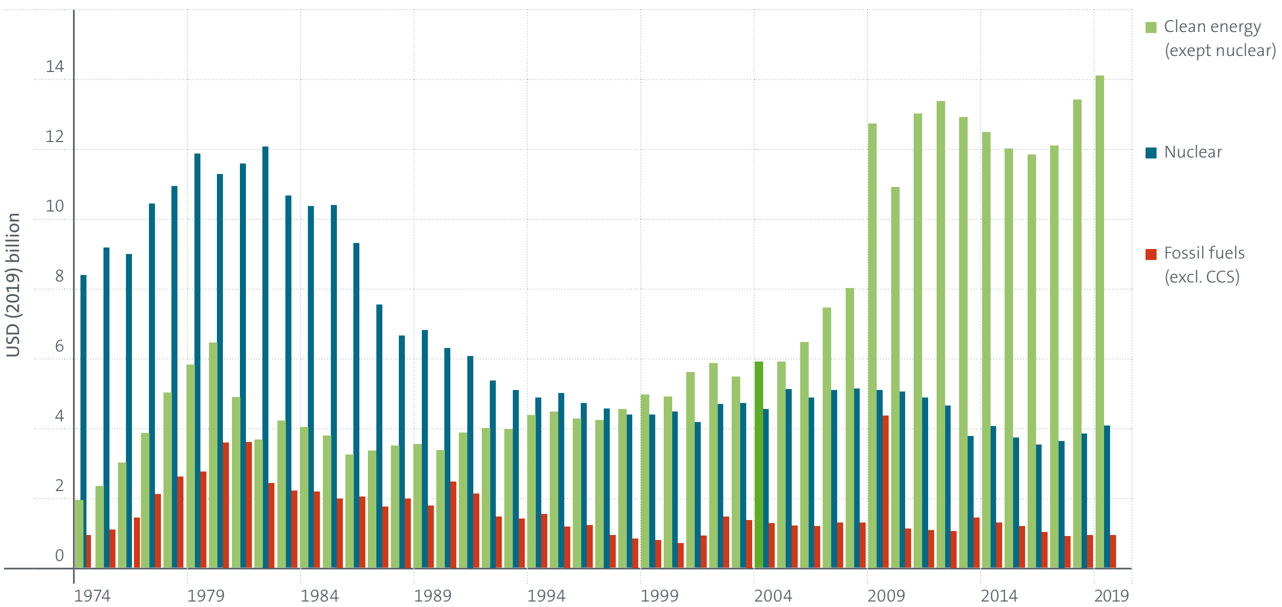
4.1 Universities and public research organisations

Public research is a key element of LCE innovation ecosystems. It can provide for the type of basic, exploratory, scientific research needed in the first development stages of emerging technologies. Industry research tends to focus on incremental innovation in technologies that have reached a sufficient degree of maturity. In total, worldwide government energy R&D reached USD 30bn in 2019 (IEA, 2020f), most of which is directed at nuclear and other low-carbon energies. The outcome of these investments is visible in the patent applications filed by universities and public research organisations (PRO).

Over the past 20 years, the overall share of IPFs in LCE technologies generated by research institutions has significantly increased, rising from 6.6% in 2000-2009 to 8.5% in 2010-2019. However, this share also differs considerably between LCE technology fields, highlighting the different degrees of maturity of the respective fields (Figure 4.1). Research institutions are especially active in LCE supply technologies such as biofuels (with 21% of IPFs in 2010-2019) and fuel from waste (16%), nuclear energy (17%) and some renewable energies (namely solar PV, geothermal, marine and solar thermal energies). In contrast, universities and PRO make only a small contribution to patenting activities in hydro and wind energies, signalling the higher maturity of these technologies.

Figure 4.1

Estimated total public energy R&D, including demonstration budget for IEA member governments, 1974-2019



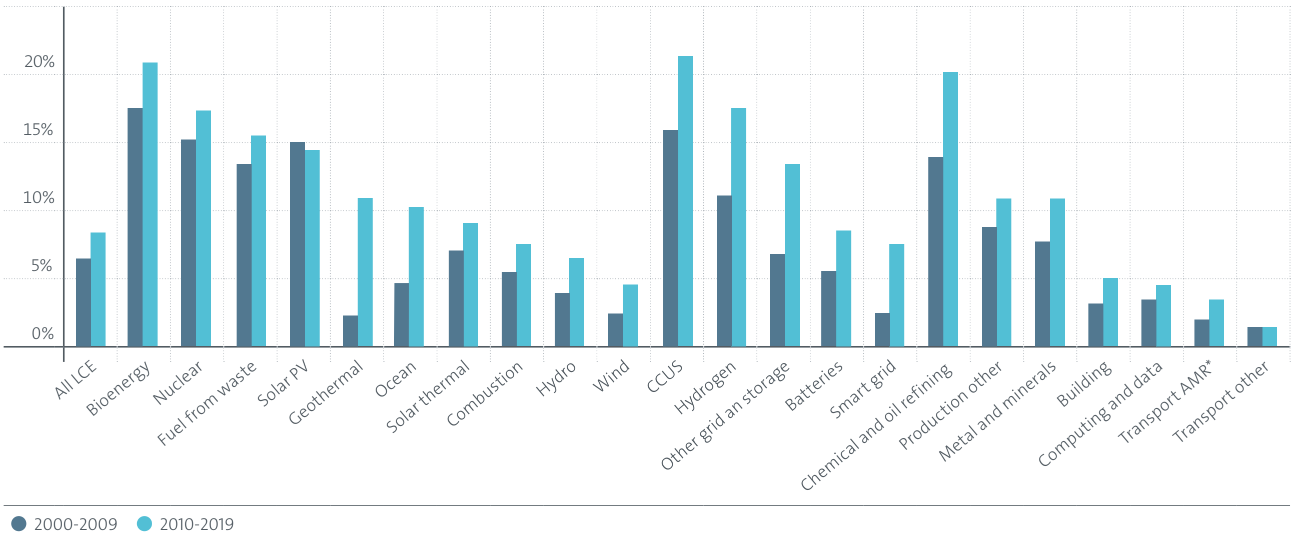
Source: Energy Technology RD&D Budgets 2020, IEA 202f

LCE enabling technology fields such as CCUS (21% in 2020-2019), hydrogen (18%) and other grid and storage technologies (14%) yet to consolidate around dominant commercial designs have a higher share of IPFs from scientific research institutions. This contrasts with commercialised battery and smart-grid technologies, for which the barriers to new market entrants are lower (section 2.3). Likewise, LCE end-use technologies are characterised by small unit sizes and competition for consumer spending, as reflected in a lower share of IPFs from universities and PROs and a higher share from the private sector. This is even more pronounced for transport, ICT and buildings. Chemical and refining (20%) technologies and, to a lesser extent, metal and mineral processing are instead characterised by large unit sizes and more market concentration.

The 15 most important PRO and universities together generated more than a quarter (27%) of all LCE IPFs originating from research institutions between 2000 and 2009. They mainly consist of large PROs with diverse specialisation profiles, of which five are located in R. Korea, three in France and one in Germany, the US, Chinese Taipei, and Japan. The remaining three are major universities in the US (MIT and the University of California) and China (Tsinghua University). The French CEA and IFP show particularly strong specialisation, respectively in nuclear energy and hydrogen, and in alternative fuels, CCUS and chemistry and oil refining. Among the other institutions, the Korean Institute of Energy Research and the US's University of California and Battelle Memorial Institute also show a technology advantage in CCUS. The CEA, Germany's Fraunhofer Institute and Chinese Taipei's ITRI dominate research in solar energy. The Korean ETRI and Myongji University show a specialisation in smart grids, the former with a strong advantage in energy-efficient ICT.

Figure 4.2

Share of IPFs originating from universities and PROs in LCE technology fields, 2000-2019



Source: European Patent Office

*Notes: AMR = Aerospace, maritime, rail

Table 4.1

Top 15 universities and PROs in LCE technologies, 2000-2019

	Country	LCE IPFs	Share of IPFs in selected fields: Combustion	Alternative fuels	Nuclear	Solar	Batteries	CCUS	Hydrogen and fuel cells	Smart grid	Other enabling	Chemical and oil refining	ICT
CEA/Alternative Energies and Atomic Energy Commission	FR	1 772	0.1%	0.2%	3.9%	0.9%	0.6%	0.0%	1.2%	0.1%	0.6%	0.2%	0.1%
Industrial Technology Research Institute	TW	846	0.1%	0.1%	0.0%	0.5%	0.2%	0.2%	0.3%	0.1%	0.2%	0.1%	0.2%
Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.	DE	725	0.1%	0.2%	0.0%	0.6%	0.1%	0.0%	0.3%	0.1%	0.2%	0.2%	0.1%
IFP Energies Nouvelles/IFPEN	FR	721	0.8%	1.2%	0.0%	0.0%	0.0%	1.4%	0.1%	0.0%	0.2%	1.2%	0.0%
University of California	US	666	0.1%	0.8%	0.4%	0.3%	0.2%	0.6%	0.4%	0.1%	0.3%	0.3%	0.0%
Electronics and Telecommunications Research Institute	KR	626	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%	0.0%	0.5%	0.1%	0.0%	1.0%
CNRS/National Centre for Scientific Research	FR	594	0.0%	0.2%	0.1%	0.3%	0.2%	0.2%	0.3%	0.0%	0.2%	0.4%	0.0%
Tsinghua University	CN	569	0.1%	0.2%	0.3%	0.2%	0.4%	0.1%	0.2%	0.3%	0.3%	0.1%	0.0%
National Institute of Advanced Industrial Science and Technology	JP	455	0.0%	0.2%	0.0%	0.2%	0.3%	0.2%	0.2%	0.0%	0.1%	0.2%	0.0%
Battelle Memorial Institute	US	402	0.1%	0.3%	0.4%	0.0%	0.1%	0.5%	0.3%	0.2%	0.2%	0.3%	0.0%
Korea Institute of Science and Technology	KR	369	0.1%	0.2%	0.0%	0.2%	0.1%	0.1%	0.3%	0.0%	0.1%	0.2%	0.0%
Korea Advanced Institute of Science And Technology	KR	368	0.0%	0.1%	0.2%	0.1%	0.1%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%
Massachusetts Institute of Technology	US	363	0.1%	0.1%	0.1%	0.2%	0.1%	0.2%	0.2%	0.0%	0.1%	0.1%	0.0%
Korea Institute of Energy Research	KR	346	0.4%	0.1%	0.0%	0.2%	0.0%	1.1%	0.3%	0.0%	0.1%	0.2%	0.0%
Myong Ji University Industry Academia	KR	333	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.9%	0.6%	0.0%	0.0%
Total 15 Top applicants		**9 155**	2.0%	3.9%	5.4%	4.1%	2.5%	4.8%	4.3%	2.4%	3.4%	3.6%	1.5%

Note: specialisation is reported in terms of share of all IPFs in the selected field, only for fields in which one or more of the listed institutions have contributed at least 0.5% of all IPFs. Different colour codes are used to highlight IPF shares in the following ranges: >0%-0.5%; 0.5%-1%; 1%-2%; >2%.

