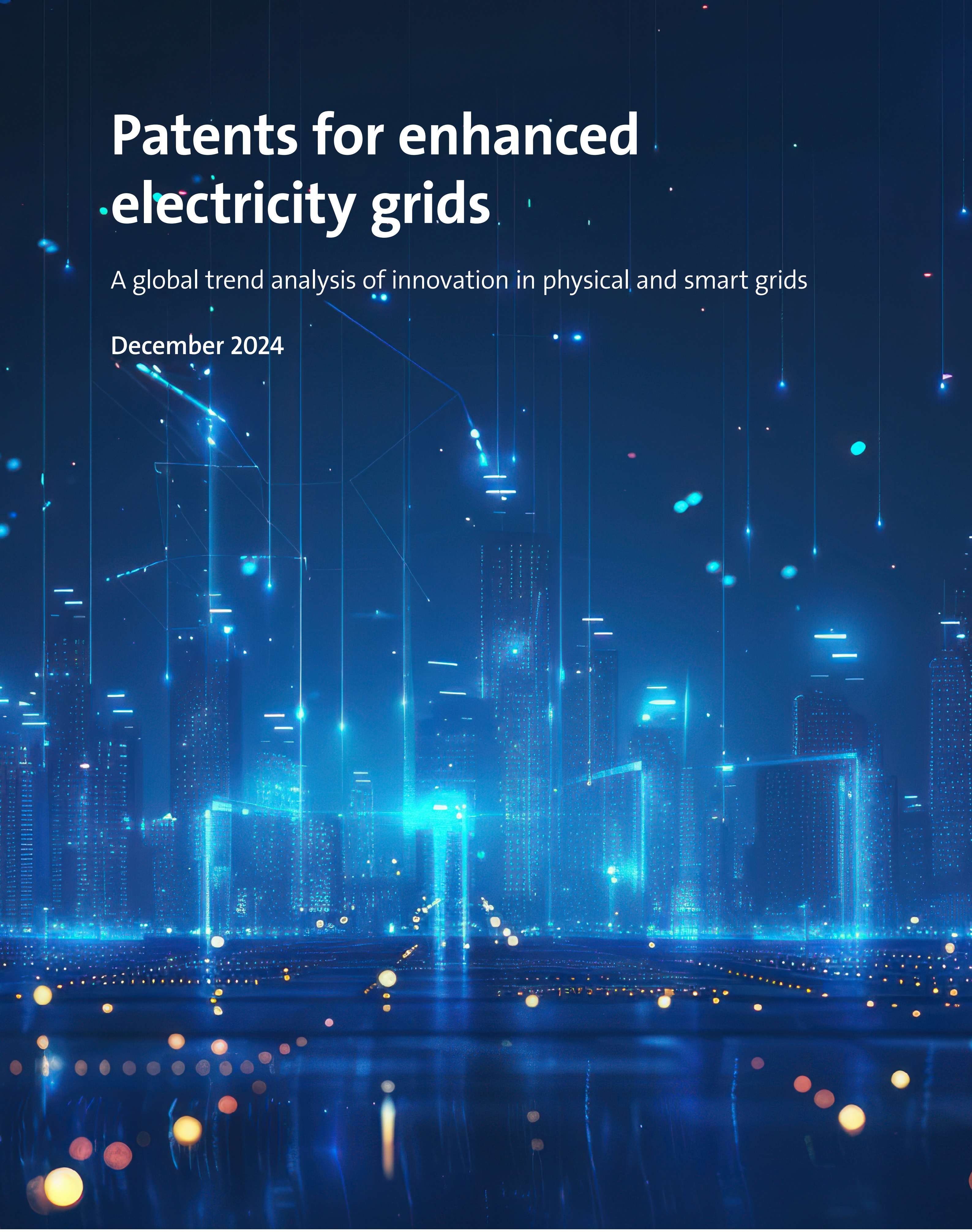
Patents for enhanced electricity grids

A global trend analysis of innovation in physical and smart grids

December 2024



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iea
International Energy Agency

Forewords

As recently emphasised in Mario Draghi's landmark report, taking the lead in new clean technologies and accelerating the energy transition away from fossil fuels are key conditions for Europe to secure the competitiveness of its economy. Significant progress has already been achieved: Europe is producing record levels of renewable energy, and electricity-powered vehicles or heat pumps are being deployed on a continental scale. These trends make it ever more urgent to also invest in smarter and more flexible transmission and distribution networks that can effectively balance the growing demand for power with new, variable sources of energy. In this context, producing reliable intelligence on available technology options related to innovation trends is key for supporting robust business and policy decisions. This is also part of the EPO's strategic commitment to sustainability.

This study – the fourth of its kind undertaken in collaboration with the IEA since 2020 – addresses innovation trends in power grids. Combining the energy expertise of the IEA with the EPO's patent knowledge, it highlights specifically the disruptive impact of digital technologies in that field, and the deep transformations taking place in a century-old industry as a result. Because patent information is the earliest possible signal of industrial innovation, this report offers a unique source of intelligence on a complex and fast-moving technology landscape that is reaching new heights of strategic importance to decision-makers around the world. Patent protection is key for innovators to transform research into market-ready inventions. Patents enable enterprises and universities to reap the rewards of their creativity and hard work. As the patent office for Europe, the EPO provides high-quality patents to protect innovations in up to 45 countries (including all EU member states). European patents are not only for large multinational companies. They are also key to helping small businesses raise funding, establish collaborations and eventually scale.

The study is a guide for policymakers, regulators and operators to anticipate technological change, assess their comparative advantage in different segments of the power distribution industry, and direct resources towards promising options. Drawing on the EPO's uniquely curated and consolidated evidence base, it introduces novel patent data search strategies to assess the modernisation dynamics affecting the components and architecture of energy infrastructure, including its physical and smart dimensions. It sheds light on the pathways opening up to innovative companies and the research sector as they contribute to long-term sustainable growth. It benefited from the support of twelve patent offices involved in the energy transition activities of the EPO's Observatory, namely Austria, Bosnia and Herzegovina, the Czech Republic, Finland, Italy, Latvia, Lithuania, Monaco, Netherlands, Spain, Sweden, and Türkiye.

The results reveal a dramatic acceleration of innovation in grids technologies in the last fifteen years, paving the way for a new age of power networks, capable of seamlessly sensing and managing myriads of electrical devices. They also highlight the major contribution of Europe to this transformation, thus underlying the opportunity for energy transitions within European industries – startups and large companies alike. Importantly, this report also reminds us all of the competitive nature of innovation in clean technologies: the global race for smarter grid technologies is on, and has even accelerated in recent years thanks to the increased impact of artificial intelligence and smart EV charging. By giving decision-makers an unparalleled perspective over patenting trends, these findings provide a valuable map for our transition to a new energy system.

António Campinos
President, European Patent Office

Grids have been the backbone of electricity systems for more than a century, underpinning economic activity by bringing power to homes, industry and services. The role of electricity is becoming even more prominent, and the International Energy Agency (IEA) has made it clear that the future of the global energy system is increasingly electric. In energy history, we've witnessed the Age of Coal and the Age of Oil – and we're now moving towards the Age of Electricity. This makes the expansion of power infrastructure even more important for continued societal and economic development.

Without adequate electricity networks to deliver new power supply to centres of demand, economic activity could be stymied while the most vulnerable in society are likely to be the worst affected. Energy access in emerging and developing economies could stall, and the integration of new energy sources would likely become more costly and complex. Ensuring the world's grids are fit-for-purpose requires not only building new lines but also refurbishing and upgrading existing networks to make the most of the infrastructure already in place.

Interconnected electricity grids bring benefits for consumers and are fundamental to energy security. It has been estimated that cross-border electricity trade in Europe delivers economic benefits of around EUR 34 billion per year. Following Russia's full-scale invasion in 2022, Ukraine's electricity grid was interconnected with the continental European system in record time and, by summer 2024, exports from Europe met nearly one-fifth of Ukraine's peak power supplies. In April 2025, the issue of electricity grids and secure power supplies will be on the agenda at the International Summit on the Future of Energy Security convened by the IEA and hosted in London by the Government of the United Kingdom.

New approaches to the expansion and refurbishment of electricity grids can contribute to national competitiveness, a pertinent policy priority for many countries following a global energy crisis and a period of high prices. Technology innovation is at the heart of this challenge. The world will continue to rely on innovators to drive forward the pace of progress to resolve a range of emerging challenges, including integrating greater shares of variable renewable energy such as wind and solar, and improving demand-side management measures to ensure consumers play their part.

Governments have a critical role in supporting innovation and encouraging grid operators to implement the latest solutions. Many countries are now seeking to foster manufacturing of clean energy technologies and stimulate domestic demand. To date, these have largely focused on products including solar PV, wind turbines, batteries, electric vehicles, electrolysers and heat pumps. But this report shows that competition for leadership in electricity grid innovation is also intensifying, with a strong case for expanding industrial strategies to encompass grid-related technologies.

This study, which is another example of the strong partnership between the IEA and the European Patent Office (EPO), is the most comprehensive analysis of patenting trends across electricity grid technologies. Such an integrated approach – that looks at physical grid technologies, smart grid technologies and the increasing overlaps between them – is essential for understanding progress towards tackling the challenges faced in advanced and emerging economies alike.

The report findings give us confidence that innovators around the world are responding to the new challenges facing electricity grids, and to the economic opportunity this represents. But the report also identifies areas where some regions risk losing their technological leadership or where more effort is required. Our continued co-operation with the EPO will allow us to track this progress going forward.

Dr Fatih Birol
Executive Director, International Energy Agency

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List of abbreviations

AC	Alternating current
AI	Artificial intelligence
BEV	Battery electric vehicles
CEIDS	Consortium for the Electric Infrastructure to support a Digital Society
DC	Direct current
DERMS	Distributed energy resources management system
EMDE	Emerging market and developing economies
EPO	European Patent Office
EV	Electric vehicles
FACTS	Flexible AC transmission systems
FCEV	Fuel-cell electric vehicles
FFR	Fast frequency response
HVDC	High-voltage direct current
ICT	Information and communications technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPFs	International patent families
LDES	Long-duration energy storage
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicles
PV	Photovoltaics
R&D	Research and development
RTA	Revealed technology advantage
SCADA	Supervisory control and data acquisition
TEN-E	Trans-European Networks for Energy
UHD	Ultra-high voltage
VAR	Volt-ampere reactive
VPP	Virtual power plant

List of countries, territories and economies

CH	Switzerland
CN	People's Republic of China
DE	Germany
EU	European Union
FR	France
JP	Japan
KR	R. Korea
RoW	Rest of world
TW	Chinese Taipei
US	United States

Other Europe
Member states of the European Patent Organisation that are not part of the EU27:
AL, CH, IS, LI, MC, ME, MK, NO, RS, SM, TR, UK

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 45 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.

In October 2023 the EPO launched the Observatory on Patents and Technology, which serves as a digital hub for transparent and informed debate on innovation.

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 over 75% of global energy consumption and includes 35 member countries, five accession countries, and thirteen association countries – Brazil, P.R. China, India, Indonesia, Morocco, Singapore, South Africa and Thailand.

Executive summary

Electricity is at the core of ongoing energy transitions. Electricity demand has grown at twice the pace of overall energy demand over the last decade, and the growth of electricity consumption is set to accelerate further in the years ahead. To achieve countries' national energy and climate goals (which go beyond policies currently in place), the world's electricity use needs to grow 20% faster in the next decade than it did in the previous one. On the supply side, electricity grids will continue to incorporate more renewable resources with variable output and different geographical distributions to current grid layouts. At the same time, many countries face rising investment needs to update ageing grid infrastructure to make it fit for modern energy systems: roughly 50 million km of older transmission and distribution lines will need to be replaced around the world by 2050.

Modern, smart and expanded grids are therefore essential for successful energy transitions. Ensuring competitiveness, security and affordability while refurbishing, extending and optimising electricity grids to more flexibly connect sources of power supply and demand are technology innovation challenges, as well as investment and policy challenges. There are many opportunities for innovators to accelerate clean energy transitions with improved grid-related technologies and capture the economic value associated with the growing market for these solutions.

However, electricity grids are often the unsung heroes of energy transitions and their infrastructure is a familiar and uninspiring part of the landscape. At best they are taken for granted, and at worst their expansion is hindered by local opposition. There is a risk that if too little attention is paid to creating new products and services to reduce the costs and improve the performance of grid technologies – including by reducing the need for overhead lines and helping electricity customers monetise their consumption choices – then grids could become a bottleneck to the modernisation of energy systems.

As this report shows, researchers and innovators around the world are responding to the challenge. Over the past 19 years, patenting of electricity grid technologies has increased to levels roughly seven times higher than in 2005. Thanks to robust data on the technological, geographic and corporate distribution of this patenting activity, governments and innovators can track the trends and gaps that concern them. As a leading indicator of technological change, patent data complement other sources of information to yield actionable insights related to regional advantages, competitive weaknesses and strategic opportunities.

This study combines the expertise of the International Energy Agency and the European Patent Office and is the most comprehensive, global and up-to-date investigation so far of patenting in the area of key electricity grid issues and opportunities. The study identifies three groups of critical challenges technology can help address. While there is huge scope for making the power network "smarter" – a process that is already well underway and involves overlaying a network of communications systems on top of the network that transports the electricity itself – each of the three challenges can only be overcome with a mixture of hardware and software improvements. While patenting in smart grid technologies is a faster-moving area, the volume of patenting to enhance physical grids is not far behind and keeping up innovation efforts in this area will be crucial in the decades to come.

Key findings

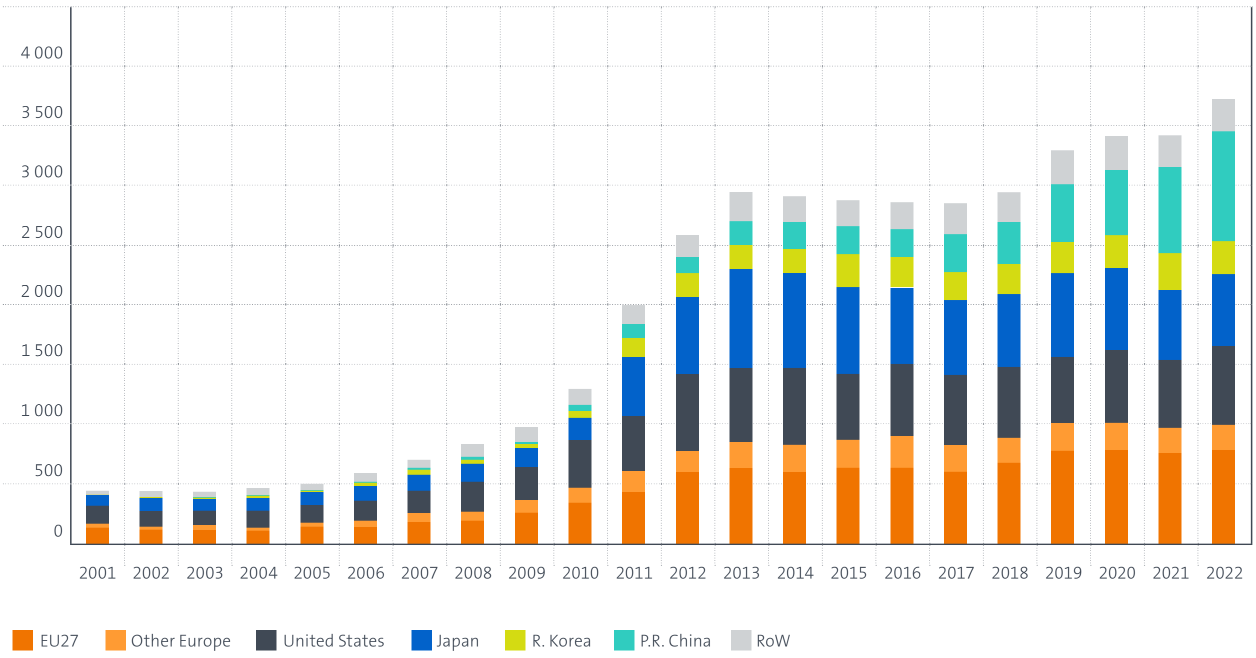
1. Grid-related patenting experienced a dramatic acceleration over the period 2009–2013. It has since stabilised in most major regions, with the exception of P.R. China; in 2022, the country overtook the EU for the first time, becoming the largest regional source of applications

Patenting activities in grid-related technologies grew at remarkable speed between 2009 and 2013. Over this period, the number of international patent families (IPFs)[1] related to grids increased at an average annual growth rate of 30% – well above the average rates of 12% for low-carbon energy technologies (EPO-IEA, 2021) and 4% for all technologies. This take-off phase reflects a period of intense industrial interest in a new suite of smart grid technologies, driven by the creation of policy-driven markets and standards for smart meters and electric vehicles, as well as the prospect of the swifter deployment of renewable energy sources of energy. The trend was also gathered impetus thanks to the emergence of software innovation as a major corporate strategy in this period. This expanded the scope of smart grid inventions being patented, resulting in 50% more physical grid patents containing smart grid elements in the period 2010–2022 than in the preceding decade.

This impressive growth mostly occurred in Europe, Japan and the US, and patenting activities remained stable at a high level afterwards in these regions. At the same time, steady progress has enabled P.R. China to gradually emerge as the new global engine of electricity grid patent growth, rising from 7% of the global total in 2013 to 25% in 2022. In that year, P.R. China became the world's top patenting region in this technology area for the first time.

Figure E1

Patenting trends by main world region (IPFs, 2001-2022)



Note: Calculations are based on country of IPF applicant, using fractional counting in the case of co-applications.