BOX 5

Emerging regional clusters in enabling technologies

Innovative activities are often geographically concentrated into regional clusters, typically in large urban agglomerations with an ecosystem of R&D-performing institutions around leading companies. Regional innovation clusters arise from the realisation of the economic efficiencies and knowledge spillovers that exist from the co-location of similar industries and suppliers in a more general sense, but also from more formal relations that can exist between different organisations that are members of the cluster. Table 4.2 shows the most important of these clusters for four different types of enabling technologies related to electrification, namely batteries, hydrogen and fuel cells, smart grids and CCUS. Enabling technologies have a cross-cutting impact on LCE supply and end-use technologies in a wide range of sectors. Regional clusters that concentrate innovation capacities in these fields are therefore poised to play a leading role in the global energy transition.

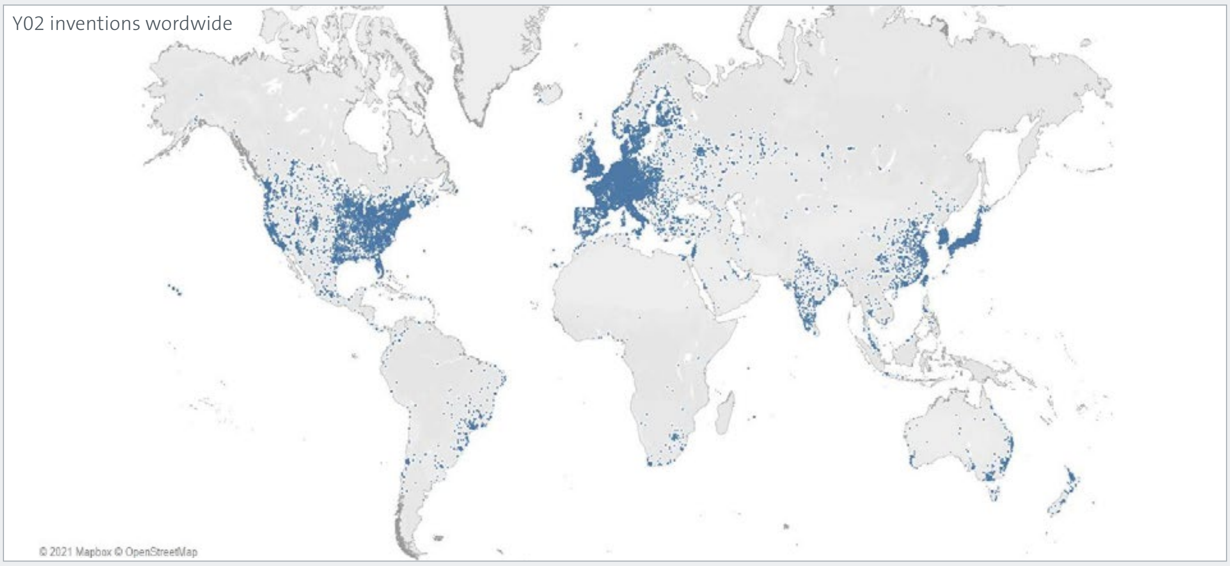
Eighteen such clusters have been identified based on the location of the inventors of LCE IPFs in the period 2010-2018 (Annex 4 for further details on the methodology). They are distributed between nine metropolitan areas, several of which are hosting top clusters in several different enabling technology fields. Japanese and Korean regions dominate the ranking, with fourteen out of the eighteen clusters identified. The regions of Tokyo and Seoul host a cluster in each of the four categories of enabling technologies, which also reflects the fact that many national companies' headquarters [5] are located in these capital cities.

The six clusters specialised in batteries show the largest volume of patenting activities as well as impressive annual growth rates of IPFs over the period of analysis. They largely overlap with the location of clusters specialised in hydrogen and fuel cells which, with the exception of the region of Nagoya in Japan, show lower average growth rates during the same period. Apart from the regions of Stuttgart (Germany) in the case of batteries and Rochester (US) in the case of hydrogen, all these clusters are located in Japan or R. of Korea. In the case of Rochester, the growth rate in IPFs has been negative in the period 2010-2018.

Three top clusters have been identified in the case of smart grid technologies. They are largely dominated by the region of Tokyo, Japan, which alone generated nearly twice the total of smart grid IPFs coming from the other two top clusters (Seoul, R. of Korea, and Beijing, P.R. of China) between 2010 and 2018. All of them show particularly impressive growth rates during the period of analysis. By contrast, the top three clusters specialising in CCUS show relatively low levels of patenting activities and contrasting dynamics, with a strong positive growth for Seoul, a negative growth for Paris, and stable patenting activities for Tokyo, which again tops the ranking.

Figure 4.3

Geographical origins of IPFs related to LCE technologies, 2000-2018



5 Some large applicants report their IP headquarters' locations as the address of the inventors, which may increase the proportion of IPFs attributed to these locations.

Table 4.2

Top global clusters in enabling technologies, 2000-2018

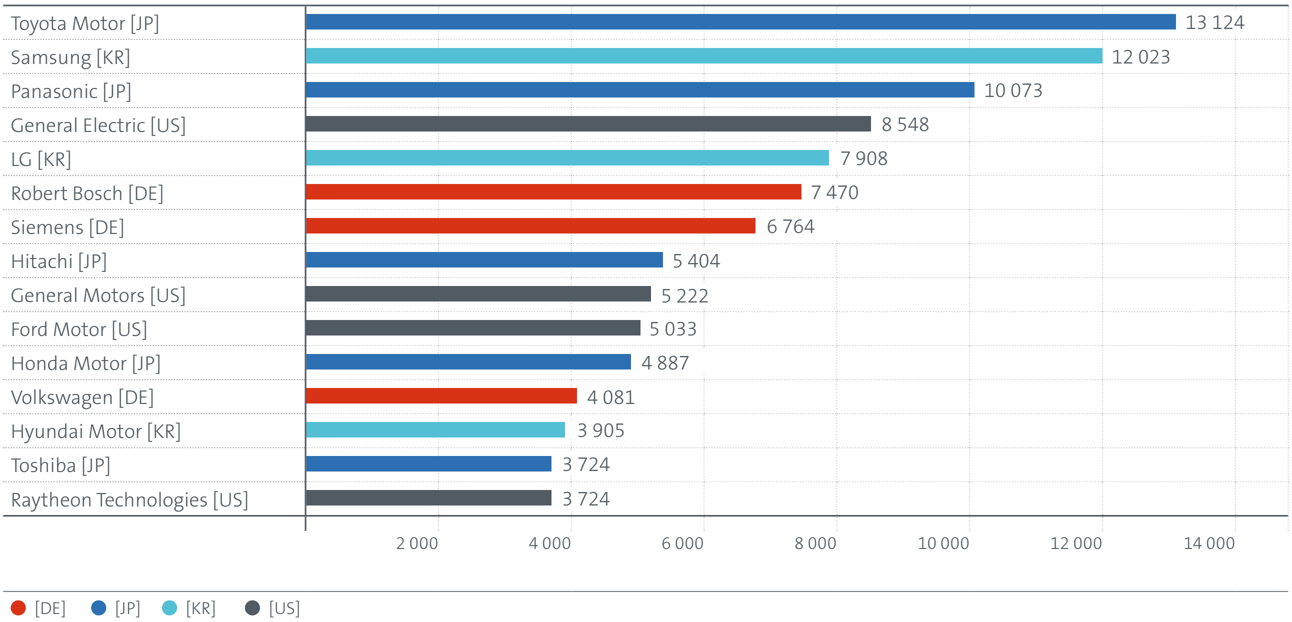
Batteries	Number of IPFs, 2010-2018	Av. growth rate, 2010-2018	Leading applicants	Related expertise
Tokyo, JP	7 629	13.3%	Nissan Motor (8%), Sony (8%), NEC (7%)	EVs, Other road transportation, Hydrogen & fuel cells, Consumer products
Seoul, KR	5 439	15.9%	Samsung (54%), LG (11%), Hyundai Motor (5%)	EVs, Other road transportation, Hydrogen & fuel cells, Consumer products
Osaka, JP	4 549	14.0%	Panasonic (45%), GS Yuasa Corp. (9%), Murata (5%)	EVs, Other road transportation, Hydrogen & fuel cells, Consumer products
Nagoya, JP	2 504	13.7%	Toyota (57%), Denso (9%), NGK Insulators (6%)	EVs, Other road transportation, Hydrogen & fuel cells
Daejeon, KR	2 939	23.0%	LG (68%), Samsung (8%), SK Group (7%)	EVs, Other road transportation, Hydrogen & fuel cells, Consumer products
Stuttgart, DE	1 526	19.4%	Robert Bosch (56%), Daimler (9%), MAHLE-Stiftung (6%)	EVs, Other road transportation, Hydrogen & fuel cells, Consumer products
Hydrogen and fuel cells	**Number of IPFs, 2010-2018**	**Av. growth rate, 2010-2018**	**Leading applicants**	**Related expertise**
Tokyo, JP	2 521	2.6%	Honda Motor (22%), Nissan Motor (13%), Toshiba (8%)	Buildings, Consumer products, EV, batteries
Seoul, KR	1 649	7.9%	Samsung (37%), Hyundai (25%), KIST (4%)	Consumer products, EV, Other road transportation, batteries
Osaka, JP	1 222	3.8%	Panasonic (45%), Sumimoto Electric (8%), Toyota (3%)	Buildings, Consumer products, Chemical and oil refining, batteries
Nagoya, JP	1 184	24.8%	Toyota (62%), Aisin Seiki (7%), NGK Insulators (4%)	Consumer products, EV, Chemical and oil refining, Other road transportation, batteries
Daejeon, KR	551	9.2%	LG (23%), Samsung (19%), KIST (12%)	Buildings, Consumer products, EV, batteries
Rochester, US	358	-14.3%	General Motors (82%), Aptiv (7%), Delphi (6%)	Consumer products, EV, Chemical and oil refining, batteries
Smart grids	**Number of IPFs, 2010-2018**	**Av. growth rate, 2010-2018**	**Leading applicants**	**Related expertise**
Tokyo, JP	1 280	34.9%	Toshiba (14%), NEC (12%), Mitsubishi Electric (12%)	Buildings, EV
Seoul, KR	496	58.8%	Samsung (20%), LG (15%), Myong Ji University (14%)	Buildings, EV
Beijing, CN	183	20.6%	State Grid Corporation of China (21%), Tsinghua University (15%), ABB (6%)	Buildings, EV
CCUS	**Number of IPFs, 2010-2018**	**Av. growth rate, 2010-2018**	**Leading applicants**	**Related expertise**
Tokyo, JP	353	0.5%	Mitsubishi Heavy (23%), Toshiba (16%), Hitachi (5%)	Chemical and oil refining
Paris, FR	165	-15.2%	Air Liquide (57%), IFP (20%), Total (2%)	Chemical and oil refining
Seoul, KR	165	15.9%	KIST (14%), Samsung (10%), Hanyang University (4%)	Chemical and oil refining