Source: author's calculations

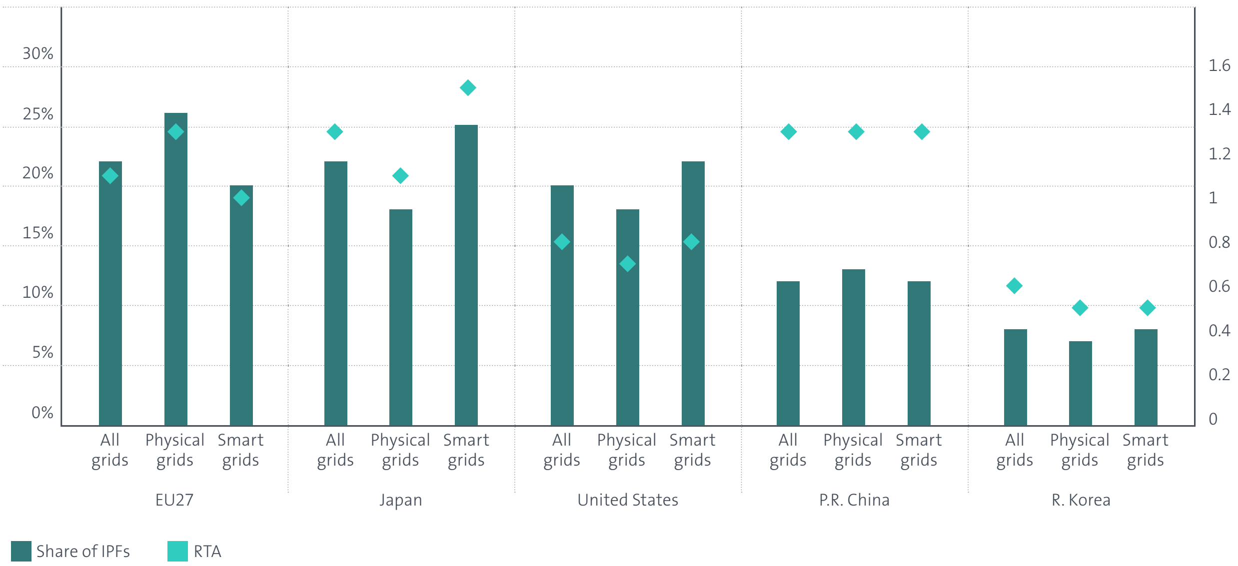
[1] Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient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

2. The EU27 and Japan have led electricity grid patenting over the past decade

The EU27 and Japan each generated more than one-fifth of IPFs related to grids over the period 2011-2022, and they possess a relative technology advantage (RTA) in these technologies compared with non-grid technology areas.[2] Europe's contribution has drawn primarily upon expertise in physical grid technologies – Switzerland alone generated 5% of all grid-related IPFs – while Japan shows a stronger relative specialisation in smart grid technologies. Among other regions, the United States contributed 20% of patenting activities related to grids, but does not have any relative specialisation in the field. P.R. China's share of all grid-related IPFs between 2011 and 2022 was significantly lower, but shows a specialisation in both physical and smart grid technologies as high as that of the EU.

Figure E2

Share of international patenting and revealed technology advantage by main world region and main type of grid-related technologies (IPFs, 2011-2022)



Note: Calculations are based on country of IPF applicant, using fractional counting in the case of co-applications.

Source: author's calculations

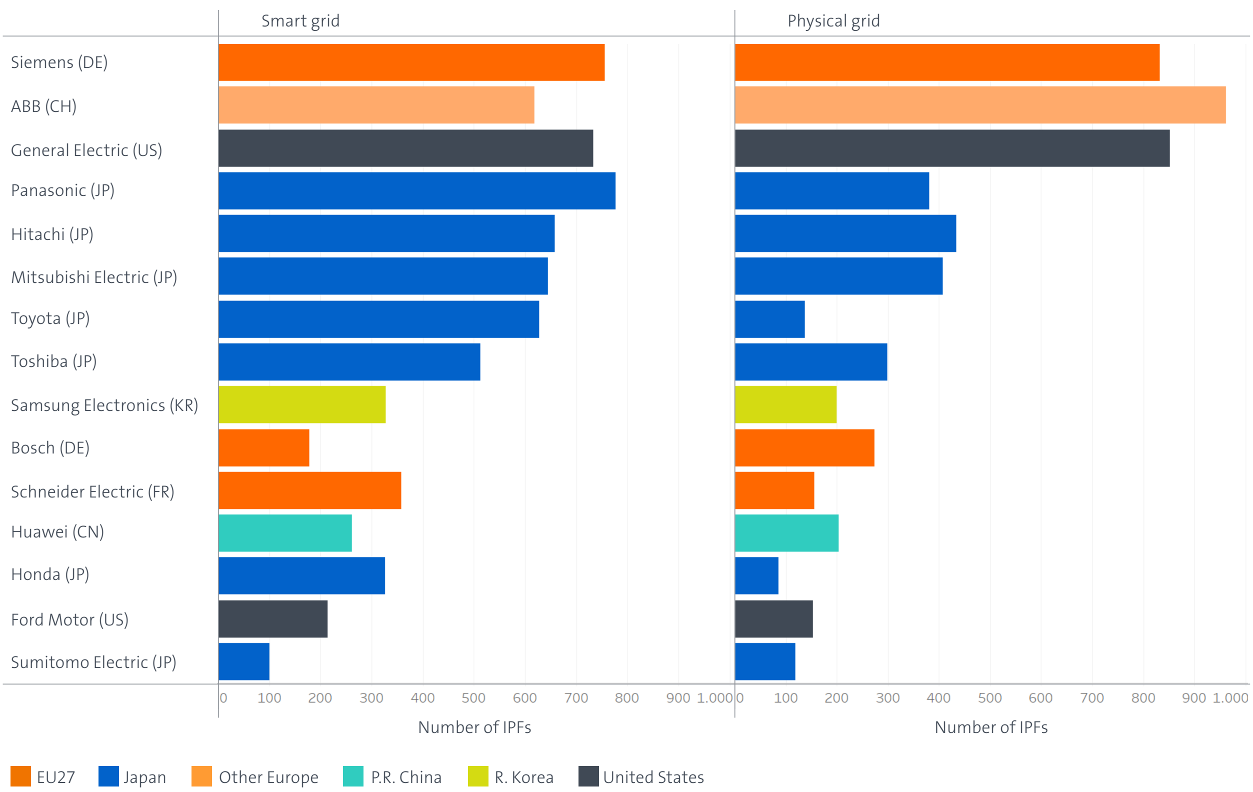
[2] The RTA index indicates a country's specialisation in terms of grid-related innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology.

3. Siemens, ABB and General Electric lead the ranking of electricity grid patent applicants, which is testament to their strengths in physical grid technologies in particular. They face strong Asian competitors when it comes to innovation in smart grids

The top 15 corporate applicants listed alone generated nearly one-third (31%) of IPFs in grid-related technologies over the period 2011-2022. Their cumulative share of IPFs is slightly higher in physical grid technologies (35%, compared to 31% in smart grids). Siemens, General Electric and ABB, three large conglomerates from Germany, the US and Switzerland respectively, lead the ranking. However, seven Japanese applicants feature too, all with a stronger specialisation in smart grids. The remaining top applicants include R. Korea's Samsung Electronics, France's Schneider Electric and P.R. China's Huawei, a telecom equipment company expanding into smart grids. Three automotive companies (Toyota, Honda and Ford Motor) feature in the ranking as a result of their strong contribution to innovation in smart EV charging.

Figure E3

Top 15 applicants in grid-related technologies (IPFs, 2011-2022)



Note: Applicants are ranked by total number of IPFs in grid-related technologies. Some of these may be relevant to more than one of the three subcategories shown; they are reported under each of these subcategories. The IPFs filed by ABB Grid have been consolidated under Hitachi.

Source: author's calculations

4. Smart grid innovation is driving the latest burst of electricity grid patenting. Although a great deal of attention is given to innovations helping customers control electricity demand, the largest smart grid patenting areas relate to control of larger grid-scale assets

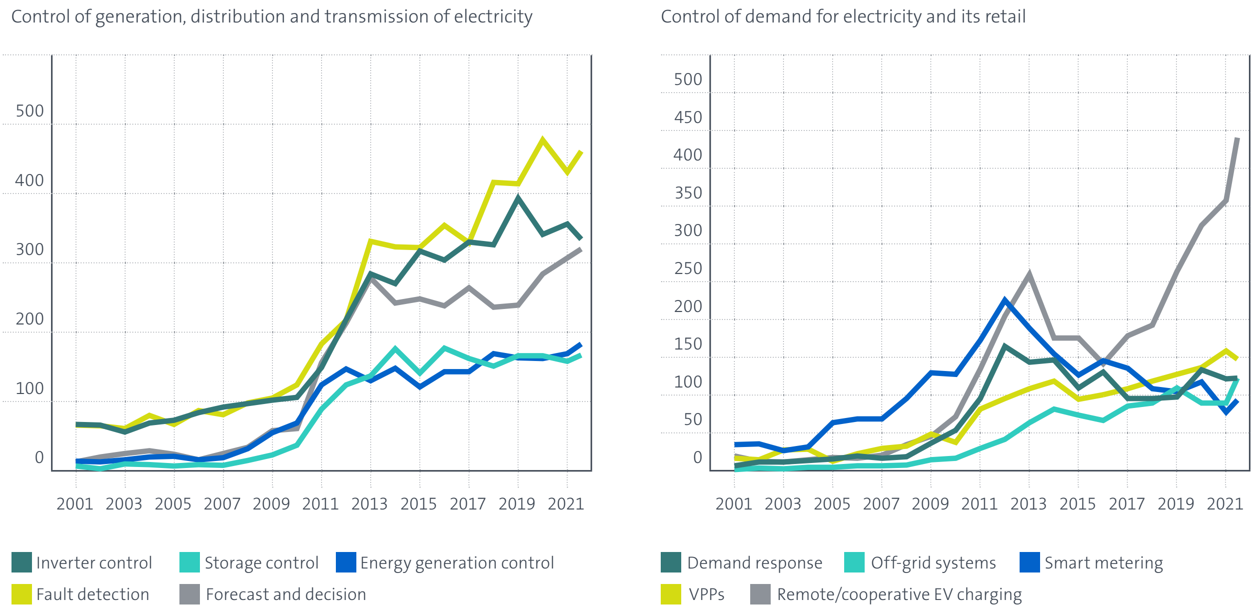
Smart technologies are being developed to address problems across nearly all aspects of electricity grids. Patenting activities in the control of grid-scale assets took off around 2010 and has kept increasing steadily since then. Japanese applicants have a strong lead in fields such as forecast and decision or remote control of inverters and electricity storage assets; the recent acceleration of patenting in fault detection has chiefly been driven by Chinese applicants.

Smart metering was the first customer-oriented field to show an increase in patenting, mainly in the US and Europe, but has shrunk significantly after a burst of activity during the period when they were first being rolled out. More generally, patenting trends tend to be more volatile on the customer side of smart grids, due to shorter product development times and the standardisation of protocols and interfaces for grid-connected equipment. As a result, it is important for innovators to secure intellectual property early in the development of new smart grid technology areas, as they may not enjoy long subsequent periods of incremental improvements.

A similar dynamic is seen in EV charging patenting, though this has returned to impressive growth since 2015 as new techniques for aggregation and remote control have emerged. The new growth phase coincides with a shift in patenting activities from equipment suppliers to OEMs, signalling the latters' increased strategic interest in mastering smart charging technology. Overall, Japanese applicants alone account for about one-third of IPFs in that field over the period 2011-2022, followed by US and European ones with about 20% each.

Figure E4

Growth of patenting in selected smart grid technologies (IPFs, 2001-2022)



Source: author's calculations

5. Grid-related AI patenting grew by over 500% in the five years to 2022, and is now the most active area of patenting among enabling digital technologies, led by the United States and P.R. China

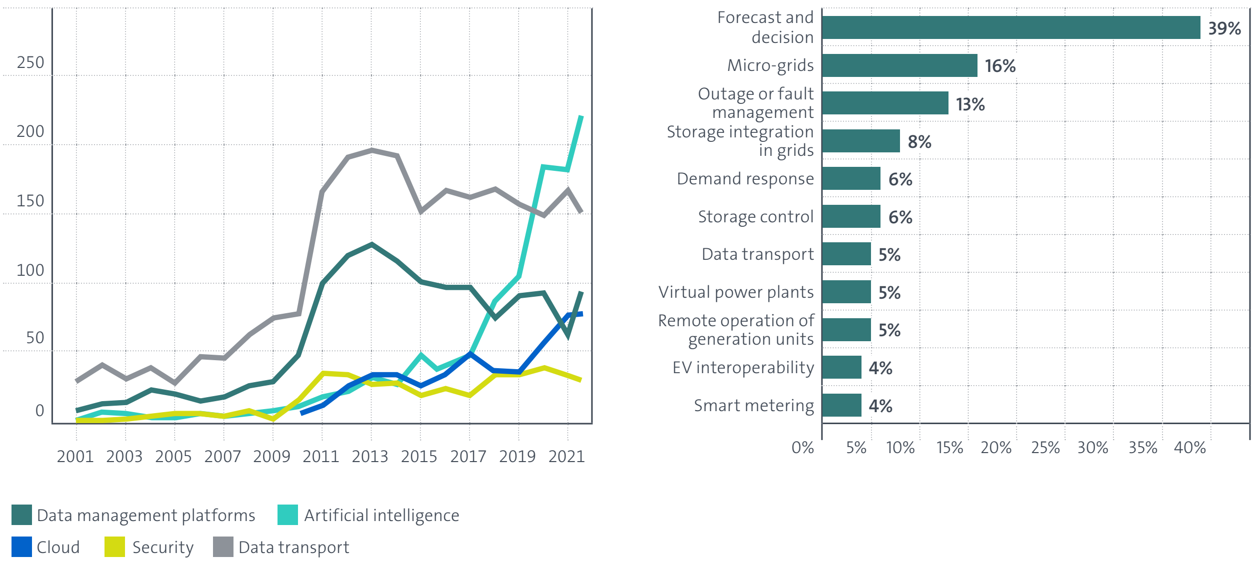
The main area of AI-related IPFs is those to support forecast and decision, a category that boasts 39% of AI-related IPFs and drove rapid growth of AI-related electricity grid patenting from 2000 to 2022. AI is nonetheless applied in patents related to other areas of smart grids, in particular micro-grids and outage management. The US and China are the main patenting regions for these technologies, with 24% and 23% of AI-related IPFs respectively, followed by the EU27 countries with 18%.

Figure E5

The growing impact of AI on innovation in smart grids

Patenting trends in selected enabling technologies for smart grids (IPFs, 2001-2022)

Smart grid technologies targeted by AI-related IPFs (2011-2022)



Note: The chart on the right shows the percentage of IPFs related to AI for grids that have also been identified as related to another category of smart grid technologies. Some of these may relate to two or more such categories; others may have no clearly identified relation to any of them.

Source: author's calculations

6. One-third of startups in electricity grid technologies hold a patent application, which is much higher than in other technology areas. These startups are mostly located in Europe and the United States.

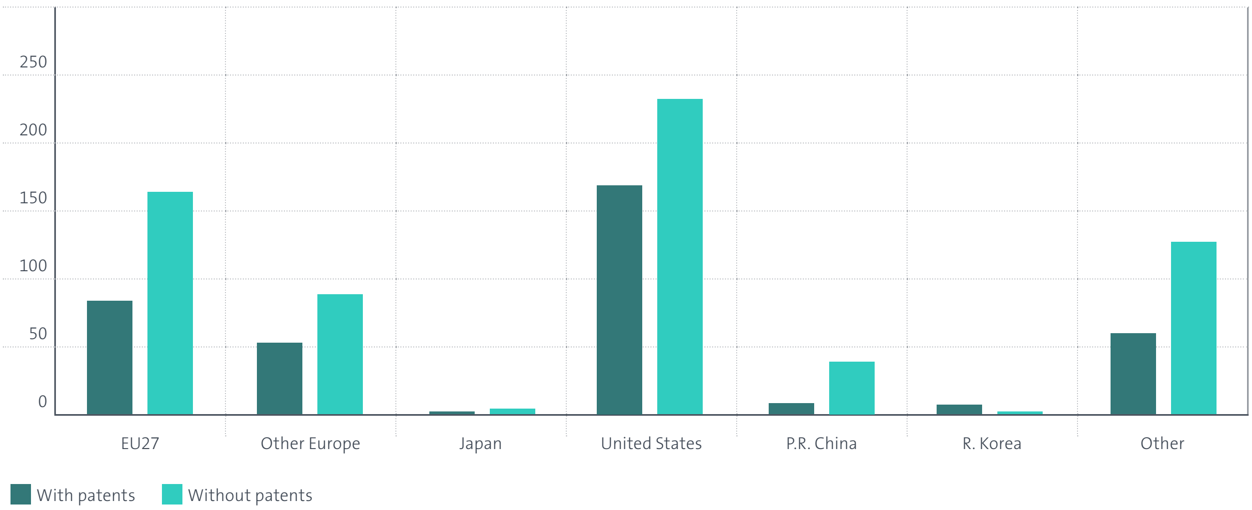
358 of the 1 085 startups identified for this report with activities relating to electricity grid technologies hold at least one IPF. This proportion is remarkably high, compared for instance with the estimated 6% share of all European startups that have a patent application. It is a positive indicator of fundraising capacity for grid-related startups, given the available evidence showing patent ownership has a positive impact of on startups' ability to attract VC funding (EPO-EUIPO, 2023).

Among smart grid technologies, one-third of startups are working on grid optimisation, and one-quarter on electricity trading. Other important areas include VPPs (20%) and meter hardware (14%). Contrary to expectations, around half of startups are developing hardware, a high-risk innovation path that typically requires patient investors and high upfront capital. Government attention should be given to the successes and difficulties encountered by these startups, to identify whether innovation ecosystems adequately support grid hardware entrepreneurs.

Most of the startups are located in the US and Europe, with each of those two regions contributing about 39% of the total, and 24% for the EU27 alone. By contrast, the small numbers of startups identified in P.R. China, R. Korea and Japan suggest a lesser role for venture capital in these countries' innovation ecosystems. Apart from these main regions, Canada (with 50 startups), India (30) and Israel (13) stand out for sizeable ecosystems of grid-related startups.

Figure E6

Startups in grid-related technologies: number of startups and patenting profile by main world region, 2011-2022



Source: author's calculations

1. Introduction

1.1. The importance of electricity grids for clean energy transitions

Modern, smart and expanded grids are essential for successful energy transitions. Vast networks of cables, pylons, transformers, meters and other assets have been the backbone of electricity systems for over 100 years and are set to become increasingly important as electricity comes to represent a larger share of the global energy system. This is because the main sources of low-emission energy – solar photovoltaics (PV), wind, hydropower and nuclear – are typically sources of electricity, unlike the combustible fuels associated with fossil energy.

Solar PV and wind are now the cheapest electricity sources in most markets. In addition, electricity is a highly versatile form of energy that is especially valuable for computing, advanced manufacturing and in the service sector, all of which are key drivers of modern economies. It is also more energy-efficient to use electricity than fossil fuels in end-use applications such as personal mobility, and it leads to less local air pollution.

However, electricity grids often receive too little attention. For every dollar spent on renewable power, 60 cents are spent on grids and storage (IEA, 2024a). Many power systems are vulnerable to an increase in extreme weather events and cyberattacks, which are growing risks that put a premium on adequate investment in grid resilience and digital security. Overall, if grids are not in the right place to connect electricity demand and supply, not properly maintained, or not technically capable of meeting the needs of a 21st-century power system, they could become a bottleneck to economic growth and tackling climate change.

Electricity use has grown at twice the pace of overall energy demand over the last decade, and demand growth is set to accelerate further in the years ahead, adding the equivalent of Japanese demand to global electricity use each year under today's policy setting, driven by light industrial consumption, electric mobility, cooling, and data centres and AI (IEA, 2024a). To achieve countries' national energy and climate goals which go beyond today's policy settings, the world's electricity use needs to grow 20% faster in the next decade than it did in the previous one. At the same time, electricity supplies will continue to incorporate more renewable resources, with variable output and different geographical distributions to current grid layouts.