4.2 Top applicants in LCE technologies

Companies generate the majority of IPFs, despite many LCE technology fields showing a high share of IPFs originating from research institutions. The top 15 applicants alone generated more than a third of all IPFs related to LCE technologies in 2000-2019. As indicated in Figure 4.4, automotive companies and their suppliers largely dominate, illustrating how EVs and their related enabling technologies have acted as a prime mover in energy transition over the past two decades. Of the top 15 applicants, six are automotive companies (Toyota, General Motors, Ford, Honda, Volkswagen, Hyundai) and another six are their main battery suppliers (Samsung, Panasonic, LG, Robert Bosch, Hitachi, Toshiba). The remaining top applicants are GE and Siemens, two conglomerates directly involved in the energy sector, and US company Raytheon, which shows a strong specialisation in LCE for aviation.

Figure 4.4

Top 15 applicants in LCE technologies, 2000-2019



Source: European Patent Office

A closer analysis of these top applicants' specialisation confirms the strong footprint of technologies related to EV in their respective IPF portfolios. Toyota tops the ranking, thanks to a strong contribution in EV, hydrogen, batteries and smart grids, although it also generated a significant share of IPFs in other LCE technologies for road transportation. Other high-ranking automotive companies show similar profiles (Box 6). Companies such as Samsung, LG and Panasonic specialise in batteries and are likewise active in EV and smart grid technologies, as well as solar and other end-use technologies (building, industrial production, ICT), with possible spillover effects.

General Electric and Siemens show a different profile, specialising in all LCE energy supply technologies, especially efficient combustion and wind power, as well as in smart grids and other grid and storage technologies. Japanese companies Hitachi and Toshiba have a comparable profile, with patenting activities in these fields, as well as in EV and batteries. General Electric, Hitachi, Toshiba and, to a lesser extent, Siemens are the only companies specialised in nuclear energy.

Nearly all top applicants are significantly active in the full spectrum of enabling technologies, with a stronger focus on batteries, hydrogen and smart grids. Raytheon is the only exception: its presence in the ranking is due to its strong specialisation in LCE technologies for aeronautics.

Table 4.3

LCE technology profiles of top 15 applicants, 2000-2019

Energy supply	Country	Combustion	Non-fossil fuel	Nuclear	Solar	Wind	Other renewables
Toyota Motor	JP	0.4%	0.4%	0.0%	0.3%	0.0%	0.0%
Samsung	KR	0.1%	0.1%	0.0%	4.0%	0.3%	0.2%
Panasonic	JP	0.5%	0.1%	0.0%	2.7%	0.2%	0.0%
General Electric	US	15.4%	0.3%	3.3%	0.8%	10.4%	0.8%
LG	KR	0.5%	0.0%	0.0%	2.8%	0.1%	0.1%
Robert Bosch	DE	0.6%	0.0%	0.0%	0.5%	0.7%	0.8%
Siemens	DE	5.0%	0.2%	0.3%	0.7%	11.4%	0.4%
Hitachi	JP	2.2%	0.2%	4.8%	0.9%	1.4%	0.3%
General Motors	US	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Ford Motor	US	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Honda Motor	JP	0.8%	0.2%	0.0%	0.1%	0.0%	0.0%
Volkswagen	DE	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Hyundai Motor	KR	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%
Toshiba	JP	1.0%	0.1%	4.4%	0.6%	0.3%	0.7%
Raytheon Technologies	US	0.1%	0.0%	0.0%	0.1%	0.3%	0.1%

Note: the results reported in the cells are the companies' respective shares of all IPFs in the technology field in the period 2000-2019. Different colour codes are used to highlight IPF shares in the following ranges: >0%-0.5%; 0.5%-1%; 1%-5%; 5%-10%; > 10%.

End-use technologies	Country	Building	Chemical and oil refining	ICT	Metal and minerals	Production other	EV	Other road transport	Other transport
Toyota Motor	JP	0.3%	0.3%	0.0%	0.2%	1.6%	11.1%	9.4%	0.1%
Samsung	KR	2.2%	0.4%	6.9%	0.4%	3.4%	1.2%	0.1%	0.2%
Panasonic	JP	3.6%	0.5%	1.8%	0.6%	2.1%	2.6%	0.1%	0.1%
General Electric	US	1.2%	0.8%	0.0%	4.0%	1.6%	0.6%	0.6%	12.6%
LG	KR	2.1%	0.4%	3.3%	0.3%	1.9%	1.7%	0.1%	0.1%
Robert Bosch	DE	1.4%	0.1%	0.2%	0.2%	0.7%	3.5%	5.9%	0.0%
Siemens	DE	1.0%	0.4%	0.5%	2.2%	3.1%	1.2%	0.5%	3.1%
Hitachi	JP	0.9%	0.3%	1.2%	0.5%	1.5%	2.1%	1.4%	0.4%
General Motors	US	0.1%	0.2%	0.1%	0.2%	0.4%	3.5%	4.4%	0.0%
Ford Motor	US	0.1%	0.0%	0.1%	0.2%	0.1%	4.2%	5.8%	0.0%
Honda Motor	JP	0.1%	0.2%	0.0%	0.1%	0.6%	3.9%	2.9%	0.2%
Volkswagen	DE	0.1%	0.0%	0.1%	0.2%	0.2%	3.0%	4.4%	0.1%
Hyundai Motor	KR	0.1%	0.0%	0.1%	0.1%	0.5%	4.1%	2.5%	0.0%
Toshiba	JP	1.3%	0.3%	1.9%	0.2%	0.9%	0.9%	0.0%	0.2%
Raytheon Technologies	US	0.2%	0.0%	0.1%	1.3%	0.1%	0.1%	0.1%	15.4%

Note: the results reported in the cells are the companies' respective shares of all IPFs in the technology field in 2000-2019. Different colour codes are used to highlight IPF shares in the following ranges: >0%-0.5%; 0.5%-1%; 1%-5%; 5%-10%; >10%.

Enabling technologies	Country	Batteries	CCUS	Hydrogen and fuel cells	Smart grid	Other grid and storage
Toyota Motor	JP	4.5%	0.7%	6.1%	2.1%	1.6%
Samsung	KR	7.2%	0.5%	3.1%	1.2%	1.1%
Panasonic	JP	6.7%	0.1%	3.4%	3.5%	2.2%
General Electric	US	0.2%	3.7%	0.5%	3.3%	3.7%
LG	KR	5.8%	0.1%	1.0%	1.0%	0.4%
Robert Bosch	DE	2.7%	0.2%	1.2%	1.1%	1.0%
Siemens	DE	0.3%	1.4%	1.0%	4.2%	4.6%
Hitachi	JP	1.7%	1.3%	0.8%	2.2%	1.5%
General Motors	US	1.0%	0.2%	3.7%	0.4%	0.3%
Ford Motor	US	0.8%	0.2%	0.4%	0.7%	0.3%
Honda Motor	JP	0.9%	0.1%	4.1%	0.8%	0.5%
Volkswagen	DE	0.7%	0.3%	0.9%	0.6%	0.2%
Hyundai Motor	KR	0.7%	0.2%	2.3%	0.5%	0.2%
Toshiba	JP	1.3%	1.5%	1.3%	1.9%	1.1%
Raytheon Technologies	US	0.0%	0.2%	0.2%	0.1%	0.1%

Note: the results reported in the cells are the companies' respective shares of all IPFs in the technology field in 2000-2019. Different colour codes are used to highlight IPF shares in the following ranges: >0%-0.5%; 0.5%-1%; 1%-5%; 5%-10%; >10%.