1.2. Electricity grids face new challenges

Growing electricity demand and more variable generation increase the operational need for flexibility in power systems, both for short-term and seasonal needs. This requires a rebalancing of power sector investment and innovation towards grids and battery storage.

Three specific challenges present themselves to grid developers and policymakers. Tackling each will require technology improvements and innovation. As this report shows, researchers and innovators around the world have shifted their attention to technologies that can help address these issues in the past decade or more. However, the scale of the challenge and its evolving nature require unwavering attention to further enhancements.

- **Expanding and enhancing physical connections.** More disparate sources of electricity need to be connected to locations of end-user demand, which are changing in advanced economies with the growth of data centres and EV charging and expanding quickly in developing economies. Technological improvements promise to help accomplish this task in a manner that minimises total capital costs by enabling highly targeted interventions, deploying more efficient or cheaper grid infrastructure, and facilitating higher capacity utilisation of cables. This cost dimension is important because the installation of low-emission electricity sources is itself a capital-intensive undertaking. It can include the use of mini- and micro-grids as the initial options for connecting new users to networked electricity services.

- **Making grid operations more flexible and bidirectional.** The operation of electricity grids must become more flexible so that demand and supply can adapt in real time to minimise the peak generation capacity needed to provide all end-users with low-emissions electricity. This must be accomplished without harming the reliability of supply or network frequency. It must allow end-users to reap the benefits of low-cost electricity at times of abundant supply and participate economically as suppliers of electricity or avoided demand, according to the resources they can offer to the system.

— **Protecting people, their data and the environment**. It is essential that electricity grids continue to operate safely and as benignly as possible for the environment, and that protection against cybersecurity keeps pace with the threats it poses.

Meeting these challenges requires the network to become smarter, a process that is already well underway and involves overlaying a network of communications systems on top of the network that transports the electricity itself. Communications networks need new hardware, such as sensors and switches, to be integrated into points on the grid where they can generate valuable data and be controlled by computer programmes. Therefore, each of the three challenges has associated elements of hardware and software. In this report, the hardware and software used to add the layer, or layers, of information flows to improve the efficiency or flexibility of grid operations are referred to as “smart grid technologies”.

1.3. Challenge 1: expanding and enhancing physical connections

It is arguable that the largest synchronous electricity grids are the largest physical machines on the planet. Connected grids – like those that span most of Europe or multiple Chinese provinces – link many power plants with millions of end-users via complex webs of transmission lines (long-distance higher-voltage cables), distribution lines (lower-voltage branches that reach each final consumer) and supporting equipment to instantaneously balance demand with supply while always keeping a stable frequency and voltage of alternating current across many millions of kilometres. This is a remarkable technical achievement. While many grids began as local systems, for example at city level, and then were connected into national grids, they have now become international, with interconnections allowing countries to trade electricity between each other to ensure supplies and stability (ACER, 2024; CEER, 2020). However, not all grids are interconnected and each has design features that are specific to their history, their market design and the local availability of different electricity-generating resources.

Box 1: Electricity grid terminology: a primer

Electricity grids are complex technical networks comprising a large range of specialist components that are described using precise terminology often unfamiliar to a non-expert audience. To assist readers of this report, we explain some of the key terms below and provide a schematic diagram of how the main components of an electricity grid interact.

AC and DC

Electricity can be transmitted either as alternating current (AC) or direct current (DC). Most distribution and transmission grids use AC, which travels in a wave form defined by its frequency. This frequency needs to be approximately the same across all connected parts of an AC grid. It is generated either by a rotating generator, such as that powered by a spinning turbine, or an inverter, which converts DC to AC.

One advantage of AC is that the voltage can be changed relatively easily to improve efficiency of transmission or supply different uses.

Ancillary services

These are essential to stable grid operation but separate from the supply of electricity to meet demand. They include the provision of inertia or other means of stabilising grid frequency, as well as active (and reactive) power control and voltage control. Most electricity markets remunerate provision of ancillary services, which are increasingly separated from the market for electricity supply as more variable, distributed and DC-based renewable resources are integrated.

Behind-the-meter and in-front-of-the-meter
These are terms used to refer to the location of electricity grid equipment in relation to whether they are on the customer's side of the electricity meter (behind-the-meter) or on the grid side (in-front-of-the-meter). Traditionally, electricity suppliers and grid operators have had less visibility over what happens in the behind-the-meter zone. However, more electricity generation, storage and demand response is now occurring behind-the-meter, for example with rooftop solar PV, and this creates requirements for better communication between the two zones.

Demand response and virtual power plants
Demand response is the shifting or shedding of electricity demand to provide flexibility in wholesale and ancillary power markets, helping to balance the grid. Shifting means moving the load curve in time (without affecting total electricity demand). Shedding means interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time (which can affect total demand). A rising number of consumers have the option of opting into demand response programmes in return for financial compensation. Aggregators of demand response into MW-scale quantities for trading are sometimes called virtual power plants (VPPs).

Distributed energy resources
Smaller-scale resources usually situated near sites of electricity use, such as rooftop solar panels, battery storage or smart EV[3] chargers. They can be behind-the-meter or in-front-of-the-meter. If situated on the grid side of the meter, they are usually connected to the distribution grid, not the transmission grid. Also known as decentralised resources.

Distribution
The distribution system is the part of an electricity grid that connects to homes, industry and other end-users. It operates at a lower voltage (up to 50 kV) than the transmission network (up to 1 000 kV or more).

FACTS
A Flexible Alternating Current Transmission System (FACTS) includes power-electronics devices to improve responsiveness, quality of service and the final product (electric power) and voltage control on an AC grid. FACTS are sometimes cheaper alternatives to building more traditional power lines or substations.

Frequency
Electricity generators can only be connected to the same grid if they supply power at the same frequency. The loss of a large generator from the grid in an unexpected outage, or a sudden increase or decrease in power consumption, can cause variations in the system frequency if there is no immediate compensation. Maintaining grid frequency at 50 Hz in most of the world (or 60 Hz in the Americas and parts of Asia) is central to grid operations.

HVDC
High-voltage direct current (HVDC) is an alternative to high-voltage AC transmission that uses DC because it has lower losses than AC. It requires special equipment to convert between AC and DC, so is typically reserved for long-distance transmission and interconnection.

Inertia
The energy stored in large rotating generators, flywheels and some industrial motors which gives them the tendency to remain rotating. This stored energy is valuable when a large power plant fails, as it can make up for the power lost for a few seconds, allowing the power plant or other connected devices to respond. Inverter-based DC resources such as solar PV and batteries do not inherently provide inertia, but there are means of supplying it separately to maintain system frequency, including "synthetic inertia" operations.

Interconnection
Interconnectors enable electricity to flow between two synchronous electrical grids without affecting their stability. They are often HVDC connections, including subsea cables.

[3] Throughout this report, unless otherwise specified, electric vehicles (EVs) refers to battery electric (BEV) and plug-in hybrid (PHEV) vehicles, excluding fuel cell electric vehicles (FCEV).

International Electrotechnical Commission (IEC)
Much of the equipment in this report is covered by technical standards developed by the IEC, an international organisation that prepares and publishes standards for all electrical, electronic and related technologies.

Mini- or micro-grid
A group of interconnected loads and energy sources that acts as a single controllable and self-sufficient entity. Typically it does not exceed a few megawatts of total capacity. While many serve campuses, hospitals or industry, they are increasingly used to provide off-grid access to electricity in emerging market and developing economies. If grid-connected, they are capable of disconnecting to operate in "island mode".

Synchronous grid
A single interconnected electricity network that is locked to the same frequency. Europe's synchronous grid covers 24 countries.

Transformer
Transformers are used to change AC voltage levels and are termed "step-up" or "step-down" transformers, depending on the direction of the change. Tap-changing transformers are instrumental for real-time voltage regulation. Transformers are often found in substations.

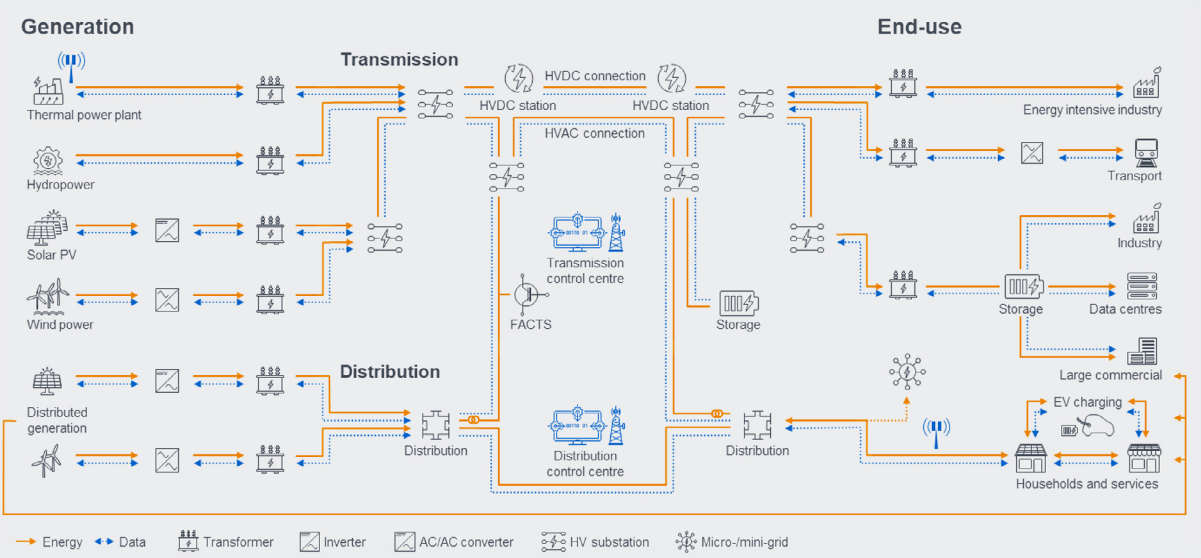
Transmission
The transmission system connects large suppliers and major industrial consumers in a single network that operates at a higher voltage (up to 1 000 kV or more) than the multiple distribution networks (up to 50 kV) to which it connects.

UHV
Ultra-high voltage (UHV) is a term applied to any power transmission line, whether AC or DC, that operates above 800 000 volts. For long-distance transmission, higher voltages are more efficient and can carry several multiples more electricity compared with equivalent cables at 500 000 volts (typical for high voltage). No country other than China currently has significant lengths of UHV lines.

Figure 1.3.1 shows how the main elements of a large modern synchronous electricity grid relate to one another. Such grids are typically national or at large state- or province-level, and may be international if interconnected by an HVDC link.

Figure 1.3.1

Schematic of the electricity grid, as covered by this report

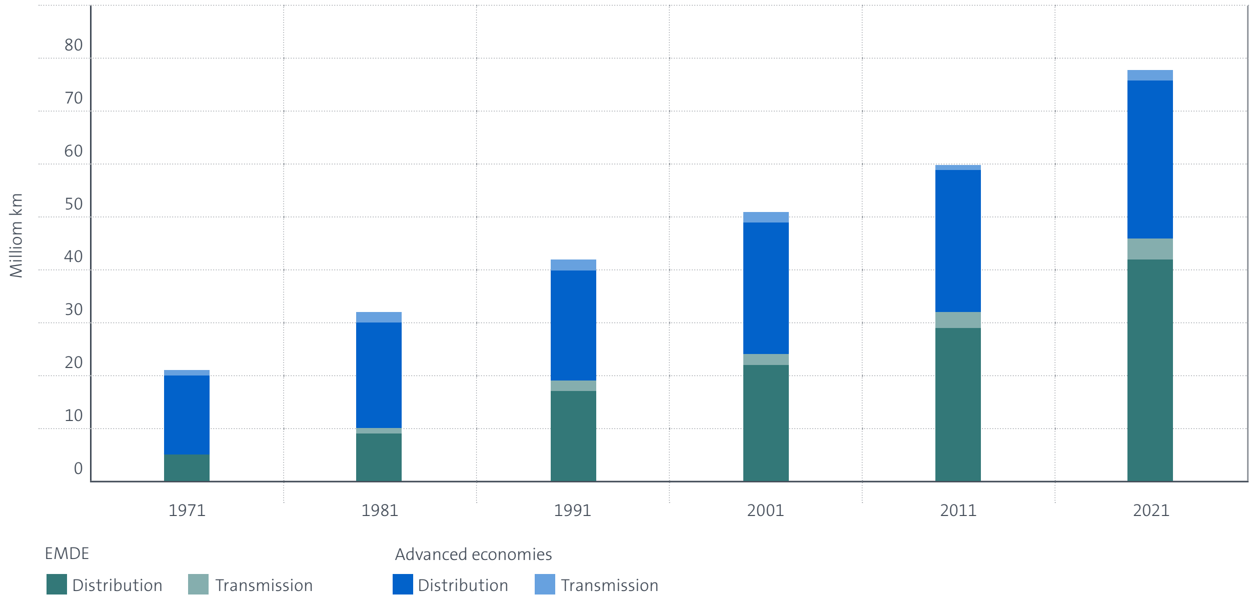


Source: EPO, IEA

Over the past five decades electricity grids around the world have experienced continuous growth, at a rate of about 1 million km per year. The majority of this expansion has occurred in distribution grids, which account for about 93% of the total length. The roughly 80 million km of wires and underground cables worldwide, of varying functions and voltage capacities, would be enough to make approximately 2 000 voyages around the earth. Between 2000 and 2020 the installed length of lines grew 50%, and it is expected to grow 50% from 2020 to 2050 (IEA, 2023).

Figure 1.3.2

Global grid length, 1971–2021



Note: Line route length of grids.

Source: IEA, 2023a

Most grid expansion has been seen at the distribution level in emerging market and developing economies (EMDEs). These have grown by over 40% in the past decade and have almost doubled over the last 25 years, playing a central role in granting electricity access to many people for the first time. One of the main advances in electricity access is the widespread acknowledgement of three reliable approaches to connecting households and industry to a dependable electricity supply: grid extension, mini-grids and standalone systems. The expansion of the distribution grid in EMDEs has resulted in impressive examples of raising electricity access. For example, nearly 100% of the populations of India and Indonesia now have electricity access, even though the access rate was less than 45% and 55% respectively only 20 years ago.

P.R. China alone accounts for over one-third of the world's transmission grid expansion in the past decade, having constructed over half a million km of transmission lines connecting, among other places, the eastern load centres to the renewable energy-rich northern and western provinces. Over the same period, China has been responsible for two-thirds of the global increase in electricity demand. To achieve this build-out it has pioneered the use of UHV cables, which are more efficient for carrying electricity and can make economic sense over very long distances.

In mature electricity grids that are experiencing the integration of variable renewable electricity sources, investment in recent years has been largely in four areas: connecting new, renewable power plants; refurbishing older lines; constructing high-voltage interconnectors between grids; and installing equipment to enable more responsive or bidirectional exchange of electricity with end-users. Upgrading or replacing existing assets at lowest cost is a particular challenge: Around 50 million km of older transmission and distribution lines will need to be replaced around the world by 2050 (IEA, 2023a). For some replacements and extensions, grid planners are avoiding the use of materials that have tight markets and high price outlooks, such as copper, rare earth elements and certain battery components. Tightness in these markets is closely related to rising demand in other areas of the energy transition as the rate of electrification increases. Investments have also been made in systems for accessing real-time knowledge about the health of the system, to help identify optimal times for equipment renewal. The use of new technologies such as drones and satellite-based technology has revolutionised inspection of power lines.

While the challenge of expanding and enhancing physical connections is multifaceted and context-dependent, there are several groups of technologies that can help address it (Table 1.3.1).

Table 1.3.1

Technologies that can help address the challenge of expanding and enhancing physical connections

Technology type	Main classification in this report	Improvement	Example application	Example sub-types
Electricity storage (mostly stationary storage)	Physical grid	Offsets the consumption of electricity from the time at which it was generated	Reduces congestion and the capacity or peak power generation needed to meet demand and allows demand to match variable renewable generation	Pumped storage hydropower; lithium-ion batteries; redox flow batteries; compressed-air energy storage
Far-field wireless power transfer	Physical grid	Sends electricity to a different location without using cables or completing a physical circuit	Could facilitate space-based solar power or wireless charging of vehicles such as drones	Microwave power beaming; laser power beaming
Improved cables	Physical grid	Lower losses of electricity over long distances	Enables remote renewables to be connected and resources to be balanced more efficiently over vast areas	HVDC; UHV; superconducting cables; aluminium cables (to reduce copper demand)
Installation, operation and maintenance	Physical grid	Reduces the time and cost of installing and operating transmission or distribution cables, including underground cables that can help improve local support	Allows more new infrastructure, including new power plants, to be built without further increasing consumer costs	Dynamic line rating; inspection drones; pylon designs; helicopter cable installation
Mini- and micro-grids (AC or DC)	Physical grid or smart grid	Connects small-scale generators and users of electricity in ways that share resources and lower the total cost of access to reliable electricity, with the potential to be grid-connected if desirable	Provides off-grid and "under-grid" communities with shared access to solar PV, battery storage and appliances; ensures uninterruptible power supplies for critical infrastructure	Control systems; power electronic switches; mesh network
Power conditioning	Physical grid	Changes the voltage, frequency or type of current more efficiently, reducing losses in the system	Unlocks the use of new cable types, such as HVDC, and the integration of DC-based renewable electricity and batteries into AC-based systems	Circuit breakers; transformers; inverters; harmonic cleansers; switchgear
Predictive maintenance	Smart grid	Uses large quantities of data to detect emerging faults and alert grid operators, avoiding outages, reducing failures, extending asset lifetimes and lowering the cost per unit of electricity supply	Reduces infrastructure needs and allows capital to be allocated to other uses, such as installing renewable electricity or electricity storage	Fault sensors and data processing; smart inverters

1.4. Challenge 2: making grid operations more flexible and bidirectional

Bidirectional energy flows over longer distances and the growing presence of variable generation sources are altering the predictability of electricity flows within the system. There are many more active participants connected to today's electricity grids than in the past, requiring ever more sophisticated approaches to monitoring and coordinating them without reducing the level of service to end-users. Less than 20 years ago there were serious disagreements among experts about whether large electricity grids could be safely and cost-effectively operated with over 10% of electricity from variable renewables. Thanks in large part to more flexible operations, grids such as that of South Australia can today operate with rooftop solar PV generation exceeding 100% of the demand on the system at certain times. Solar PV and wind provided two-fifths of Spain's electricity in the first half of 2024 (Renew Economy, 2024). Increasing power injections from distributed generation facilities can result in more dynamic system conditions and local line overloads, depending on the equipment involved.

Digital technologies play a crucial role in addressing these changes as they arise in the energy context, requiring the deployment of technologies commonly associated with the concept of smart grids (CRE, 2023). Smart grids co-ordinate the needs and capabilities of all players in the power system (generators, grid operators, end-users and other markets) in more responsive, flexible and integrated ways than were traditionally possible in highly-centralised systems with more limited communication technologies. Smart grid technologies are designed to contribute to more efficient operation of all parts of the grid, minimising costs and environmental impact while maximising system reliability, resilience, flexibility and stability.