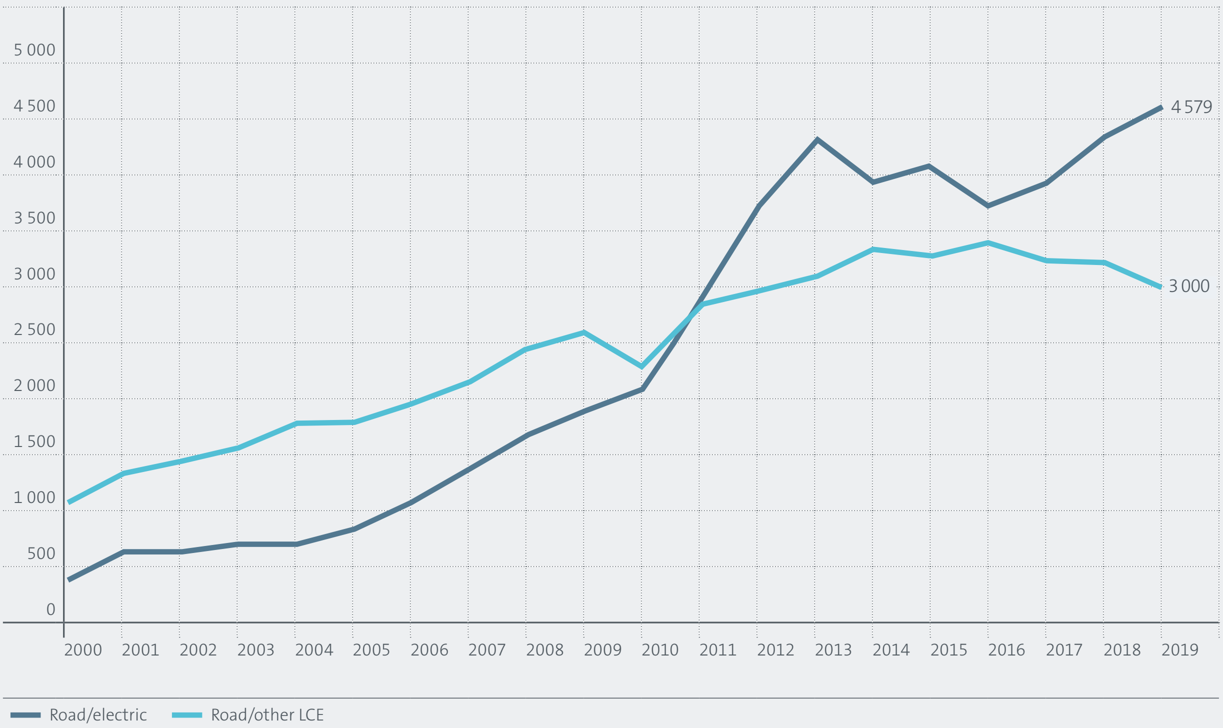
BOX 6

The automotive industry shifts towards EV

Road transportation is one of the most important end-use sectors for LCE technologies, with almost 100 000 IPFs between 2000-2019. This reflects its global importance as a major economic sector and one that is currently undergoing a discontinuous transition to lower-emitting technologies. Patent data illustrates the speed with which the sector is transforming. Innovative activity has increased in line with the strong pressures for companies to innovate to compete in a changing and more global landscape. Moreover, in the past decade, EVs have emerged as the dominant focus of invention, leading the industry in a radical new direction. Patenting activities in EV (and its associated infrastructure) overtook other clean energy technologies for road vehicles[6] as of 2011, before sales of EV started to take off (Figure 4.5). Until then, the reduction of fuel consumption and carbon emissions in conventional fuel engines was clearly the dominant paradigm in the automotive industry.

Figure 4.5

Global growth of IPFs in electric vehicles versus other LCE technologies for road transportation, 2000-2019



Source: European Patent Office

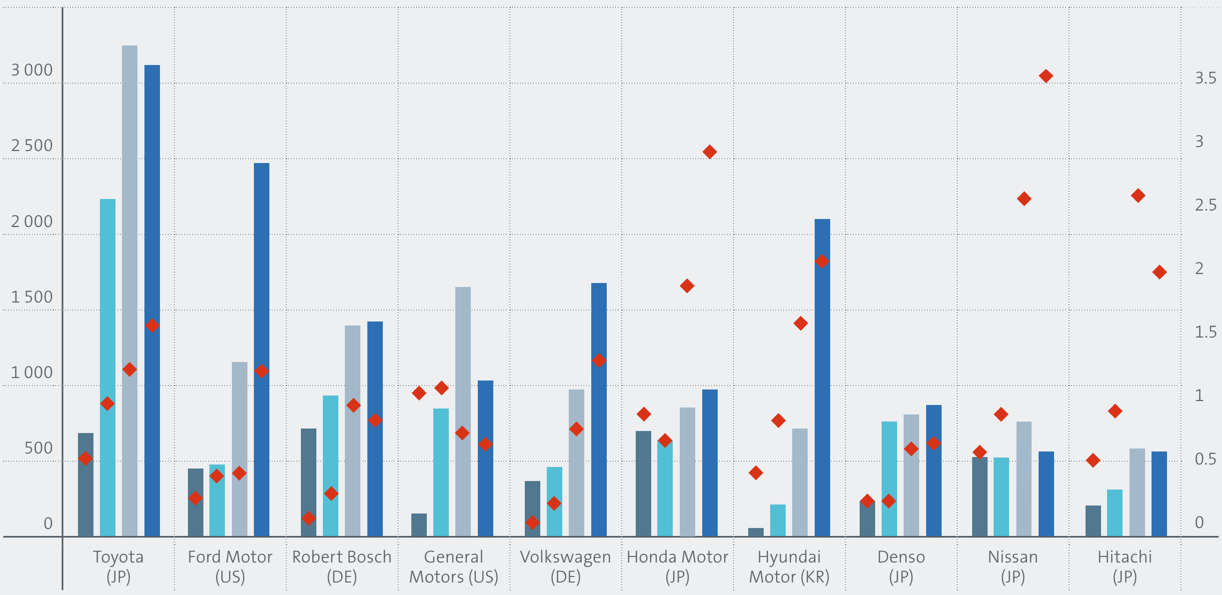
6 These technologies aim at more efficient combustion engines, as well as improved aerodynamics, weight reduction, or more energy-efficient components and subsystems.

Figure 4.6 shows the ten companies that contributed most to clean road transport innovation between 2000 and 2019. Toyota, as the leader in all LCE technologies, dominates the list, consisting exclusively of incumbent car manufacturers and their suppliers. With over 9 000 IPFs, Toyota alone contributed more than the second and third biggest applicants, Ford and Robert Bosch, together. However, when looking at the latest five-year period, important changes in innovation efforts by top applicants are clear to see. For example, Toyota, Robert Bosch and Honda maintained their strong positions in clean road transportation, while Nissan and especially General Motors saw a steep decline in their contributions. At the same time, Hyundai, Volkswagen and Ford significantly expanded their innovation activities.

Beyond their overall contribution to LCE technologies for road transportation, companies have also reoriented their LCE innovation efforts from internal combustion engines (ICE) towards EV technologies. Figure 4.6 shows the ratio between the top applicants' IPFs in both technology fields. A ratio above one represents higher contribution to EV than to other clean road transportation technologies. Most companies increased their ratios over the last two decades; for seven of the top ten companies the ratio exceeded one in the most recent five-year period. Nissan and Honda even generated twice as many IPFs in EV than in ICE in 2015-2019. Hitachi, Toyota, Ford and Volkswagen also showed a significant effort to reach and surpass parity between the two fields. Robert Bosch, Denso and in particular General Motors are the only top applicants that saw their ratios remaining at or declining to below one.

Figure 4.6

Top 10 applicants in LCE road transport technologies, 2000-2019



Source: European Patent Office

5. Geographical distribution of low-carbon energy innovation

5. Geographical distribution of low-carbon energy innovation

This chapter reports on the geography of LCE innovation, as identified by the locations of the inventors of IPFs for LCE technologies. It focuses on the main global LCE innovation centres. Europe is defined here as comprising all 38 member states of the European Patent Convention (EPC).

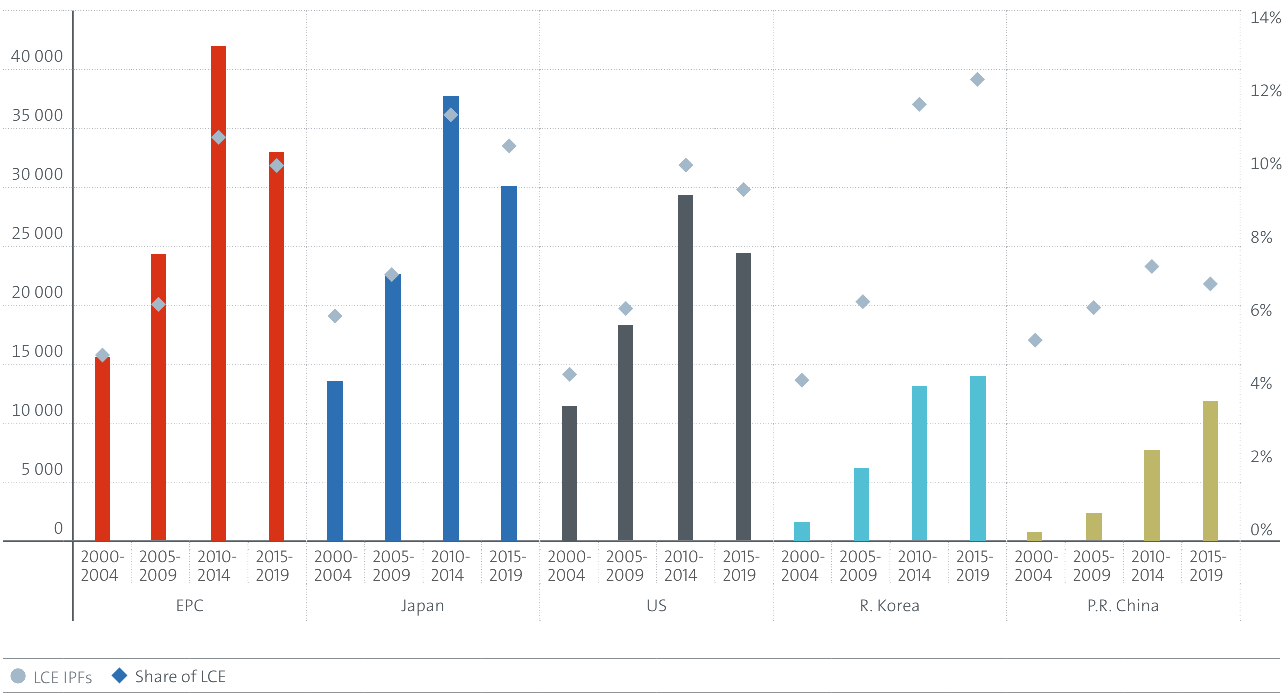
5.1 Global innovation centres

Europe, Japan and the US dominate the global LCE innovation landscape, together accounting for more than three quarters of all IPFs generated from 2000 to 2019. After initial rapid growth, all regions have stagnated since 2015, with patenting activities in LCE technologies declining relative to non-LCE technology fields.