The smart meter represents the first point from which the visibility of load flows in the distribution grid can be enhanced, even at the low-voltage level, making customers more aware of their own consumption and enabling new billing structures, such as dynamic and time-of-use tariffs.

Advanced monitoring and control devices, along with the corresponding software, have the capability to improve real-time system information monitoring and grid management. Remote control of the grid minimises intervention times and the number of operations that need to be performed locally on the grid, making operation possible from a single control centre using dedicated supervisory control and data acquisition (SCADA). Advanced automation tools allow the grid to act autonomously, quickly identifying and automatically isolating a faulty element to prevent cascading power outages; this is sometimes known as a "self-healing" grid. Embedded advanced analytics and AI algorithms can process vast amounts of data to predict electricity demand patterns and potential grid issues. By anticipating demand peaks and identifying potential transmission bottlenecks, operators can take proactive measures to reinforce the grid and enhance its capacity.

The ability to access real-time knowledge on the health of the system enables more accurate forecasts and more efficient utilisation of existing resources, allowing grids to operate closer to their true limits without compromising reliability.

Various technological tools for addressing the challenges associated with more decentralised and variable grid resources are shown in Table 1.4.1.

Table 1.4.1

Technologies that can help address the challenge of making grid operations more flexible and bidirectional

Technology type	Main classification in this report	Improvement	Example application	Example sub-types
Control of electricity generation or grids	Smart grid	Automatically or remotely dispatches or regulates electricity supplies or the geographic distribution of power in the grid	Allows reliable management of highly complex electricity grids with large numbers of generators and storage plants, minimising reserve margins, outages (duration and frequency) and labour costs	SCADA; phasor measurement units; smart inverters; distributed energy resource management (DERMS)
Demand response and VPPs	Smart grid	VPPs are aggregated small-scale decentralised resources that can provide power plant-like services when controlled in unison	Reduces the instantaneous electricity consumption of many EV chargers or heaters in response to a dip in wind energy generation	Smart EV chargers; DERMS; smart appliances; smart thermostats
Forecasting grid needs	Smart grid	Analyses big datasets of weather, transport, economic activity and other inputs to predict supply or demand	Reduces the need for costly reserve capacity, allows maintenance to be scheduled and lowers risks of unplanned outages (blackouts and brownouts)	Sensors; statistical packages
Frequency response	Physical grid	Mimics the frequency stabilising effects of AC-generating thermal power generators and hydropower turbines	Allows grid frequency to be maintained at a fixed level even with connection of many inverter-based generators such as solar PV and wind, which produce DC not AC power	Grid-forming inverters; smart transformers; flywheels; synchronous condensers, virtual synchronous generators
New approaches to electricity trading	Smart grid	Provides alternatives to traditional billing methods designed for centralised grid services	Makes it more attractive and economically rewarding to install decentralised generation, and can incentivise deployment in most-needed locations	Blockchain peer-to-peer markets; pay-as-you-go mobile payments; locational bidding
Rapid power and voltage adjustment	Physical grid	Flexible AC transmission systems (FACTS) use power electronics to act on a short timescale - less than a wave cycle - to improve voltage, impedance or phase angle	Improves the reliability of a grid with rapidly-changing requirements due to variable renewable electricity supplies or unpredictable demand	Static VAR compensators; thyristor-controlled series capacitors; thyristor-controlled phase-shifting transformers
Smart metering	Smart grid	Smart meters collect, and sometimes display, real-time information about consumers' electricity consumption	Enhances an electricity retailer's prediction of a customer's demand, enables more accurate billing and monitoring of losses, and allows customers to benefit from time-of-use tariffs	Two-way communications protocols; power line communication; wireless ad hoc networks; user displays

1.5. Challenge 3: protecting people, data and the environment

Electricity grids comprise equipment that operates at high voltages in close proximity to human activities, which presents risks to people, infrastructure and the environment. They are also considered to be critical national infrastructure that must be protected from disruption. With increasing amounts of detailed data about grid operations being communicated wirelessly, there are rising risks to privacy and risks of acts of terrorism or warfare.

In advanced economies electricity grids tend to be older, with infrastructure that has sometimes been operational for 50 years or more. Only around 23% of the grid infrastructure in advanced economies is less than ten years old, and over 50% is more than 20 years old. In the European Union, more than 50% of the grid has been in operation for over 20 years, which is approximately half its average lifespan. These ageing electrical assets can present significant safety and reliability risks. Over time, insulation materials – for example in transformers – can degrade, resulting in an increased likelihood of electrical faults, short circuits and even fires. Circuit breakers, as they age, may become less reliable in their ability to trip during faults.

The age of electricity grids varies by country, influenced by factors such as historical development, investment and ongoing modernisation efforts. The lifespan of grid equipment also varies depending on specific components, overloading and capacity issues, environmental factors, maintenance practices and technological advancements. Electricity grids are expensive assets that are often in service much longer than the equipment they connect.

Some high-voltage grid assets – such as circuit breakers and switchgear – rely on insulating gases that can have negative impacts on the environment or human health if they are released to the atmosphere. One example is the use of sulphur hexafluoride, which has a global warming potential 23 500 times greater than carbon dioxide (over a 100-year time frame).

Greater digitalisation, including the interconnection of many entities through communication technologies, brings cybersecurity risks to the electricity grid. The 2023 UK National Risk Register, for example, puts the likelihood of a cyberattack on critical infrastructure at between 5% and 25%, ranking as moderate, with a potential impact of hundreds of millions of pounds in losses (HM Government, 2023). In recent years the number of cyber incidents has been increasing, reaching five to ten significant incidents in each of the past five years (CSIS, 2023). There have been many cases in which cyberattacks on key infrastructure have caused major social disruption around the world. In 2015 it took up to six hours to restore power to around 225 000 people affected by a malware-based cyberattack on the electricity grid in western Ukraine, and in December 2016 power grid control equipment was disrupted and taken over by unauthorised access, resulting in a 200 MW outage for about an hour. A military cyberattack on a satellite in February 2022 caused collateral damage; approximately 5 800 wind turbines in Germany lost their internet connections, making remote monitoring and control difficult.

There are technological means of addressing the challenges of safety, resilience, environmental protection and privacy, some of which are summarised in Table 1.5.1.

Table 1.5.1

Technologies that can help address the challenge of protecting people, data and the environment

Technology type	Main classification in this report	Improvement	Example application	Example sub-types
Encryption and data protocols	Smart grid	Programmes grid-connected devices to follow communications protocols that are secure	Prevents grid outages caused by a weak link among many thousands of decentralised assets connected behind-the-meter	Cryptography, authentication, integrity checks
Hazard detection	Smart grid	Uses sensors and analytics to identify potential risks posed by extreme events or malfunctioning equipment	Reduces the risk of forest fires or other incidents caused by power lines, transformers or batteries	Sensors; statistical packages
Less harmful materials	Physical grid	Provides alternatives to materials that can be harmful to human health or the natural environment	Avoids the use of sulphur hexafluoride (a potent greenhouse gas) in gas-insulated circuit breaker for high-voltage lines	Fluoronitrile mixtures

1.6. Structure of the report

This study uses patent information to track technical progress in electricity grid-related technologies and assesses their alignment with the needs of energy transitions. The data presented show trends in high-value inventions for which patent protection has been sought in more than one country (IPFs). While some long-term trends are examined, most of the analysis is focused on the last decade (2011–2020) so as to provide an up-to-date picture of the current state of play by highlighting technology fields that are gathering momentum and the cross-fertilisation taking place. The study is designed as a guide for policymakers and decision-makers to assess their comparative advantage at different stages of the value chain, shed light on innovative companies and institutions that may be in a position to contribute to long-term sustainable growth, and direct resources towards promising technologies.

With the combined expertise of both the EPO and IEA, the report has been able to map electricity grid-related technologies to patent data with both relevance and precision. The analysis aims to include all technologies that are being pursued to help address the three key challenges introduced in Sections 1.3 - 1.5. While existing patent classification systems and the EPO's Y02 Y04S tagging scheme for climate change mitigation technologies already contain dedicated classes for many technologies related to smart grids, there has to date been less focus on the needs of physical grid technologies to mitigate climate change. Drawing on recent IEA efforts to model and analyse electricity grid needs for clean energy transitions, the scope includes technical improvements to traditional grid components, newer types of hardware for adapting the grid to the demands of a clean energy system and the diverse range of digital tools (both hardware and software) to enable responsive communication and control (IEA, 2023a and 2023b)[4].

[4] Patent statistics on a broader set of technologies related to the clean energy transitions, based on the OECD STI Micro-data Lab: Intellectual Property Database and EPO's Y02/Y04S tagging scheme for climate mitigation technologies, can be consulted on the IEA's Energy Technology Patents Data Explorer.

The search tools[5] and expertise of the EPO were used to identify all relevant technologies within the universe of international patent applications and design search strategies that fairly present the relevant trends.

The resulting scope covers the whole value chain as comprehensively as possible. To reflect policy interest in the progress of smart grids, the technologies are divided into those that primarily relate to the physical grid and those that are primarily related to smart grid technologies.

— **Physical grid.** These are technologies that seek to improve the performance or reduce the cost of carrying electricity from generators to end-users. They are mostly associated with addressing the challenge of expanding and enhancing physical connections, including by integrating remote renewable power sources, networking off-grid or grid-edge resources, interconnecting nearby grids, and maintaining system frequency or upgrading existing lines. A smaller share of physical grid technologies are being developed to make grid operations more flexible, including FACTS technologies, or protect people and the environment by reducing hazards and using less harmful materials.

— **Smart grid.** These are technologies that individually facilitate increased observability and controllability of the electricity grid, and have the potential to collectively make all the elements of the grid operate more responsively to changes in supply, demand, environmental or operating conditions (IEA, 2011).[6] They are mostly associated with addressing the challenge of making grid operations more flexible and bidirectional, for example to help match end-user demand instantaneously to variable renewable electricity output, both temporally and geographically, or shifting the time of demand to reduce peak power generation requirements and thereby lower costs. A smaller share of smart grid technologies relate to enhancing the grid through fault detection or protecting data through cybersecurity upgrades. In addition, this report includes technologies that apply a set of enabling digital approaches to electricity grid challenges in general, including Artificial Intelligence, cybersecurity tools and modes of data transport and exchange.

For each category, the patent analysis has been further split into groupings to reveal the trends within physical and smart grids. This allows for a fine-grained comparative analysis of patenting trends as lead indicators of emerging innovation hotspots that might be translated into major real-world impact in coming years. The analysis is also able to identify potential weaknesses in global or regional innovation by comparison with the needs of clean energy transitions. Furthermore, it enables comparative analysis between countries and regions, as well as between the main technology fields.

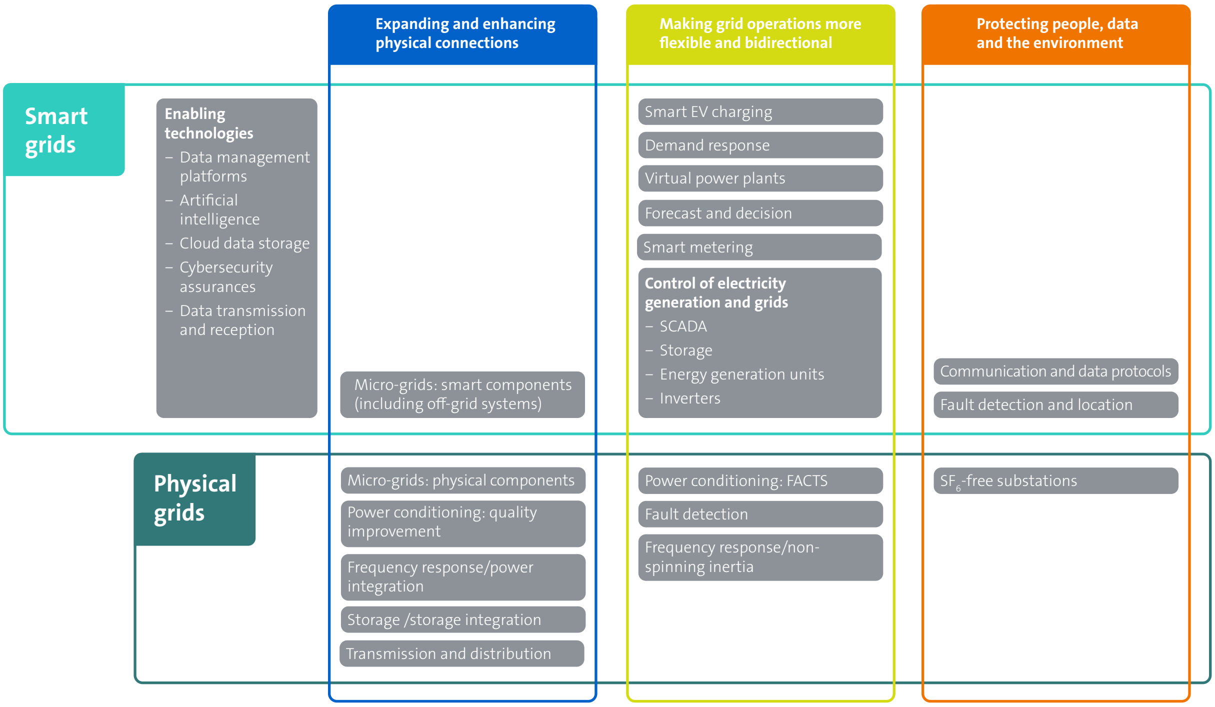
Some of the splits that have been made are not entirely clear cut and rely on the judgement of the authors. For example, the category "improved cables" includes HVDC cables and technologies enabling the use of these, such as insulated-gate bipolar transistors that can handle high voltages and currents. Other switching technologies that perform similar functions for lower voltage cables are included in "power conditioning". As another example, we have included technologies related to physical assets for storing electricity for grid services (stationary storage, as opposed to batteries on board EVs) and its integration into networks within physical grids, while the digital-related technologies that seek to optimise the operation of these assets on the grid is included in smart grids. Due to the very high levels of overlap between lithium-ion battery components and packs for stationary and electric vehicle applications, and the much larger market for the latter, we have not included lithium-ion battery design within the scope of this report.

[5] The identification of relevant patent documents is based on expert queries developed by EPO examiners specialised in the field, using their professional search tools and related patent databases. The primary extraction was filtered to select only international patent families with applications filed either in a regional office (WIPO, EPO) and/or in at least two national offices.

[6] According to IEA (2011), "Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience and stability".

Figure 1.6.1

Mapping of electricity grid-related technologies



Chapter 2 provides a high-level overview of patenting trends in electricity grids since the year 2000. It benchmarks the relative levels of patenting in physical and smart grids and offers a geographic perspective on electricity grid innovation ecosystems at global and regional levels.

The following two chapters specifically address the dynamics of innovation in the main areas of the cartography. Chapter 3 focuses on physical grids and analyses trends in established distribution and transmission technologies, and emerging fields such as stationary storage, FACTS and superconductivity. Smart grid technologies are addressed in Chapter 4, including important enabling technologies such as applying artificial intelligence to electricity grids.

Box 2: The importance of electricity grid enhancement in Europe and its policy context

The continuous expansion and integration of Europe's synchronous electricity grid, spanning the EU's internal international borders and connecting with neighbouring countries, is one of the great technical and political feats of recent decades. The IEA estimates that Europe will spend around USD 85 billion in 2024 on electricity grid investments, an increase of 50% in just five years, and roughly equal to Europe's total estimated investment in solar PV and onshore wind in the same year. In the process of improving and growing its electricity grid, Europe has helped pioneer many technologies of global significance, including smart meters, HVDC, interconnectors between national grids, as well as offshore cables to connect offshore wind and solid state transformers.

However, Europe faces the key challenges outlined in the introduction to this report, namely the need to refurbish the grid and connect new renewable resources at lost cost; make the grid more responsive and flexible; and improve its safety and security. Ageing and congested power grids are particularly an issue in Europe. While Europe's transmission grid expanded by 12% between 2012 and 2021, 90% of its transmission grid and 93% of its distribution grid are more than a decade old (IEA, 2023a). The cost of managing grid capacity constraints in 2023 was estimated at EUR 4 billion, a figure that is expected to rise in coming years (ACER, 2024). A lack of grid capacity is one of the reasons behind the curtailment, or wastage, of renewable electricity generation, which amounted to around 2% in Spain and 5% in the United Kingdom in 2022. Additional interconnections between countries will help to share Europe's electricity resources more evenly while reducing the need for storage and back-up. They will also enable Europe to reap the benefit of the fact that it is almost always windy, sunny and wet in Europe, but not always in the same place at the same time (European Commission, 2024). Efforts towards coordination and interoperabiliy are also essential to ensure flexibilitiy and innovation at the distribution level (DSO Entity, 2024; E.DSO, 2024). These efforts have been hampered in recent years by issues relating to timelines for permits, tendering procedures, land procurement, social acceptance and finance.

The importance of upgrading and investing in Europe's electricity grid was recognised in the 2024 report to the European Commission entitled "The Future of European Competitiveness" (Draghi, 2024). The report identifies cross-border grids as a public good that will underpin future EU competitiveness, but which is at risk of undersupply in the current market and policy context. It points out that power price volatility during the energy crisis resulting from Russia's full-scale invasion of Ukraine would have been around seven times higher if national markets had been isolated. The report makes the case for doubling down on technology leadership, and states that "supporting the EU grid manufacturing industry and addressing current barriers (e.g. a lack of standardisation, access to raw materials, security risks associated with third-country providers) is essential to reduce delays linked to the grid component supply chain and enable the adequate roll-out of grid infrastructure".

To address these challenges, the EU has adopted a range of initiatives. These include the European Grid Action Plan, which outlines 14 measures to make Europe's electricity grids stronger, more interconnected, more digitalised and cyber-resilient. Since 2013, the EU Regulation on trans-European energy infrastructure ("TEN-E") has labelled more than 100 electricity grid projects as projects of common interest in order to facilitate the building permit process and their construction. It has also allocated funds to many of them, with EUR 4.1 billion from the Connecting Europe Facility. In 2022, the European Commission adopted an action plan for digitalising the energy sector. This plan outlined 24 key actions such as providing financial support for R&D and the market uptake of digital technologies in the energy sector (through the Digital Europe Programme, LIFE, cohesion policy and a flagship programme for Digitalisation of Energy in Horizon Europe). In the area of technological innovation, the BRIDGE initiative has been designed to unite EU-funded projects in the areas of smart grids, energy storage, electricity islands and digitalisation and help them to address cross-cutting issues. Launched in 2016, BRIDGE currently includes 183 projects bringing together 2 200 project partners from 38 countries and has attracted EUR 1.6 billion of EU funding in total.