Since 2000, Europe has consistently led patenting activities related to clean energy, generating 28% of all IPFs in LCE technologies between 2010 and 2019. Japan followed close behind, with about 25% IPFs between 2010 and 2019, and the US came a more distant third (20%). The US recorded about 30% less than Europe, with about 60 000 IPFs in LCE technologies since 2010. R. Korea and P.R. China remain modest innovation centres in the domain of LCE technologies, with only 10% and 8% respectively of all IPFs generated from 2010 to 2019. However, both countries have experienced a sustained increase of patenting activities in these technologies. R. Korea, in particular, had the highest share of domestic IPFs related to clean energy from 2015 to 2019 – the only innovation centre in which this increased during that time.

Figure 5.1

Growth of IPFs in LCE technologies by global innovation centres, 2000-2019



Source: European Patent Office

For governments seeking to understand their country's comparative advantage in battery technology in more detail, the revealed technological advantage (RTA) [7] index indicates a country's specialisation in terms of LCE technology innovation relative to its overall innovation capacity. An RTA above one reflects a country's specialisation in a given technology. Conversely, countries with a lower RTA in a given technology face a bigger challenge in developing the technological leadership needed to add significant value to their economies in future decades. Given the level of technological detail in this report, the data provided may also reveal niches in which countries can build on their relative strengths even if their RTA is less than one at a higher level of aggregation.

RTA indicators show that Europe specialises in nearly all renewable energy technologies, and in particular in wind energy (Table 5.1). However, it also specialises in fossil energy supply technologies (reported in this section as a benchmark). The main exception is solar PV, where Europe doesn't specialise, but nonetheless dominates BOS technologies such as mountings, tracking and PV systems relevant to maximising the value of local deployment (Box 3). Europe also has a relative technological advantage (RTA) [8] in energy efficiency and fuel-switching technologies for most end-use sectors, with the notable exception of ICT. It generates a relatively low share of enabling technologies, apart from CCUS in which Europe exhibits an RTA.

Japan and the US show divergent specialisations. With the exception of solar cells (Box 3), Japan specialises less in LCE supply technologies. Japan though is a world leader in cross-cutting technologies enabling energy transitions, such as batteries, hydrogen and fuel cells and, to a lesser extent, smart grids. This translates into a strong RTA in electric road transportation, which complements Japan's strong position in other established LCE technologies for road transportation.

The US does not appear among the most important players in innovation in renewable energies and LCE enabling technologies, apart from CCUS. However, it does have an RTA in LCE combustion technologies (alternative fuels, efficient combustion) and geothermal energy, as well as nuclear and LCE end-use technologies for chemicals, oil refining and long-distance transport. This advantage is likely linked to strong US technology specialisation in fossil fuel technologies. In addition, as a result of its leadership in ICT (EPO, 2020), it also specialises, together with P.R. China, in energy-efficient technologies for the ICT sector.

R. Korea specialises in battery technologies and also has RTAs in solar PV and nuclear energy, hydrogen and fuel cells, plus LCE end-use technologies in the ICT, consumer goods, maritime transportation and EV sectors.

Patenting activity in LCE technologies in P.R. China has emerged more recently and does not yet reveal a clear specialisation pattern. Notable exceptions are railway transportation and the ICT sector, reflecting the country's strong performance in IT hardware and connectivity technologies (EPO, 2020). However, this strength in LCE for ICT has not translated into specialisation in digital-intensive LCE enabling technologies such as smart grids.

7 An RTA is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology.

8 The RTA index indicates a country's relative specialisation in a given technology innovation in relation to other countries. An RTA above one indicates that a country tends to produce more innovation in that technology area than it does in others. It is calculated as a country's share of global IPFs in a category divided by the country's share of IPFs in all fields of technology.

Table 5.1

Specialisation (RTA) of global innovation centres by LCE technology fields, 2010-2019

Energy supply	*No. of IPFs 2010-2019*	EPC	US	JP	KR	CN
Solar PV	*33 248*	0.84	0.83	1.12	1.78	0.91
Solar thermal	*6 988*	1.69	0.93	0.37	0.42	0.65
Wind	*13 470*	2.07	0.74	0.40	0.44	0.64
Geothermal	*650*	1.58	1.21	0.35	0.57	0.51
Hydro	*2 477*	1.58	0.64	0.44	0.89	0.60
Ocean	*2 462*	1.67	0.79	0.25	0.99	0.71
Bioenergy	*5 394*	1.16	1.79	0.38	0.64	0.37
Fuels from waste	*3 222*	1.64	1.22	0.37	0.64	0.37
Efficient combustion	*4 312*	1.44	1.37	0.69	0.48	0.36
Nuclear	*3 436*	0.93	1.44	0.77	1.33	0.65
Fossil fuels	*55 969*	1.10	2.10	0.22	0.28	0.47

Note: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

End-use technologies	*No. of IPFs 2010-2019*	EPC	US	JP	KR	CN
Building	*34 244*	1.17	0.84	0.83	1.01	1.08
Chemical and oil	*14 308*	1.17	1.43	0.59	0.62	0.79
Metal mineral	*11 889*	1.32	1.09	0.87	0.55	0.65
Agriculture	*2 905*	1.07	1.05	0.57	0.80	0.99
Consumer products	*17 672*	0.93	0.64	1.33	2.02	0.56
Electric vehicles	*37 373*	1.01	0.76	1.67	1.25	0.44
Other road vehicles	*30 485*	1.34	1.04	1.36	0.66	0.18
Railways	*710*	1.72	0.79	0.59	0.23	1.26
Aviation	*12 550*	1.51	2.38	0.17	0.12	0.11
Maritime and waterways	*966*	1.39	0.64	1.06	1.44	0.25
ICT	*24 093*	0.51	1.32	0.74	1.53	1.81

Note: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

Enabling technologies	*No. of IPFs 2010-2019*	EPC	US	JP	KR	CN
CCUS	*4 195*	1.18	1.50	0.74	0.86	0.22
Batteries	*51 737*	0.57	0.59	1.71	2.22	0.86
Hydrogen and fuel cells	*18 820*	0.92	0.85	1.49	1.47	0.28
Smart grid	*9 934*	0.99	1.19	1.06	0.90	0.73
Other grid & storage	*11 570*	1.23	0.92	1.17	0.90	0.83

Note: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

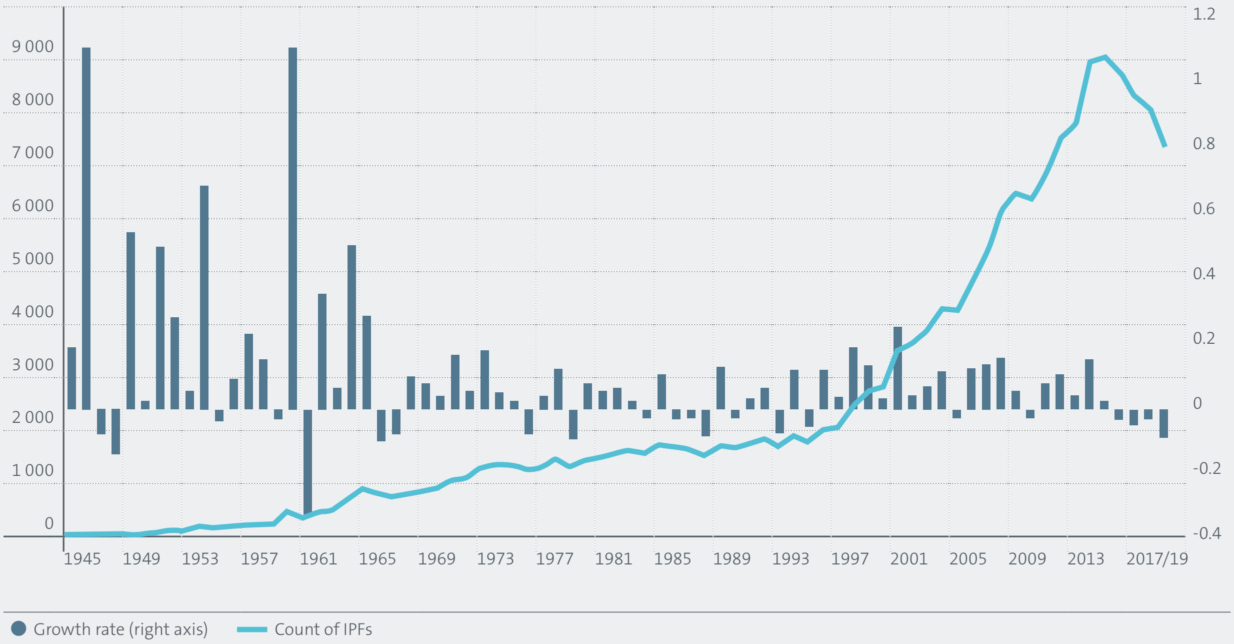
BOX 7

Patenting activities in fossil fuels versus LCE supply technologies

The identification of IPFs related to fossil fuel technologies (Annex 2) provides a particularly relevant benchmark for trends in LCE supply technologies. While there remain regional differences in the relative strengths of LCE and fossil fuel patenting, the global trend in fossil fuel patenting in recent years has been downwards. Since 2015, fossil fuel patenting activity has declined for four straight years globally, an outcome that has only one precedent since 1900 and that was prior to the second World War (Figure 5.2). In the 1940s, the annual number of IPFs in this area was around 150 times less than today, making the recent drop in patenting much more significant in absolute terms. It is all the more significant given that LCE technology patenting activity has risen the past three years, while that for fossil fuels has fallen. Unless there is a sudden uptick in fossil fuel patenting in the near future, it appears possible that rapid annual growth since 1995 – averaging over 8% per year- has ended with a historic peak of 9 000 IPFs per year. It cannot yet be known whether this reflects less spending on fossil fuel supply R&D (for public spending see Figure 4.1), or lower incentives to patent technologies in the current uncertain market outlook for fossil fuels.