2. Patents for electricity grids: an overview

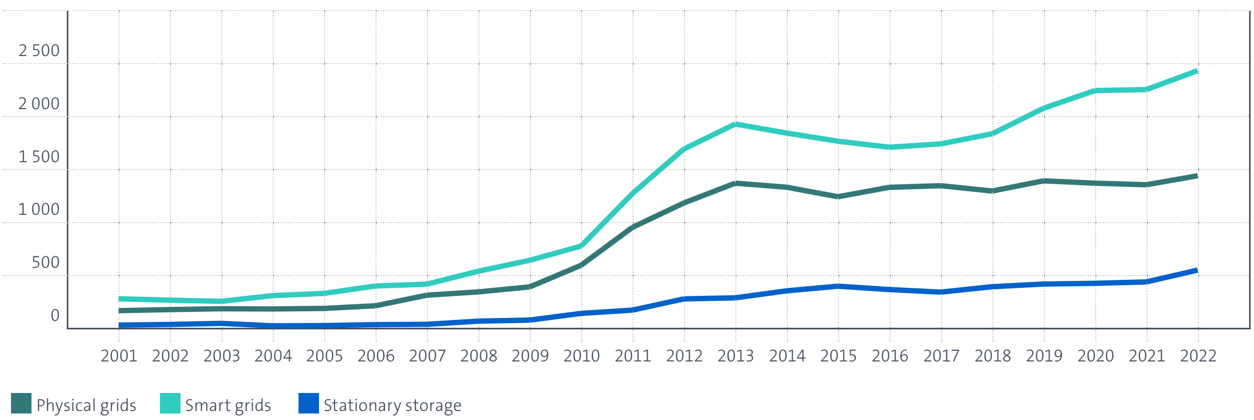
Published international patent families (IPFs) are used in the study as a uniform metric to measure patenting activities in the different categories of grid-related technologies. This section reports on the main aggregate trends in patenting in these technologies, and on the profiles and geographic locations of the applicants of IPFs for grid-related technologies.

2.1. General patenting trends

Figure 2.1.1 provides a trend analysis of IPFs in physical grids, smart grids and stationary storage technologies (excluding lithium-ion). It shows an impressive take-off of innovation in both physical and smart grid technologies over the period 2009–2013, with compound average growth rates of about 30% in all three subfields, compared to 12% for low-carbon energy technologies and 4% for all technologies over this period. This acceleration phase marks a renewed interest in grid technologies in the industry, with new innovation opportunities created by digital technologies and the prospect of the wider deployment of renewable sources of energy. It also coincides with rising penetration of software and software patents in the industry.

Figure 2.1.1

Patenting trends in physical grids, smart grids and stationary storage (IPFs, 2001-2022)



Source: author's calculations

After stagnating until 2016, a second period of strong growth then starts for smart grids, with a compound average growth rate of 4.7% over the period 2016-2022 (compared to 2.6% for all technologies), whereas annual numbers of IPFs in physical grids increase at a lower rate of 2.1%. Patenting in selected stationary storage technologies did not experience the same peak around 2013, and instead shows continuous growth from 2001 to 2022. Overall, innovation in these three technology fields generated about 42 500 IPFs over that period, with stationary storage accounting for only a minor share in this total.

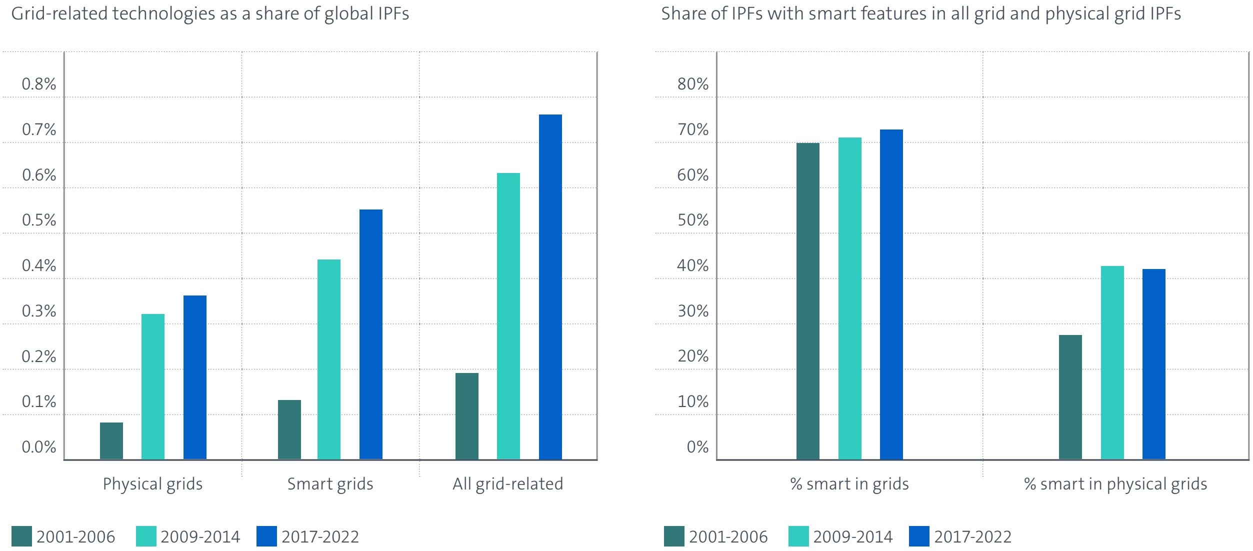
Innovation in grids has been more dynamic than in other technology fields. As a result, their weight in all patenting activities increased significantly, from 0.19% of all IPFs in 2001–2006 to 0.76% in 2017-2022 (Figure 2.1.2).

[7] The selection used for the study focuses on technologies that are specifically purposed for stationary storage. It therefore excludes lithium-ion batteries which, among other applications, can be used for short-duration grid-scale storage.

The proportions of IPFs related to smart grids has remained relatively stable over time: around 70% of all grid-related IPFs. However, the acceleration of innovation around 2009 marks a stronger convergence between the two fields. In 2001–2006 only 28% of IPFs related to physical grids involved a smart grid component. Since 2009, this proportion has stabilised at 42%, denoting high penetration levels of digital and software technologies in the hardware components of grids.

Figure 2.1.2

Growth of patenting in grid-related technologies, (IPFs, 2001-2022)



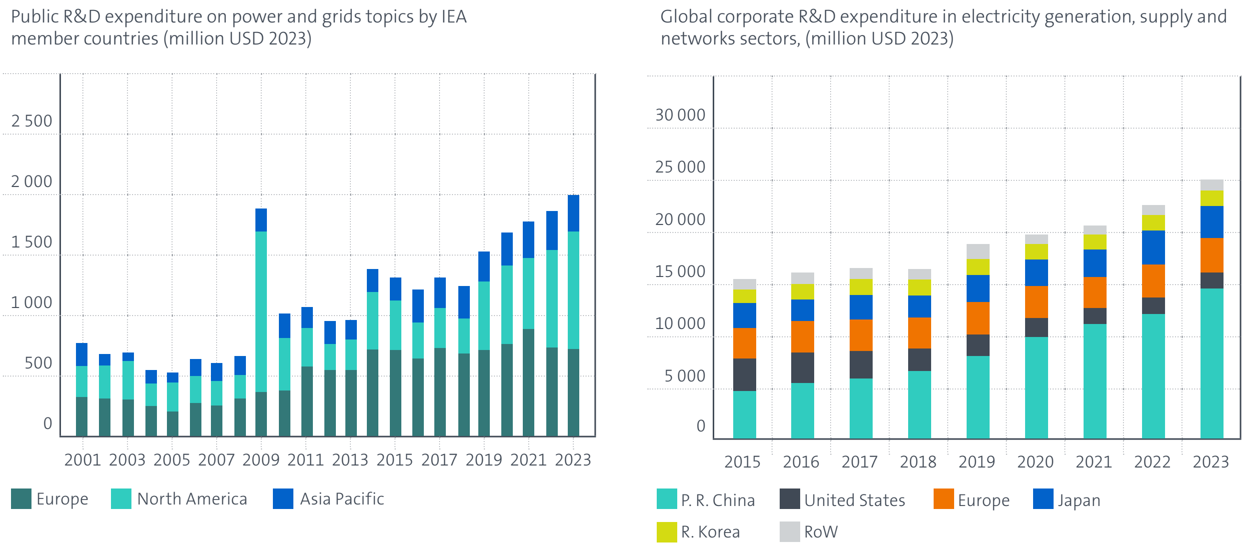
Source: author's calculations

The growth of patenting in grid-related technologies reflects an increase in R&D spending by the public and private sectors in this technology area. With patenting rates per unit of financial input varying over time and between technology areas, there is no fixed correlation between R&D expenditure and patenting, but R&D efforts appear to have responded to the same grid challenges and opportunities highlighted in this study. The relatively steady increase in grid-related public R&D spending in IEA member countries since around 2007 precedes the sharp increase in patenting. Given the catalytic effect that publicly funded research can have in stimulating the most radical and highest-risk innovation, this may be directly connected to the patenting trend.

While Europe has been the main driver of growth in reported public R&D spending on grids over the past 15 years, governments in North America have rapidly increased their budgets more recently and their spending is now similar to levels seen in Europe. The slowdown in patenting among IEA countries therefore appears unrelated to changes in public R&D spending during this period and may be more closely linked to commercial factors. The total reported corporate R&D spending by companies active in electricity supply and networks has declined slightly in real terms since 2015. On the other hand, there has been a sharp increase in R&D spending by Chinese companies, which correlates with the surge in Chinese electricity grid-related IPFs in this period.

Figure 2.1.3

Public R&D expenditure in grid-related areas



Source: IEA

2.2. Geography of electricity grid innovation

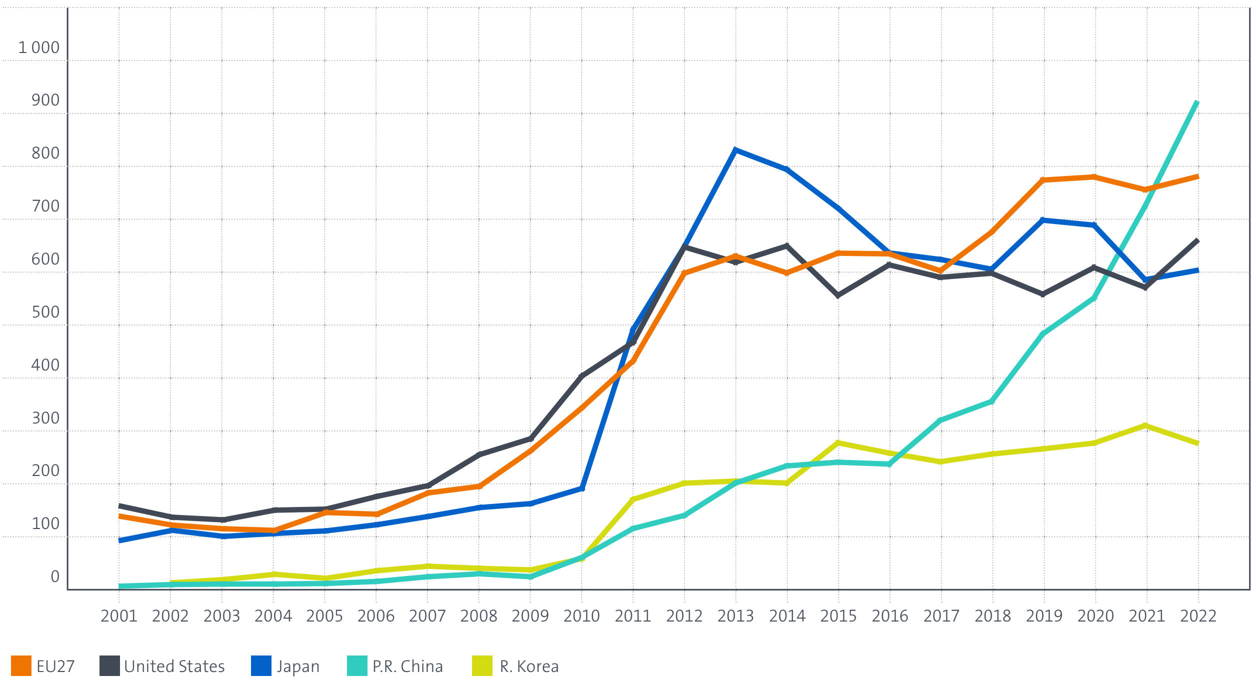
Figure 2.2.1 provides a trend analysis of grid- and storage-related IPFs originating from the world's five largest innovative regions (the EU countries being considered as a block) since 2001. It shows a lead on the part of the EU, Japan and the US over most of this period, with a similar pattern of rapid take-off from 2011 to 2013, followed by slower growth in the EU, a plateau in the US and a relative decrease in Japan. P.R. China did not experience the rapid growth observed around 2010 in the other regions, but shows regular progress over the whole period, with a strong acceleration after 2016 which enabled the country to attain top ranking by number of IPFs in 2022.[8] R. Korea shows a slight acceleration in 2011 and regular growth afterwards, but still generates a relatively small number of IPFs.

[8] P.R. China likewise ranks first in 2022 in physical grids, smart grids and stationary storage taken separately.

Figure 2.2.1 also sheds some light on the shape of the aggregate electricity grid patenting trend since 2009, including the striking peak in 2013 and subsequent dip before annual IPF growth recovered in the past five years. Geographically, it is noticeable that a rise in patenting by Chinese entities has been responsible for much of the recent growth, whereas those in Japan, Europe and the United States were responsible for the earlier peak and stagnation. However, it has not been possible in this study to reach a conclusive answer to the question of why electricity grid patenting peaked among the first-mover regions in 2013. Several possible contributing factors suggest themselves, and these may have coincided to drive the overall trend. First, there appears to have been a rush among some major patent applicants to secure their intellectual property in areas such as smart meters and EV charging during a flurry of equipment deployment starting around 2008. This push to influence and profit from standardisation in the sector may have front-loaded IPFs in an unusually lumpy pattern. Second, between 2011 and 2013 the United States and, to a lesser extent, Europe, experienced the "clean tech bust" as value was lost from venture capital investments in startups that struggled to find ready markets for their pioneering products. The rapid deflation of this first clean tech hype cycle caused a cooling of investor expectations for clean energy hardware innovation in general. Additional contributors may have included the stimulus effect on R&D from countercyclical public research and infrastructure spending in the aftermath of the financial crisis, as well as an emerging mismatch between smart grid R&D and the pace of deployment by grid operators and utilities.

Figure 2.2.1

Patenting trends by main world region (IPFs, 2001-2022)



Note: Calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

Table 2.2.1 shows these regions' shares of IPFs in the main segments of grid technologies over the same period. It also provides insights into their respective specialisation profiles, as measured by the RTA index. An RTA indicates a country's specialisation in terms of grid 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.

These indicators confirm the leadership of the EU27 and Japan in grid innovation, each with about 22% of global grid-related IPFs and an RTA in these technologies. However, Japan's RTA is larger, and can be observed in all segments of grid-related technologies. It is especially strong in smart grids, where Japan has the largest share of IPFs (25%). By contrast, the EU27's lead in grid innovation is primarily due to its strong innovation performance in physical grid technologies, with a strong RTA and 26% of IPFs in those technologies (including 14% from Germany and 5% from France), compared to 18% for Japan and the US. Unlike Japan, the EU27 does not show specialisation in smart grids or stationary storage technologies.

Among the other major regions, P.R. China stands out, with RTAs comparable to those of Japan in all main segments of grid-related technologies. While its share of all IPFs remains lower (12%), this was secured in a relatively short period and a continuation of that trend would rapidly position P.R. China as the global leader in grid-related patenting. The US generated 20% of all grid-related IPFs, but does not show any specialisation in grid-related technologies or their main subsegments. The pattern is similar for R. Korea, which generated 8% of all IPFs and actually shows a lack of specialisation in grid-related technologies (with a very low RTA).

Table 2.2.1

Revealed technology advantages in grid technologies by segment, 2011-2022

	All grids technologies		Smart grids		Physical grids		Stationary storage	
	Share of IPFs	RTA	Share of IPFs	RTA	Share of IPFs	RTA	Share of IPFs	RTA
EU27	22%	**1.1**	20%	1.0	26%	**1.3**	20%	1.0
Japan	22%	**1.3**	25%	**1.5**	18%	**1.1**	18%	**1.1**
United States	20%	0.8	22%	0.8	18%	0.7	23%	0.9
P.R. China	12%	**1.3**	12%	**1.3**	13%	**1.3**	11%	**1.1**
R. Korea	8%	0.6	8%	0.5	7%	0.5	11%	0.8
Germany	11%	**1.4**	10%	**1.2**	14%	**1.7**	9%	**1.2**
Switzerland	5%	**3.0**	3%	**2.1**	8%	**5.1**	1%	0.8
France	4%	**1.1**	3%	0.9	5%	**1.3**	4%	**1.1**
United Kingdom	2%	**1.4**	2%	**1.2**	2%	**1.4**	4%	**2.4**
Italy	1%	0.8	1%	0.7	1%	0.9	1%	1.0
Austria	1%	**1.8**	1%	**1.5**	1%	**2.2**	1%	**1.2**
Denmark	1%	**2.3**	1%	**2.2**	1%	**3.1**	1%	**1.9**

Note: Calculations are based on country of IPF applicant, using fractional counting in the case of co-applications.
The unshaded rows of the table report on the top seven European countries in terms of number of IPFs.

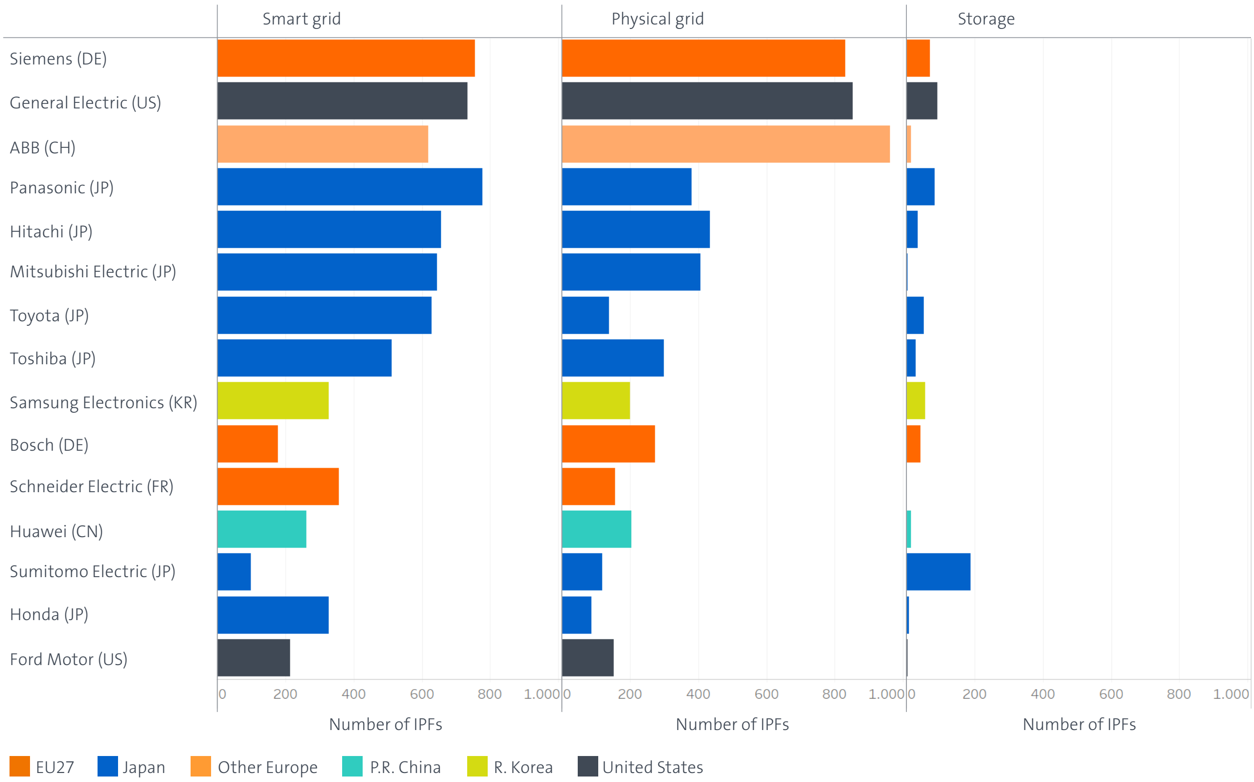
A closer analysis of patenting activities at the country level (in the lower part of the table) highlights the strong contribution made by Germany in grid-related innovation. Germany generated 11% of all grid-related IPFs over the period 2011-2022, half of the EU27 patenting activities in grids, and is comparable to the share of P.R. China. It also shows an RTA in all segments of grid technologies, with a particularly strong specialisation in physical grid innovation. Among smaller European countries, Switzerland (which is not part of the EU27) and Denmark also stand out, with 5% and 1% respectively of all grid-related IPFs and strong RTAs in both physical and smart grid technologies.

2.3. Applicant profiles

The top 15 corporate applicants listed in Figure 2.3.1 alone generated nearly one-third (31%) of IPFs in grid-related technologies over the period 2011-2022. Their cumulative share of IPFs is slightly higher in physical grid technologies (35%, compared to 31% in smart grids), and much lower in stationary storage technologies (15%).

Figure 2.3.1

Top 15 corporate applicants in grids and selected stationary storage technologies (IPFs, 2011-2022)



Note: Applicants are ranked according to their total number of IPFs in grid-related technologies. Some of these IPFs may be relevant to more than one of the three subcategories shown; they are reported under each of these subcategories. The IPFs filed by ABB Grid have been consolidated under Hitachi.

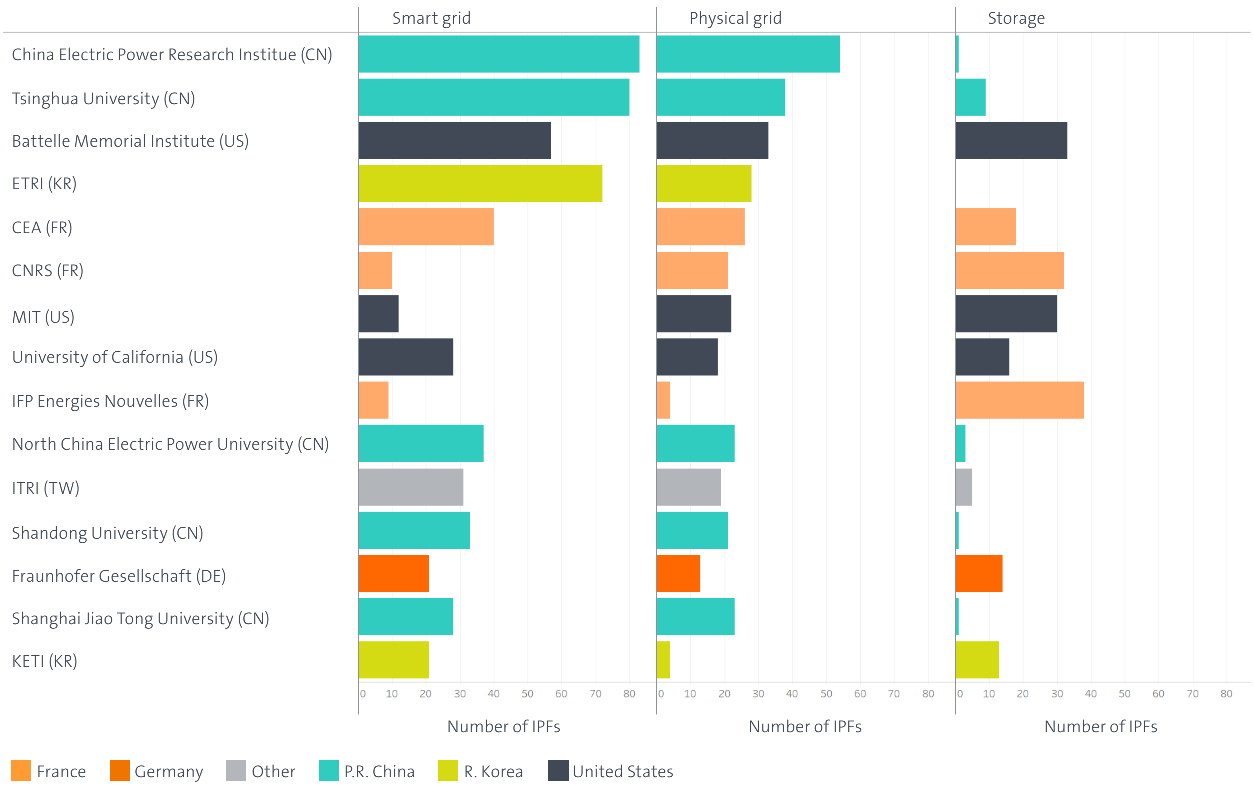
Source: author's calculations

Siemens, General Electric and ABB, three large conglomerates from Germany, the US and Switzerland respectively, lead the ranking. However, Japan is the most visible country, with seven of the top 15 applicants, including Panasonic, Hitachi, Mitsubishi Electric and Toyota holding fourth to eighth positions. Compared to their European and US counterparts, these top Japanese applicants show stronger specialisation in smart grids.

Besides other German (Bosch), US (Ford Motors) and Japanese companies (Sumitomo Electric and Honda), the remaining top applicants include R. Korea's Samsung Electronics, France's Schneider Electric and P.R. China's Huawei, a telecom equipment company expanding into smart grids. Interestingly, three of the top 15 applicants in grid-related technologies are automotive companies: Toyota, Honda and Ford Motor.

Figure 2.3.2

Top 15 research applicants in grids and selected stationary storage technologies (IPFs, 2011-2022)



Note: Applicants are ranked according to their total number of IPFs in grid-related technologies. Some of these may be relevant to more than one of the three subcategories shown; they are reported under each of these subcategories.

Source: author's calculations

With 2.4% and 2.2% of all IPFs related to smart grids and physical grids respectively, the top 15 research-oriented applicants have a weighting of less than one-tenth of the patenting activities of corporate applicants. However, their share of IPFs in stationary storage technologies is significantly higher at 4.7%, signalling the importance of fundamental research in some those fields (see Section 3.2 for a more detailed analysis).

The top research applicants are dominated by public research organisations, which represent nine out of the 15 top applicants, the six remaining being universities (Figure 2.3.2). In contrast with the list of top corporate applicants, they do not feature any Japanese organisation. The ranking is dominated by P.R. China (with five research organisations, including the top two), the US and France (three each) and R. Korea (two). The last two applicants are public research organisations from Chinese Taipei (ITRI) and Germany (the Fraunhofer Gesellschaft). Like top corporate applicants, most of these large research applicants are more active in smart grids, in particular the Chinese ones. However, the CNRS and IFP of France and MIT of the US are notable exceptions, with patenting activities related mainly to stationary storage and physical grids.

Box 3: Startups and patents in grid-related technologies

Startups are one of the possible routes by which grid-related innovations reach the market. Many of the underlying technologies depend on advanced science coming out of public research organisations and universities, and represent high-risk, disruptive bets for business developers. Both risks and funding needs are especially significant when startups aim to industrialise and commercialse hardware technology involving manufacturing capacity and relatively long development times. However, given that many of the technologies also have small unit sizes that lend themselves to standardised manufacturing, they can remain attractive to venture capital investors hunting for exponential returns as the clean energy transition gathers speed.

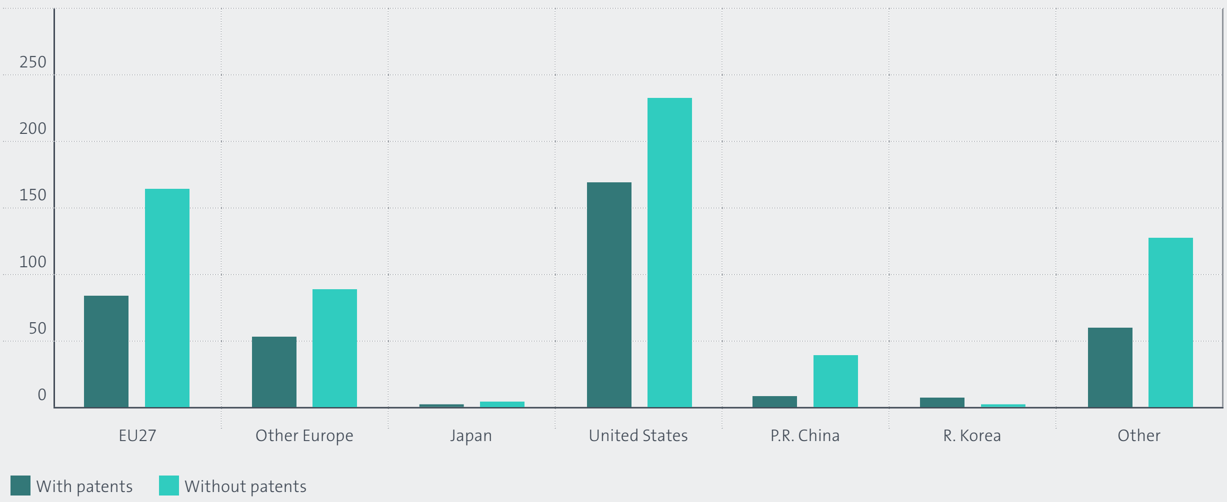
The IEA regularly monitors startups operating in the energy sectors. It has categoried a total of 592 startups primarily focused on power and grids, as well as another 453 startups with grid-relevant activties. Overall, more than one-third (37%) of these have a portfolio of patent applications, including at least one international patent family in 90% of the cases.

This proportion of patenting startups is remarkably high, compared for instance with the estimated 6% share of all European startups that have a patent applications (EPO-EUIPO, 2023). It is a positive indicator of fundraising capacity for grid-related startups, given the evidence that patent ownership has a positive impact on startups' ability to attract venture capital funding (EPO-EUIPO, 2023). To facilitate this matching process, European startups with patent applications at the EPO can be searched online using EPO's free Deep Tech Finder.

Most of the startups are located in the US and Europe, with each of those two regions contributing about 39% of the total, and the EU27 alone 24% (Figure 2.3.2). By contrast, the small numbers of startups identified in P.R. China, R. Korea and Japan suggest a lesser role for venture capital in these countries' innovation ecosystem. Apart from these main regions, Canada (with 50 startups), India (30) and Israel (13) stand out with sizeable ecosystems of grid-related startups.

Figure 2.3.3

Startups in grid-related technologies: number of startups and patenting profile by main world region (2011-2022)

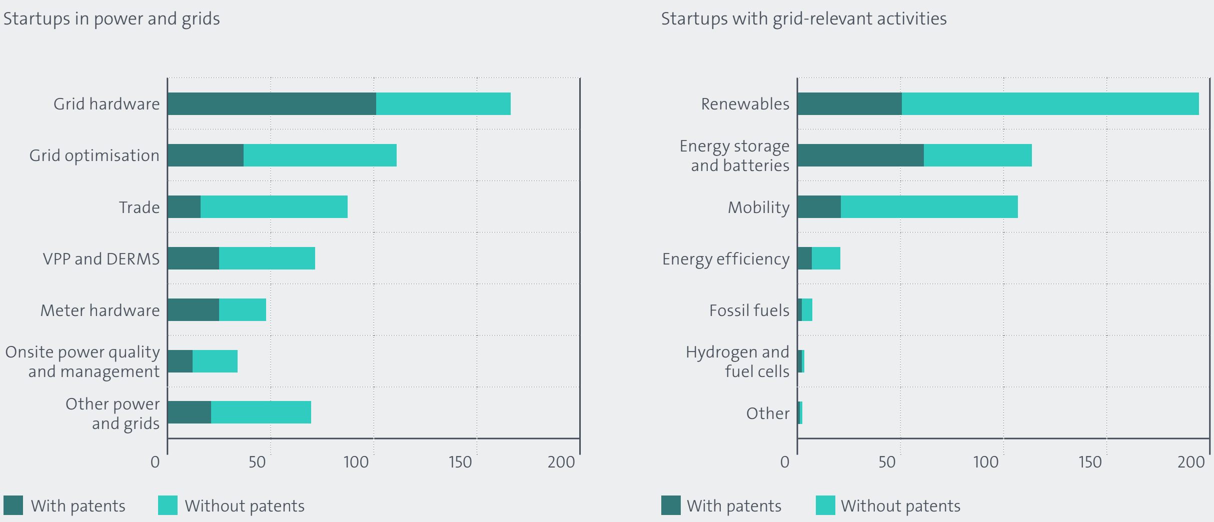


Source: IEA, EPO

About half of the startups primarily focused on power and grids are developing grid hardware (Figure 2.3.3). Another third are working on grid optimisation, and a quarter in electricity trading. Other important areas include VPPs (20%) and meter hardware (14%). The proportion of startups with patenting activities is significantly higher in hardware-related activities, such as grid hardware (61%) and meter hardware (59%), reflecting more R&D-intensive forms of innovation and the need to protect technology embodied in tangible products over relatively long time periods. A large number of startups primarily focused on renewable energies, energy storage and mobility have also been found to have grid-relevant acitivities. Among these, startups innovating in storage and batteries rely most frequently on patent protection.

Figure 2.3.4

Startups with grid-related profiles: number of startups and patenting profile by primary activity (2011-2022)



Source: IEA, EPO

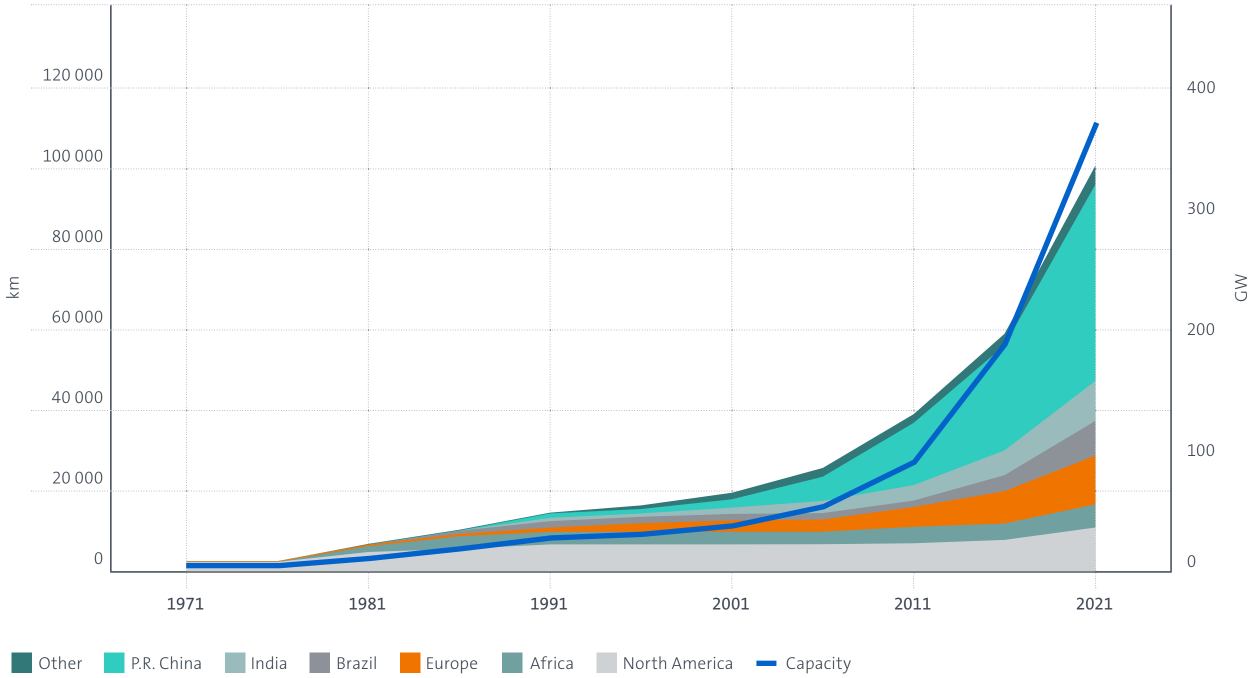
3. Physical grids and stationary storage

3.1. Main patenting trends in physical grid technology

The main physical electricity-carrying elements of grids – cables, transformers, switches, pylons, electricity storage facilities – have been in existence for a century or more and have been continuously improved by innovation. Many of these changes are barely visible to the general population, but they have radically improved the efficiency, competitiveness and safety of equipment. For example, high-voltage electricity transmission and interconnection has enabled much lower losses of electricity over long distances, allowing grids to be operated effectively over ever-wider areas. This has required the development of new ecosystems of complementary technologies, including new materials, insulation, solid state thyristors and transistors. HVDC transmission, which is more efficient than its AC equivalent, has experienced a major expansion since the early 2000s, building on half a century of learning from experience, first in the United States, then in Africa, and now predominantly in China.