Figure 5.2

Long-term trend of patenting in fossil fuels technologies, 1945-2019



Source: European Patent Office

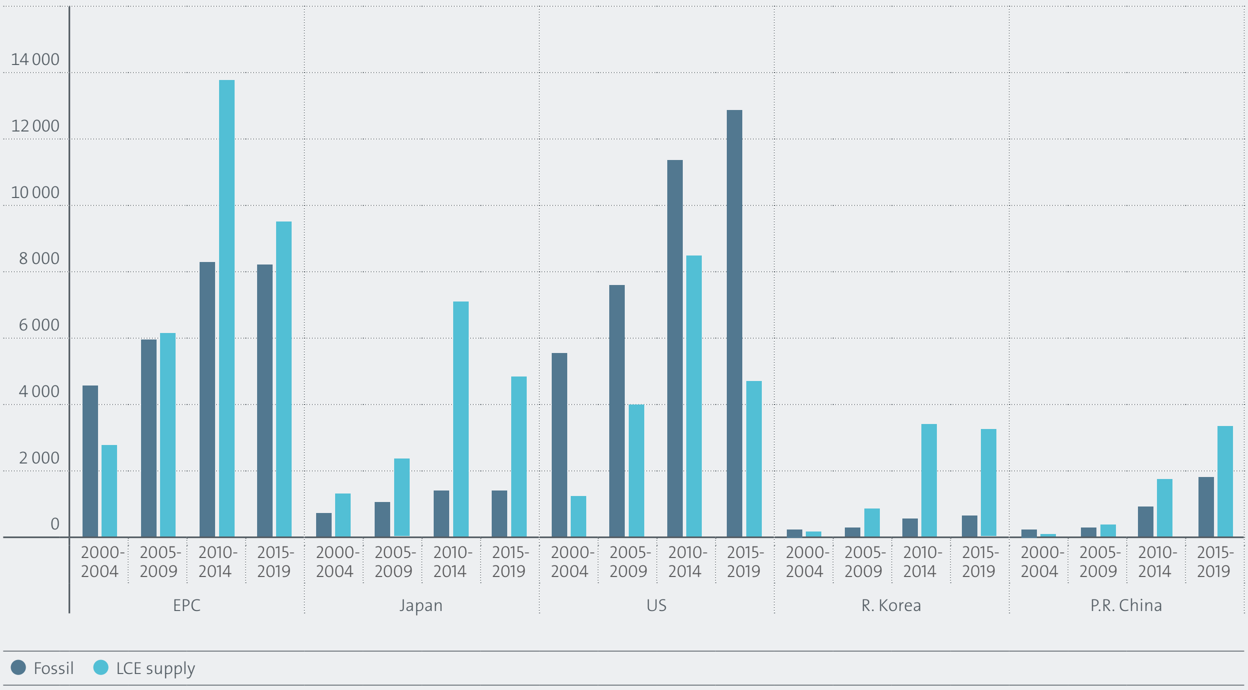
As reported in Figure 5.3, patenting activities in fossil fuels were below those in LCE supply in major innovation centres between 2000 and 2019, with the major exception of the US. Fossil fuel technology is hardly present in R. Korea's and Japan's patenting technology mix, but remains an important part of energy innovation activities in the other innovation centres.

In Europe, Japan and R. Korea, innovation in fossil fuel technologies stagnated after 2010, while LCE technologies experienced fast growth. The resulting gaps persisted afterwards, despite the decline in the number of IPFs related to LCE supply from 2015 to 2019. P.R. China showed a steady increase in both types of technologies from 2000 to 2019, with a significantly larger volume of IPFs in LCE supply.

The US stands out due to its significantly larger volume of patenting in fossil fuel technology during the entire period of analysis. A faster growth of IPFs in LCE supply caused convergence between 2000 and 2014. A steep drop in the number of IPFs in LCE supply technologies then further widened the gap between 2015 and 2019, accompanied by a significant increase of IPFs in fossil fuel technologies.

Figure 5.3

Growth of IPFs in fossil fuel versus LCE supply technologies by global innovation centres, 2000-2019



Source: European Patent Office

5.1.1. Focus on Europe

LCE innovation increased very significantly in all leading European countries after 2010 (Figure 5.4), and accounted for about 10% of all patenting activities in most countries during the following decade. It is largely dominated by Germany, which alone contributed about 11.6% of global IPFs between 2010 and 2019. Interestingly, Denmark also shows a particularly high LCE share of patents, which indicates a strong specialisation in these technologies. All countries, except Sweden, registered a drop in 2015-2019 compared with the previous period.

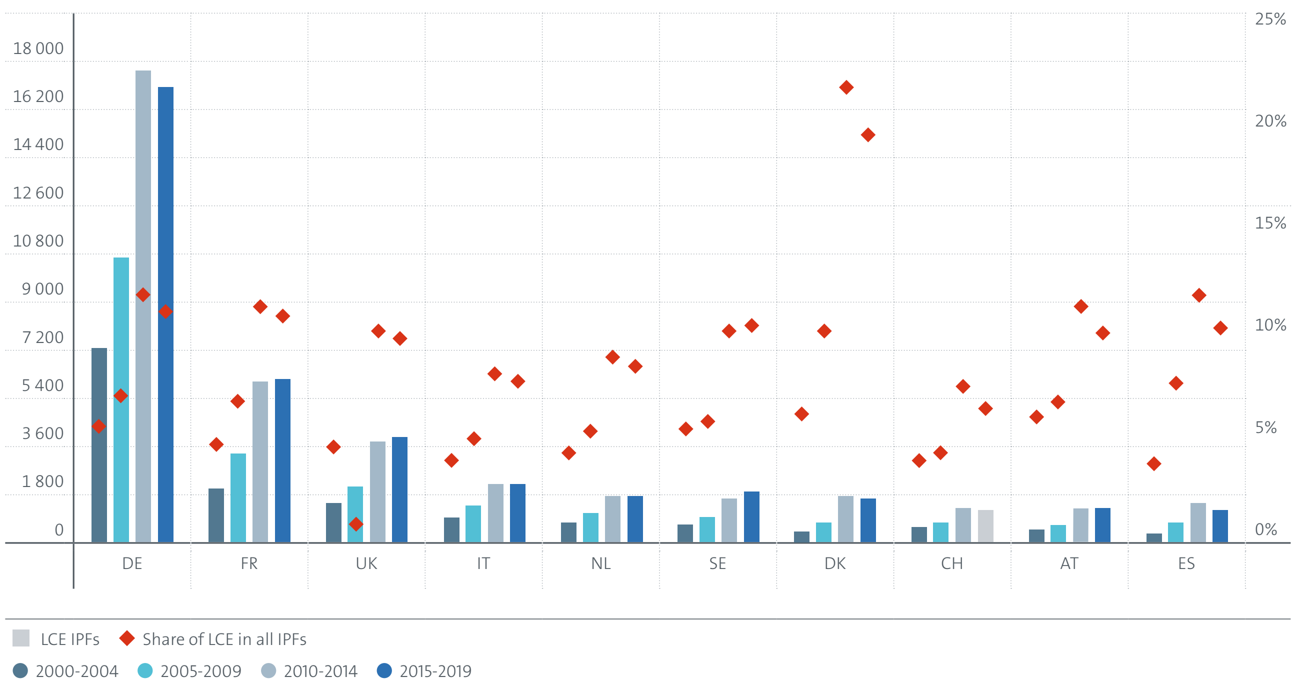
There are some notable examples of extreme specialisation in LCE supply sub-categories. Denmark's focus on wind technologies is the most evident example (Table 5.2). Spain is also notable in a number of domains (wind, solar thermal, hydroelectric and ocean technologies, fuel from waste); the UK in ocean and hydroelectric technologies, and Austria in hydroelectric and solar thermal technologies. European countries with an active oil and gas industry, such as the UK, Denmark, the Netherlands and France, also specialise in fossil fuel supply technologies at a similar high level to LCE technologies.

National specialisations in LCE end-use technologies follows the importance of the end-use sectors in that country's economy. Austrian specialisation in railways would fit this pattern, as would French specialisation in railways and aeronautics, and Dutch specialisation in agriculture. However, other cases are less easily explicable in such terms (e.g. Denmark in consumer products).

For LCE enabling technologies, Dutch specialisation in CCUS stands out, as does Denmark's specialisation in other technologies that relate to the storage (e.g. capacitors and thermal storage), transmission and distribution of electric power.

Figure 5.4

Growth of IPFs in LCE technologies in European countries, 2000-2019



Source: European Patent Office

Table 5.2

Specialisation (RTA) of top 10 EPC countries by LCE technology fields, 2010-2019

Energy supply	AT	CH	DE	DK	ES	FR	IT	NL	SE	UK
Solar PV	0.60	1.09	0.95	0.31	1.10	0.87	0.87	0.88	0.30	0.72
Solar thermal	2.56	2.44	1.57	1.31	6.46	1.42	2.40	0.96	0.90	0.85
Wind	1.11	0.58	1.83	28.91	5.65	0.65	0.91	1.57	0.72	1.82
Geothermal	1.88	2.56	1.39	1.57	1.86	1.08	1.93	1.25	2.37	0.77
Hydro	2.80	1.24	1.04	0.65	2.42	1.60	1.50	0.99	1.08	2.55
Ocean	0.44	0.32	0.65	1.61	3.56	1.79	1.16	1.22	2.12	4.18
Fuel from waste	1.76	0.70	1.39	3.63	2.04	1.49	1.43	2.34	1.64	1.26
Bioenergy	0.84	0.44	0.72	4.14	1.86	1.20	0.90	2.56	1.44	0.97
Combustion	1.56	2.78	1.49	1.27	0.70	1.14	1.69	0.80	1.80	1.04
Nuclear	0.14	0.43	0.59	0.11	0.78	2.89	0.54	0.20	1.41	0.93
Fossil fuels	0.75	0.29	0.63	2.01	0.52	1.35	0.67	1.69	0.66	2.19