Figure 3.1.1

Expansion of HVDC transmission, 1971-2021



Source: IEA

Patent analysis confirms that technical innovation for physical grids is a dynamic area that has experienced very rapid growth over the past 15 years. Furthermore, the technology areas underpinning this growth tackle some of the key challenges facing electricity grids in relation to clean energy transitions. These mostly involve:

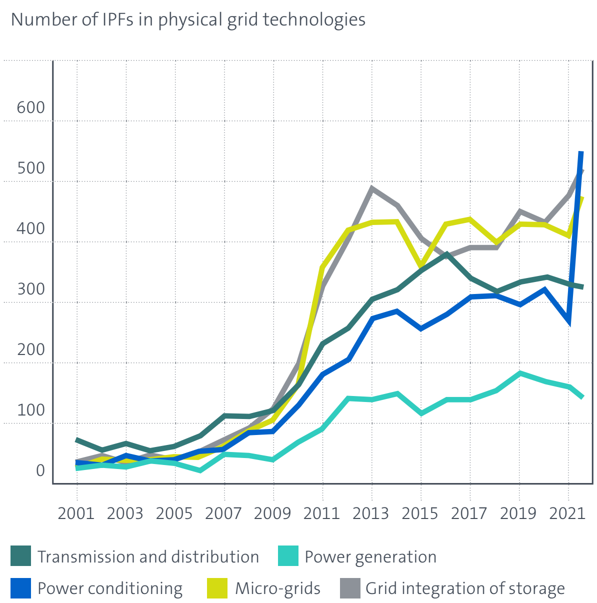
— enabling the connection of new sources of renewable electricity – over long distances, offshore or in mini-grids – at minimal cost, including reducing reliance on costly raw materials such as copper
— ensuring grid frequency despite lower levels of spinning generators
— upgrading legacy infrastructure for higher efficiency and reliability
— responding rapidly to sudden changes in power flows in different parts of the grid
— enhancing safety and environmental performance

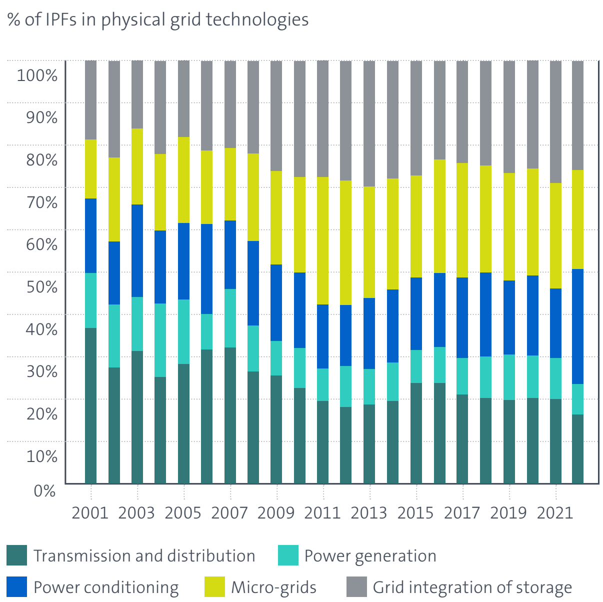
Patenting related to physical grids has broadly followed the overall trend for electricity grid patenting. It grew very strongly from 2009 until 2013, when it departed sharply from the steady rate of around 200 IPFs per year before then (Figure 2.1.1). However, unlike for smart grids, physical grid patenting has not risen noticeably since 2013, with only power conditioning exhibiting a recent spurt.

Within this overall trend the breakdown by technology field reveals a rebalancing of patenting activities over the past decade. Transmission and distribution (including conductors, cables and substations) accounted for about 30% of all IPFs in physical grid technologies in 2001-2003, but less than 20% in 2020-2022. Technologies supporting the integration of energy generation technologies generated a lower number of IPFs, and likewise saw their share of IPFs in all physical grid technologies fall, from 14% in 2001-2003 to less than 10% in 2020-2022.

Figure 3.1.2

Growth of patenting in grid-related technologies, 2001-2022





Note: IPFs classified in several different technology fields are counted as one IPF for each filing in the chart on the right-hand side.

Source: author's calculations

By contrast, the weight of patenting activities targeting micro-grids and integration of stationary storage in the grid has increased over time, from less than 20% in 2001-2003 to 25% in 2020-2022 in the case of micro-grids, and from around 20% to more than 25% for storage integration. The final category of physical grid technologies relates to power conditioning (e.g. FACTS and quality improvement). Its weight in physical grid technologies remained relatively stable until 2021, with a large increase in 2022. Power conditioning technologies likewise are in median position amongst physical grids when it comes to penetration of smart features (44% of IPFs over the period 2011-2022).

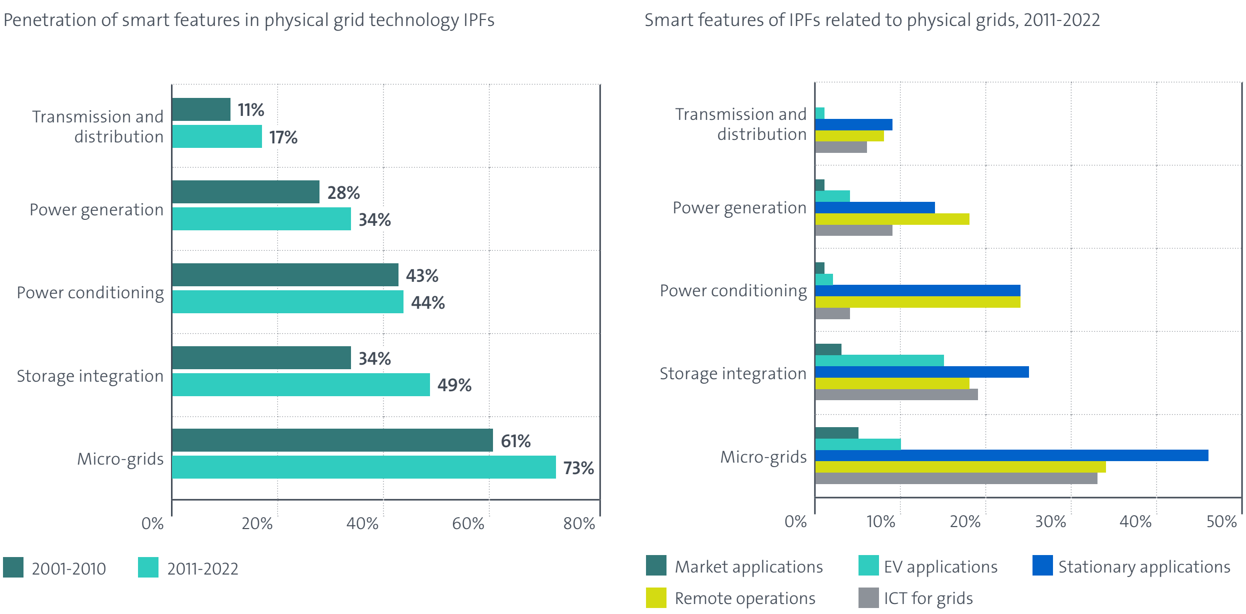
Across the board, technologies for physical grids are getting smarter, a finding that is in line with the need for more flexible grid operations, even for components that have traditionally been considered dumb devices. A rising number of physical grid patents overlap with categories of smart grid features (Figure 2.1.2).

This is especially the case for micro-grids and integration of stationary storage in the grid. In the case of micro-grids (which operate in isolation as a local source of generation, but can also switch to become a component of a larger distribution network to ensure security of supply), nearly three-quarters of IPFs had a smart component over the period 2011-2022.

Smart features particularly enable real-time information and energy flows between consumers and providers on a local (e.g. urban) grid scale. Over the same period, about half of IPFs related to storage integration also had smart features. Storage integration is the segment of physical grids that shows the highest overlap with EV applications (15% of IPFs). Transmission, distribution and integration of power grid technology patents are also more likely to have smart features than a decade ago, but show relatively low penetration of smart features compared to other physical grid technologies.

Figure 3.1.3

Penetration of smart features in physical grid technologies



Note: The share of IPFs with smart features in distribution lines does not exceed 1% and is not reported.

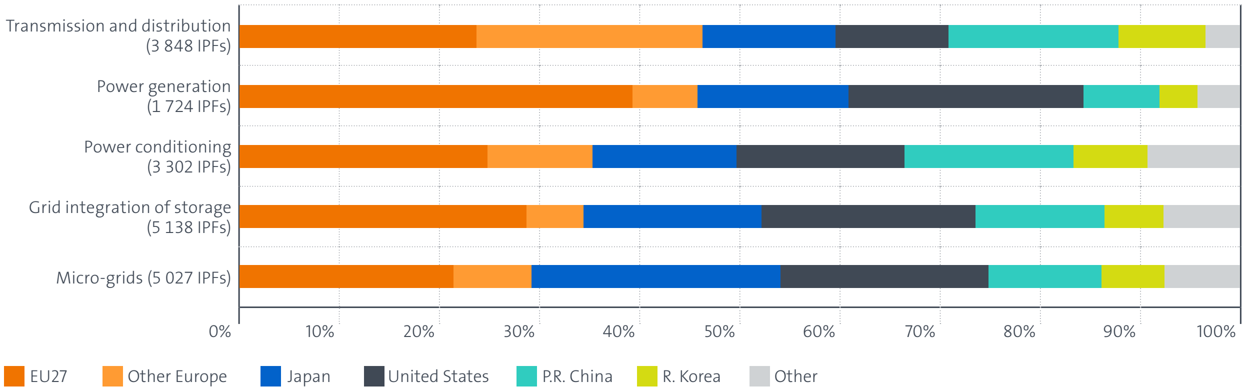
Source: author's calculations

The geographic origins of the IPFs over the period 2011-2022 reveal a lead by European applicants in most segments of physical grid technologies. The cumulative share of IPFs generated by EU27 countries is particularly high in integration of power generation (39.4% of all IPFs), storage in grids (28.7%) and power conditioning (24.8%). In transmission and distribution the combined share of the EU27 and other European countries reaches 46%, with 19.4% contributed by Switzerland alone.[9] The US, Japan and P.R. China alternate in second and third positions in these four segments, with relative specialisation in integration of power generation and storage integration for the US and Japan, and in power conditioning and transmission and distribution for P.R. China.

Micro-grids – a segment for which the physical grid elements are heavily reliant on associated smart grid technologies – are the only segment in which the EU27 ranks second (with 21.4% of IPFs), with Japan first (24.9%) and the US close behind (20.8%).

Figure 3.1.4

Global origin of IPFs related to physical grids, 2011-2022

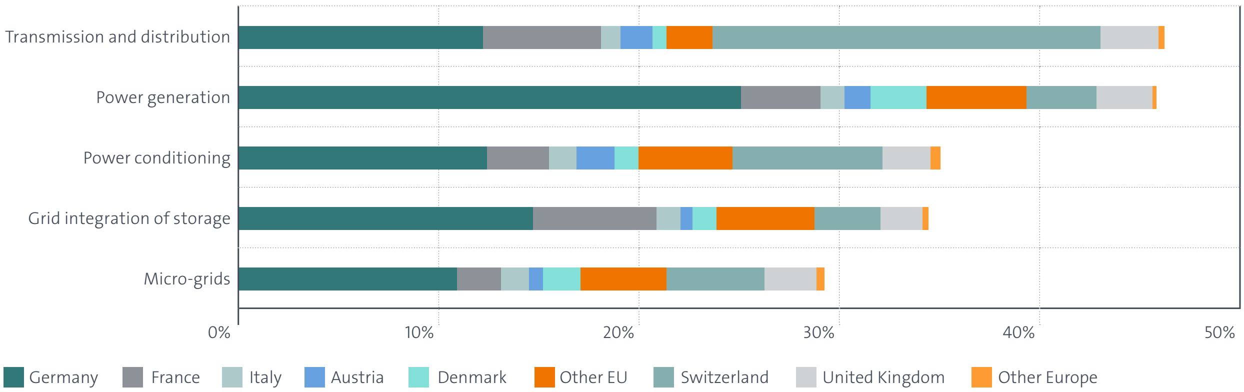


Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Figure 3.1.5

European origin of IPFs related to physical grids, 2011-2022



Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

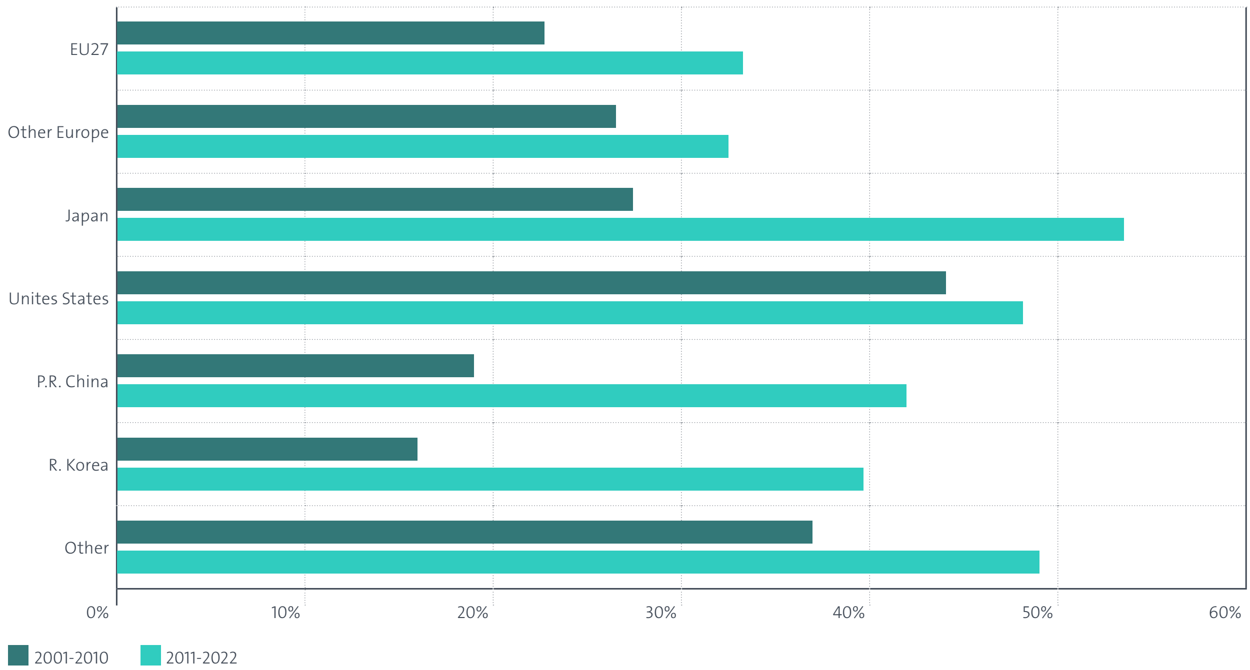
Source: author's calculations

[9] This includes IPFs contributed by ABB Grid, a subsidiary of Japan's Hitachi, when filed from a Swiss address.

Overall, Europe's leadership in physical grid patenting is in developing technologies that are less smart (Figure 3.1.6). Compared to other major patenting regions, Europe's share of IPFs in physical grids that included smart features was lower in 2011-2022. This was despite Europe being ahead of P. R. China and R. Korea by this measure in 2001-2010. Both the EU27 and other European countries show a relatively low penetration rate of smart technologies. The penetration of smart features was much higher in Japan, P.R. China and R. Korea in 2011-2022, despite an initial lag with respect to Europe in the case of P.R. China and R. Korea. The US stands out with a relatively high penetration rate of smart technologies in both periods.

Figure 3.1.6

Penetration of smart features in physical grid technology IPFs by main region, 2011-2022



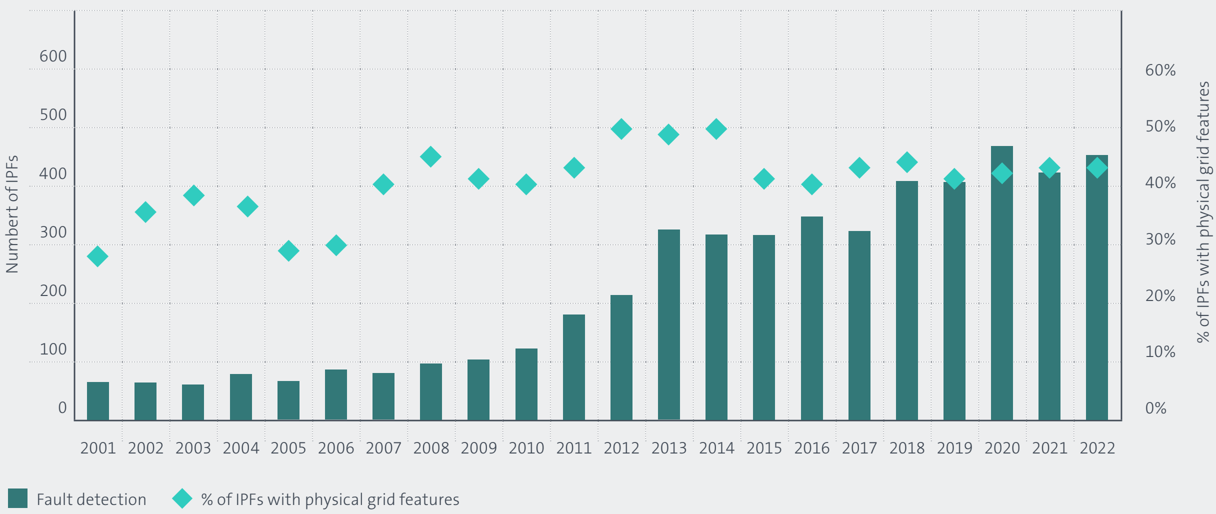
Source: author's calculations

Box 4: Detecting and locating faults in grids

Faults in electric power systems are usually associated with an abnormal electric current, such as a short circuit, in which current exceeds normal operating conditions. Detecting, analysing and clearing such faults is essential to enhance performance and minimise interruptions. This allows the grid to operate more evenly, efficiently and with less need for costly back-up arrangements. By facilitating faster power restoration times, fault detection is a means of addressing challenges related to expanding and enhancing physical connections and it has particular relevance in the context of the escalating impact of extreme weather events. Nonetheless, it is an area that is not only related to physical grid technologies; digital techniques have made it possible to detect, analyse and clear faults quickly and efficiently using intelligent controls. In fact, most IPFs in this field now relate to smart grid technologies aiming to detect and locate faults. Other inventions are designed to become integral components of physical grids.

Figure 3.1.7

Patenting trends in remote fault detection and location (IPFs, 2001-2022)



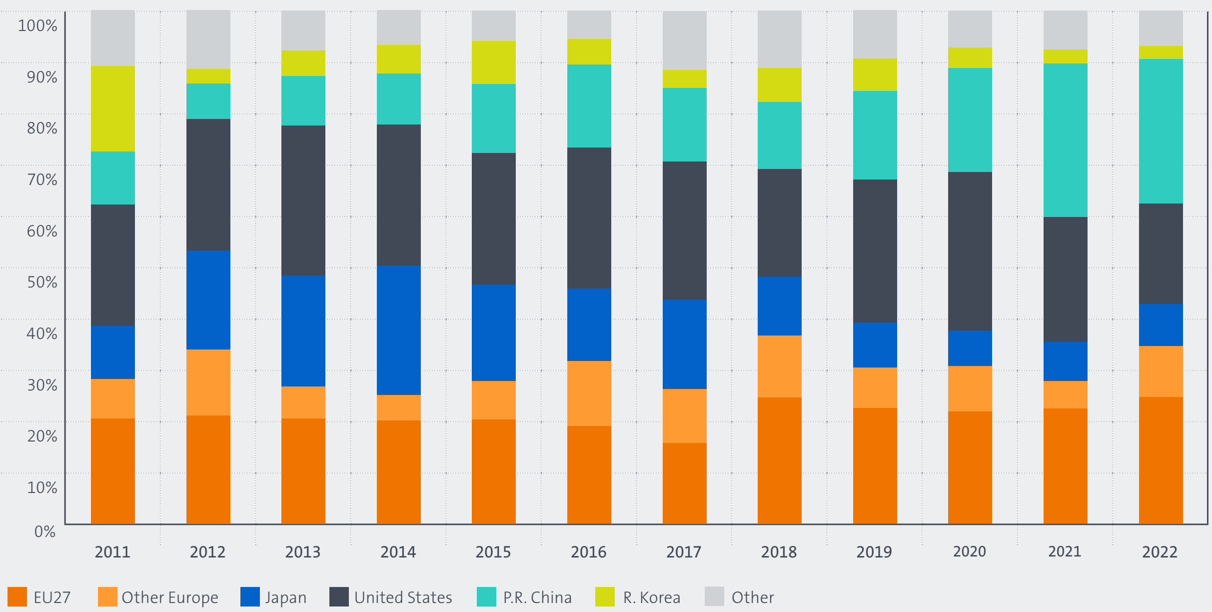
Source: author's calculations

Patenting activities in fault detection and location increased rapidly over the period 2009–2013 (at an impressive average compound rate of 27%), and again after 2017 (though at a lower rate of 7%).