Note: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

End-use technologies	AT	CH	DE	DK	ES	FR	IT	NL	SE	UK
Building	2.07	1.08	0.96	1.74	1.23	0.97	1.53	2.43	0.81	1.11
Metal and mineral	1.79	1.05	1.55	0.50	1.31	1.22	1.03	0.64	1.33	1.15
Chemical and oil	0.80	0.90	0.93	2.47	1.37	1.24	1.15	2.43	0.57	1.05
Agriculture	0.59	1.17	0.59	1.41	2.22	1.09	1.31	2.47	0.71	1.01
Consumer products	0.77	0.64	0.82	4.23	1.05	0.88	1.27	1.50	1.28	1.41
Electric vehicles	1.13	0.37	1.62	0.08	0.43	1.07	0.49	0.26	1.17	0.61
Other road vehicles	1.44	0.46	1.85	0.81	0.41	1.44	1.14	0.35	1.44	0.98
Railways	6.54	1.14	1.95	0.00	0.18	3.17	1.46	0.67	0.48	0.53
Aviation	0.25	0.50	1.22	0.20	1.60	4.07	0.48	0.20	0.52	2.96
Maritime and waterways	0.77	0.64	0.82	4.23	1.05	0.88	1.27	1.50	1.28	1.41
ICT	0.18	0.19	0.27	0.29	0.31	0.43	0.19	0.41	2.42	0.95

Note: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

Enabling technologies	AT	CH	DE	DK	ES	FR	IT	NL	SE	UK
CCUS	0.96	1.13	0.93	1.18	1.36	1.59	0.76	2.51	0.75	1.33
Batteries	0.80	0.29	0.92	0.11	0.22	0.63	0.20	0.13	0.24	0.37
Hydrogen and fuel cells	1.16	0.56	1.08	1.54	0.63	1.18	0.48	0.51	0.26	1.13
Smart grid	1.16	0.56	1.08	1.54	0.63	1.18	0.48	0.51	0.26	1.13
Other grid and storage	1.13	0.99	1.31	2.26	1.47	1.29	0.65	0.58	1.45	1.56

NNote: the RTA is calculated with respect to a region's share in all types of technologies. Highlighted ranges are: 1-1.25; 1.25-1.5; 1.5-1.75; 1.75-2; >2.

BOX 8

International R&D collaboration

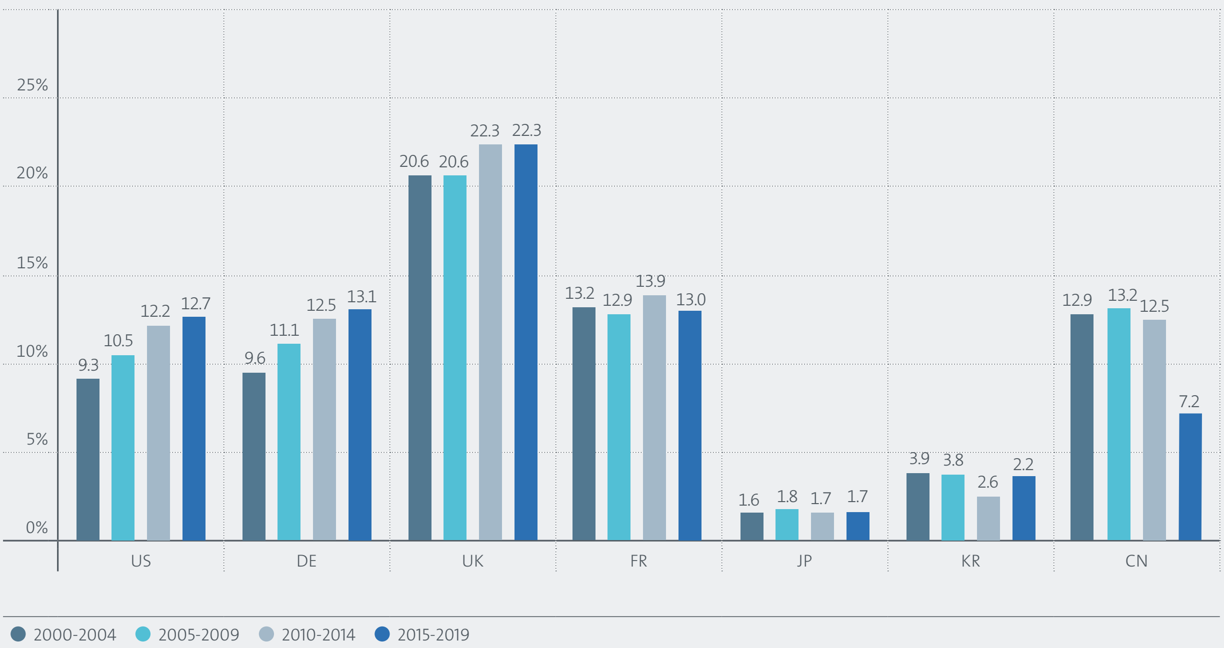
Climate change is a global challenge, so sharing some of the burden and opportunities between countries will lead to more technological progress internationally. IPFs originating from international teams of inventors illustrate existing cross-country co-operation for the development of LCE technologies. Co-operation can accelerate R&D efforts made by leading innovation centres and enable other countries to more rapidly absorb and exploit LCE technologies.

The share of co-invented IPFs in LCE technologies indicates the respective degree of involvement of leading innovation centres in international R&D collaboration. It reveals a striking contrast between the relatively high share of international co-inventions in the US and Europe and the much lower figures reported for Asia. Between 2015 and 2019, about 13% of the IPFs originating from the US, Germany and France stemmed from international collaboration, even exceeding 22% in the UK. Moreover, the share of international co-inventions has increased over time in all these countries, with the exception of France, where it has remained constant at a relatively high level.

In contrast, Japan and R. Korea are much less engaged in international R&D collaboration, representing less than 2% and 3% respectively of international co-inventions in 2015-2019. After a relatively high share (13%) of co-inventions in 2000-2009, co-inventions in P.R. China as a share of all LCE IPFs reached just 7% in 2015-2019. Although international co-inventions in P.R. China and R. Korea have been constant since 2012, they have been outpaced by IPFs with no overseas collaboration, indicating self-sufficient national innovation systems, but also potential missed opportunities for shared learning.

Figure 5.5

Share of IPFs in leading innovation centres that are co-invented with other countries, 2000-2019



Source: European Patent Office

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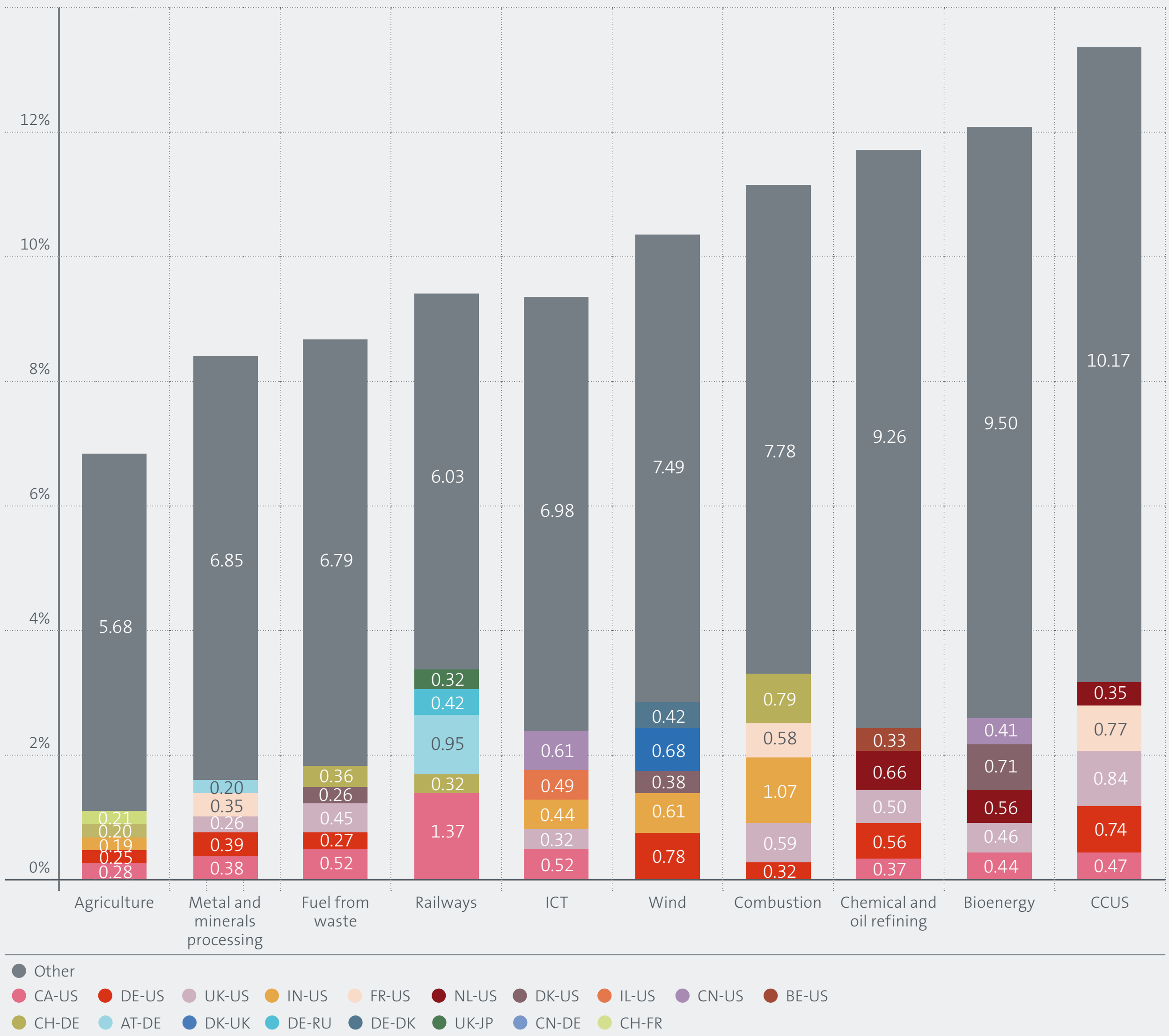
The high share of co-invention in US IPFs means that the top LCE technology fields for international collaboration are largely determined by US participation. As a result, the top four fields – and seven of the top ten – are fields in which the US has an RTA (CCUS, biofuels, chemical and oil refining, combustion, ICT, metal and mineral processing, and agriculture). It is also a partner in nearly all of the main bilateral collaborations reported for these fields; with the field of railways being the only noticeable exception.

Canada and India also have high shares of co-invention, appearing eight and three times respectively among the five biggest bilateral parings for the top ten technologies. The US is the partner in each case. In 2005-2019, co-invented IPFs represented 29% of all IPFs related to LCE in Canada, and up to 45% in India. In both cases, this was the result of a steady growth in the share of co-invented IPFs over the past two decades, from an initial 20% (Canada) and 26% (India) in 2000. In contrast with European countries, Japan, R. Korea and P.R. China are only involved in a few of the collaborations in the chart.

Figure 5.6

Top 10 fields for share of IPFs stemming from international collaboration (with top 5 pairs of collaborating countries highlighted in each field), 2000-2019



Source: European Patent Office

Annex

Annex 1 Cartography of LCE technologies

This annex provides a description of the LCE cartography used in the study to identify IPFs that constitute the building blocks of LCE technologies. It is based on a rigorous selection and re-organisation of different sections of EPO's dedicated classification schemes for climate change mitigation technologies (Y02 scheme) and smart grids technologies (Y04S scheme). For the purpose of the study, these Y02/Y04S data have been aggregated into three main sectors, namely "LCE supply technologies", "enabling technologies" and "end-use technologies", each of which are subdivided into several technology fields. Table A1 below provides the details of these subdivisions as well as the corresponding Y02/Y04S codes.

Table A.1

Cartography of LCE technologies

Low-carbon energy supply	Wind		Y02E10/70/LOW
	Solar	Solar PV	Y02E10/50/LOW
		Solar thermal	Y02E10/40/LOW
		Other solar	Y02E10/60
	Other renewables	Geothermal energy	Y02E10/10/LOW
		Hydro	FY02E10/20/LOW
		Marine	Y02E10/30/LOW
		Other	Y02E10/00
	Technologies for the production of fuel of non-fossil origin	Biofuels	Y02E50/10
		Fuel from waste	Y02E50/30
		Other	Y02E50/00
	Combustion technologies with mitigation potential		Y02E20/00/LOW
	Energy generation of nuclear origin (electricity)		Y02E30/00/LOW
Enabling and cross-cutting energy systems (enabling technologies)	CCUS		Y02C20/00/LOW
	Batteries		Y02E60/10
	Hydrogen and fuel cells		Y02E60/30/LOW
	Other		Y02E60/00 Y02E60/13 OR Y02E60/14 OR Y02E60/16 OR Y02E70/00/LOW OR Y02E60/60 OR Y02E40/00 or Y02E40/10, 20, 30, 40, 50, 60
	Smart grids		Y04S
Energy substitution and efficiency in end use (end-use technologies)	Buildings		Y02B
	Production/chemical and oil refining		Y02P20/00/LOW OR Y02P30/00/LOW
	Production/metal and minerals processing		Y02P10/00/LOW OR Y02P40/00/LOW
	Production/other	Agriculture	Y02P60/00/LOW
		Consumer products	Y02P70/00low
		Other production	Y02P80/00/LOW OR Y02P90/00/LOW
	Transportation/ electric vehicles and EV infrastructure	EV and infrastructure	Y02T10/60/LOW OR Y02T10/92 OR Y02T90/10/LOW
		Fuel cells for road vehicles	Y02T90/40/LOW
	Transportation/other road technologies		Y02T10/00 OR Y02T10/10/LOW OR Y02T10/80, 82, 84, 86, 88, 90 OR Y02T90/00
	Other transportation/ aeronautics, maritime and railways	Aeronautics	Y02T50/00/LOW
		Maritime and waterways	Y02T70/00/LOW
		Railways	Y02T30/00
	Computing and communication		Y02D10/00 OR Y02D30/00/LOW

Note: A marker "/LOW" has been placed at the end of some of the CPC Classes above; this indicates that for each of these CPC classes, not only the class itself but also its respective subclasses should be taken into account for the corresponding cartography label.

Annex 2 Cartography of fossil fuel technologies

This annex provides a description of the new cartography used in the study to identify the IPFs related to fossil fuel technologies. It is based on a rigorous selection by IEA and EPO experts of patent documents related to the supply of fossil fuel energy, from upstream oil and gas exploration to processing, transport and distribution. The structure of the cartography is indicated in Table A2 below and the details of the identification methodology are available in a separate document that will be available on epo.org/trends-energy and the iea.li/patents-in-transitions.

Table A.2

Cartography of fossil fuel supply technologies

Level 1	Level 2
Upstream	Conventional oil and gas exploration and extraction
	Unconventional oil and gas exploration and extraction
	Coal and solid fuels exploration and mining
Processing and downstream	Oil refining
	Gas conditioning
	Solid fuel conditioning
	Coal-to-gas
	Coal-to-liquids and gas-to-liquids
	Hydrogen production from hydrocarbons
Transmission and distribution	Liquid fuel pipelines
	Gas fuel pipelines
	Liquid fuel tanker shipping
	Liquefied gaseous fuel shipping
	Compressed gaseous fuel shipping
	Solid fuel shipping
	Road tanker liquid fuels transport
	Road tanker gaseous fuels transport
	Rail tanker liquid fuels transport
	Rail tanker gaseous fuels transport
	Rail solid fuel transport
	Underground liquid fuels storage
	Underground gaseous fuels storage
	Stationary tank storage for liquids
	Stationary tank storage for gases
	Solid fuel storage
	Liquid fuel distribution (gas stations)
	Gaseous fuel distribution

Annex 3 Patent metrics

The property rights granted through patents are strictly territorial. To protect a single invention in multiple markets, a number of national, regional, or international patent applications may be required. A large number of patent applications, therefore, does not necessarily mean a large number of inventions. A more reliable measure of inventive activity is to count international patent families (IPFs), each of which represents a unique invention and includes patent applications targeting at least two countries. More specifically, an IPF is a set of applications for the same invention that includes a published international patent application, a published patent application at a regional patent office or published patent applications at two or more national patent offices. The regional patent offices are the African Intellectual Property Organization (OAPI), the African Regional Intellectual Property Organization (ARIPO), the Eurasian Patent Organization (EAPO), the European Patent Office (EPO) and the Patent Office of the Cooperation Council for the Arab States of the Gulf (GCCPO).

IPFs are a reliable and neutral proxy for inventive activity because they provide a degree of control for patent quality and value by only representing inventions deemed important enough by the applicant to seek protection internationally (Dernis et al., 2001; Harhoff et al., 2003; Van Pottelsberghe and van Zeebroeck, 2008; Frietsch and Schmoch, 2010; Martinez, 2011; Squicciarini et al., 2013; Dechezleprêtre et al., 2017). A relatively small proportion of applications meet this threshold, and this varies widely across country of residence of the inventor and other important vectors. As such, this concept enables a comparison of the innovative activities of countries, fields and companies internationally, since it creates a sufficiently homogeneous population of patent families that can be directly compared with one another, thereby reducing the national biases that often arise when comparing patent applications across different national patent offices.

Each IPF identified as relevant to LCE technologies is assigned to one or more sectors or fields of the cartography. The analysis covers the period 2000-2019. The date attributed to a given IPF always refers to the year of the earliest publication within the IPF. The geographic distribution of IPFs is calculated using information about the origin of the inventors disclosed in the patent applications. Where multiple inventors were indicated on the patent documents within a family, each inventor was assigned a fraction of the patent family.

Where necessary, the dataset was further enriched with bibliographic patent data from PATSTAT, the EPO's worldwide patent statistical database, as well as from internal databases, providing additional information, for example, on the names and addresses of applicants and inventors, or whether the applicant is a company or a research organisation. In addition, information was retrieved from the Bureau van Dijk ORBIS (2020 version) database and used to harmonise and consolidate applicant names and their addresses. Each applicant name was consolidated at the level of the global ultimate owner according to the latest company data available in ORBIS. If that information was not available, the data was cleaned manually.

Annex 4 Cluster analysis

To identify the regional innovation clusters in enabling technologies (Box 5), the density-based DBSCAN algorithm (Ester et al. 1996) was applied to the geocoded inventor locations for all relevant IPFs. This algorithm groups together location points with a dense neighbourhood into clusters and has two important advantages. First, it is able to represent clusters of arbitrary shape, and second, it labels location points that do not belong to any cluster as noise. This allows the analysis to focus on the identified innovation clusters and dismiss inventor addresses outside said clusters.

For each IPF, the locations of all unique inventor-address pairs listed in one of the patent applications in the patent family were selected and represented as separate data points. No duplicates of any address were removed, i.e. two different inventors having the same address produced two separate points in the same location. Equally, if the same inventor was listed in multiple patent applications, then multiple points were placed in the same location.

The DBSCAN clustering algorithm was then applied to the set of points. Two parameters were required as inputs to the algorithm: the eps radius, which defined the radius of the neighbourhood around each point (i.e. each inventor address), and the minimum number of points in the neighbourhood of a point to consider it as a core point, i.e. a point in a high-density region. The characteristics of the clusters found by the algorithm depend directly on the selection of these two parameters.

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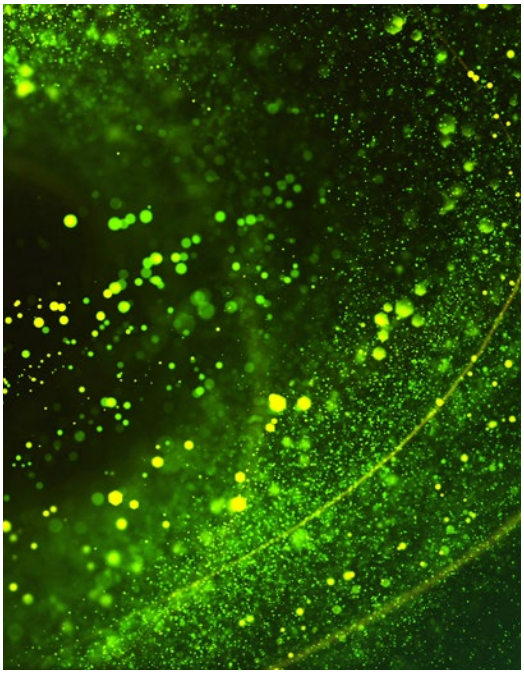

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