A significant share of IPFs in fault detection include both physical grid and smart grid features (Figure 3.1.7). The proportion of those dual IPFs increased over time, before stabilising around 40% in the late 2010s.

Figure 3.1.8

Global origin of IPFs in remote fault detection and location (IPFs, 2011-2022)



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

Growth in patenting actitvies in fault detection and location has not been evenly distributed across the world's main regions (Figure 3.1.8). It was consistently supported by US and European innovation efforts, led by top applicants in physical grids such as General Electric, ABB and Siemens (with about 9.7%, 7.6% and 7.3% respectively of IPFs in fault detection and location over the period 2011-2022), as well as France's Schneider Electric (8.3%). While Japan, a country that has ensured reliable power supplies despite exposure to natural disasters and extreme weather, was a driving force in the first growth period – with Toshiba (5.7%), Hitachi (5.0%) and Panasonic (4.7%) featuring in the top ten applicants in 2011-2022 – its contribution to patenting activities has significantly dimished since then. By contrast, P.R. China has emerged more recently as the main driver of the second period of growth, and the top region in 2021 and 2022. As a result, two Chinese groups, Huawei (4.0%) and State Grid Corporation of China (3.4%) also feature in the top ten for the period 2011-2022.

Box 5: Recent developments in frequency response and non-spinning inertia

As thermal power generation sources – coal, gas and nuclear – account for a lower share of countries' power generation mixes, electricity grids are losing access to a resource that has been fundamental to their effectivity since they first adopted AC power. This resource is the ability to store energy in the large rotating generators of these power plants. In some places this resource is also threatened by less certain output from large hydropower plants due to climate change-related factors. The inertia of such large spinning masses allows grid operators to maintain a stable frequency during moments of mismatch in supply and demand, or in exceptional situations when a power plant fails. Spinning generators can balance frequency in just a few seconds, allowing for controlling systems to detect and respond to the failure.

By contrast, renewable generators including solar PV, wind turbines and batteries connect their DC output to the AC grid via power converters, which do not provide any inherent inertia. Without new means of responding to rapid fluctuations in grid frequency, it will be very challenging to phase out thermal power plants, even in cases where they are not a competitive source of electricity.

There are several technological options for providing frequency response. Large-scale battery storage systems can provide fast frequency response (FFR) by rapidly injecting or drawing power from the grid whenever imbalances in supply and demand are leading to disturbances outside the normal frequency within two seconds.

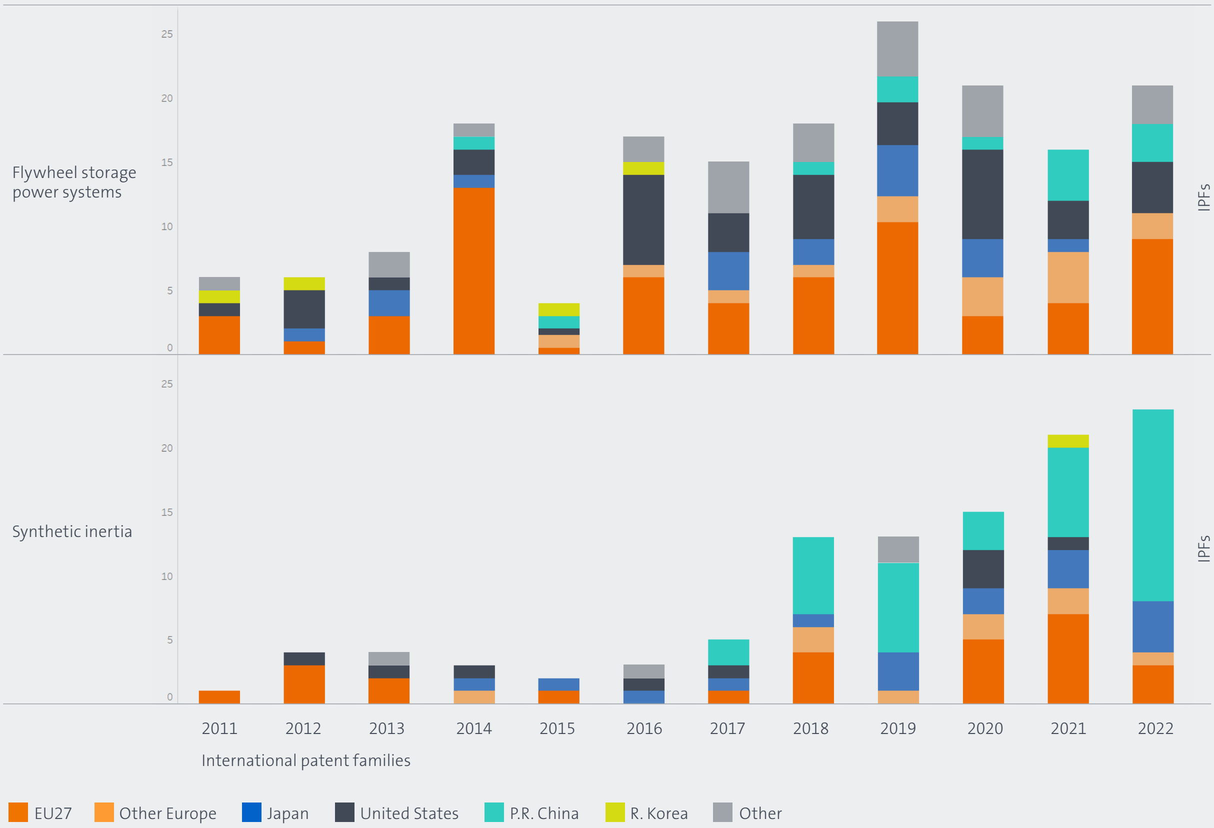
Flywheel-based energy storage can also be used to create spinning inertia with electricity and disconnected from the source of power generation. Flywheels store energy as rotational motion and can be as large as a 30 MW plant commissioned in P.R. China in October 2024. Flywheels can absorb or release energy to support grid frequency on the timescale of seconds to adjust to changes such as fluctuations in wind or solar power output.

A third means of regulating frequency is often referred to as "synthetic inertia" or "virtual inertia". This is provided by technologies that allow electricity resources such as batteries, solar PV and wind to modulate their output automatically on sub-second scales in response to frequency or voltage changes on the grid. This has been successfully tested in combination with wind turbines, which have rotational energy, and through the use of so-called grid-forming inverters as well as grid-following inverters. While synthetic inertia is expected to play an increasingly important role in ensuring grid stability as more synchronous generators retire, further technical development is needed for it to be a primary source of frequency control as rapid and large-scale as synchronous generators.

Figure 3.1.9 reports on the evolution of electricity grid patenting activities related to flywheels and synthetic inertia from 2011 to 2022. The level of patenting activities targeting both technologies was low until recently, with less than ten IPFs per annum in the early 2010s. However, the number of IPFs related to flywheels has been on the rise since then in response to the emergence of the issue as a major future grid challenge; with an even stronger rise in patenting related to synthetic inertia seen as of 2018. Patent data therefore suggests that synthetic inertia is the more active area of development today, potentially accompanied by higher long-term commercial expectations.

Figure 3.1.9

Patenting trends in flywheels versus synthetic inertia by region (IPFs, 2011-2022)



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

Most IPFs related to flywheels originate from Europe and the US (36% and 23%, respectively, of all IPFs in the period 2011-2022) and are filed by a limited number of applicants led by Siemens Energy, ABB and Hitachi. By contrast, the acceleration of patenting in flywheels has been chiefly driven by Chinese applicants (accounting for 45% of the total since 2018), followed by Europeans (32%, and 22% for the EU27 alone). Besides top applicants in grid technologies such as Japan's Hitachi, France's Schneider Electric or the State Grid Corporation of China, the main applicants in synthetic inertia include two European specialists in wind power, Vestas and Enercon. A large number of research centres and universities are also active in this field, especially in P.R. China, suggesting significant public support for the development of technologies facilitating the integration of renewable energy generation.

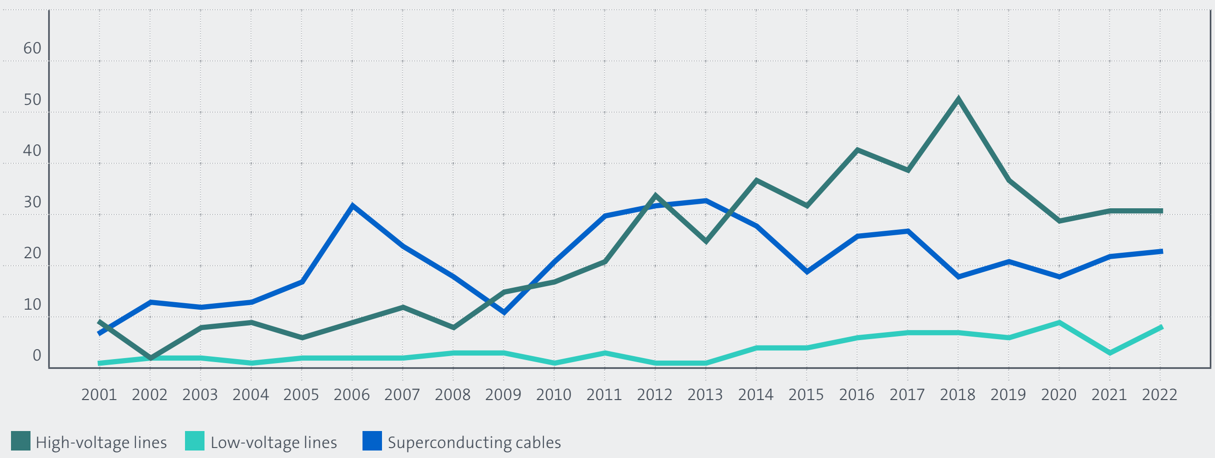
Box 6: Superconducting cables

The dream of a superconducting electricity grid that almost eliminates electricity losses has enthused innovators for many decades, and is starting to be realised in some specialist applications today. The science of superconductivity was discovered in 1911, but required low temperatures close to absolute zero to reduce electricial resistance almost to zero. It was not until the mid-1980s that a material was discovered requiring much less cooling for the same effect: yttrium barium copper oxide is a superconductor at -183°C. This triggered exploration of possible applications in electricity grids, but research only succeeded in raising the required temperature by a further 50°C over the subsequent decade. However, in parallel, there were successes for superconductivity in applications that can tolerate the expense of cooling to very low termperatures, such as electromagnetism for particle accelerators and nuclear fusion, and these helped to further propel basic research.

Scientific advances in materials, coupled with cheaper approaches to cooling cables, has stimulated greater interest in superconductivity for electricity grids in recent years. Superconducivity offers several advantages as a potential solution to the challenge of balancing renewable electricity output over a very wide geographic area, something that is advocated to take advantage of high solar or wind output in one area when it is low in another, and reduce curtailment of renewable power. More efficient transmission reduces wasted electricity and therefore the amount of generation capacity needed to meet demand. Low electricial resistance translates into high carrying capacity per cable cross-section, which means cables require less space to do the same job, potentially improving public support for new cable routes (Thomas H. et al., 2016). In addition, it can enable the transmission of the same power with fewer changes in voltage level, reducing substation and other equipment needs (Ren, L. et. al., 2009). However, it remains costly and in need of further technical development.

Figure 3.1.10

Patenting trends in power transmission (IPFs, 2001-2022)

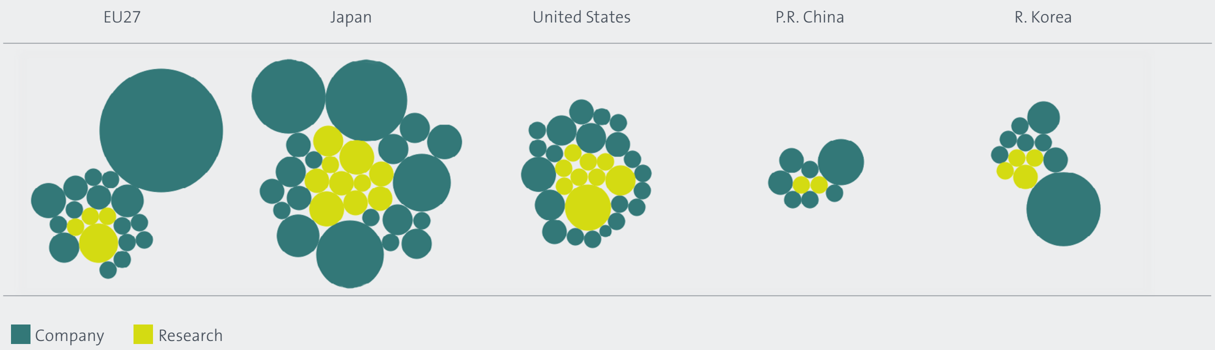


Source: author's calculations

From a baseline of fewer than 25 IPFs per year between 2000 and 2005, patenting of electricity applications for superconductivity began to rise thereafter, peaking in 2018 at around 75 IPFs. At first this growth was based around cable designs, including integration of liquid nitrogen cooling and use of materials that are much more complex to handle than metal wires. In 2004 Sumitomo (Japan) successfully developed a technique for commercialising cables made of a high-temperature cuprate superconductor (Bi-2223 or BSCCO – "bisko"), a rare earth ceramic they invented in the late 1980s. As cable design began to show more promise, there was a steady increase in patenting for ways of using superconductivity in the specific application of electricity transmission. While the annual rate of IPF applications has waned since 2018, it remains much higher than 15 years previously. It is unclear whether this dip is related to less enthusiasm for near-term market opportunities or slowing technical improvements.

Figure 3.1.11

Regional ecosystems in superconducting cables (IPFs, 2011-2022)

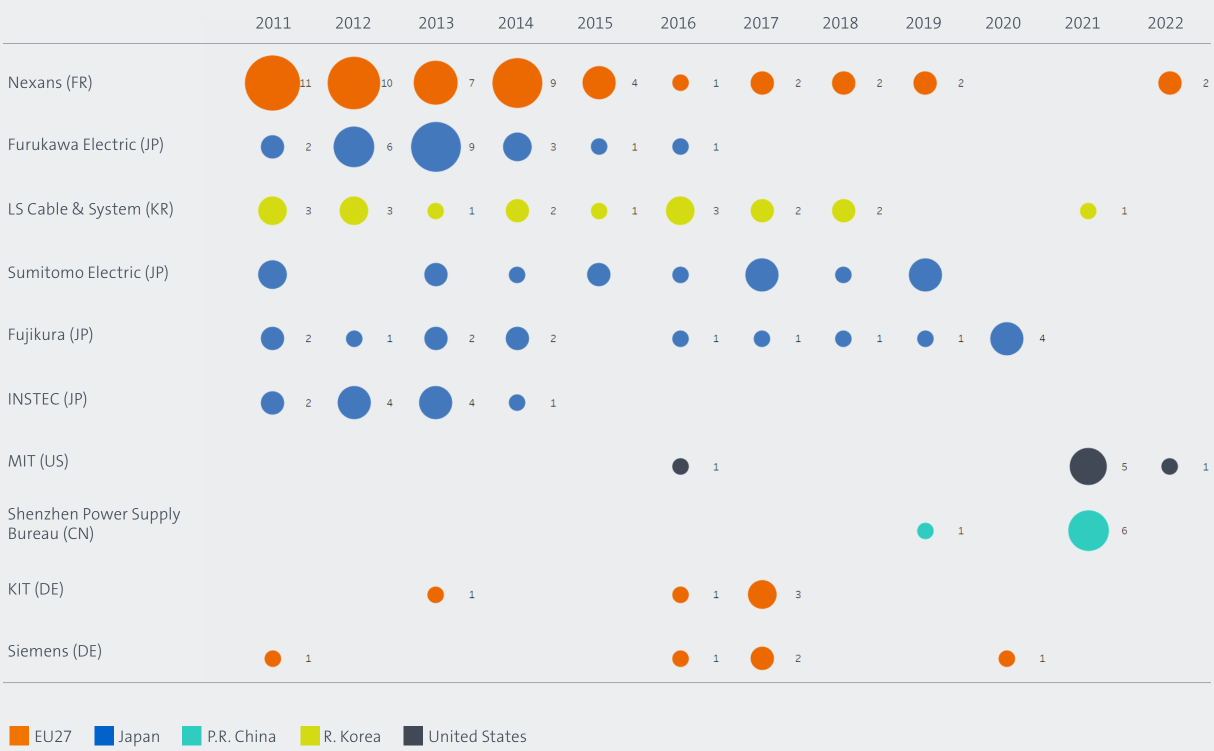


Note: Each bubble in this chart signals a different applicant. The size of the bubbles are proportional to the number of IPFs produced by the respective applicants. The colours indicate the category of applicant.

Source: author's calculations

Figure 3.1.12

Top 10 applicants in superconducting cables, 2011-2022



Source: author's calculations

Today there are six examples of uses of superconductivity for electricity grid applications that have been in operation since 2014. Two of these are in Europe, and Japan. Russia, R. Korea and the United States host one each (ENTSO-E, 2024). Some of these are primarly technology demonstrations, while others also serve a more immediate practical purpose. For example, the Shingal project in R. Korea operates over a distance of 50 km to alleviate the demands on one substation by connecting it with an underutilised substation, avoiding the need to expand capacity. The distribution of international patenting activity reflects the locations of these projects, with Japan and Europe showing the most applicants. Among these, Nexans of France and Furukawa Electric of Japan have the most IPFs, mostly received between 2011 and 2015. R. Korea and the United States have somewhat lower levels of patenting, with no major patenting companies among the US applicants. China is further behind overall, but Chinese company Shenzhen Power Supply Bureau was the highest single IPF applicant in 2022, signalling growing research interest there.

As an indication of the advances that have been enabled by these innovations, in 2024 Nexans is scheduled to complete installation of a superconducting cable at Montparnasse train station in Paris to increase electrical capacity for its electric rail system by overcoming space constraints (IEEE, 2024).

3.2. Recent trends in stationary storage technologies

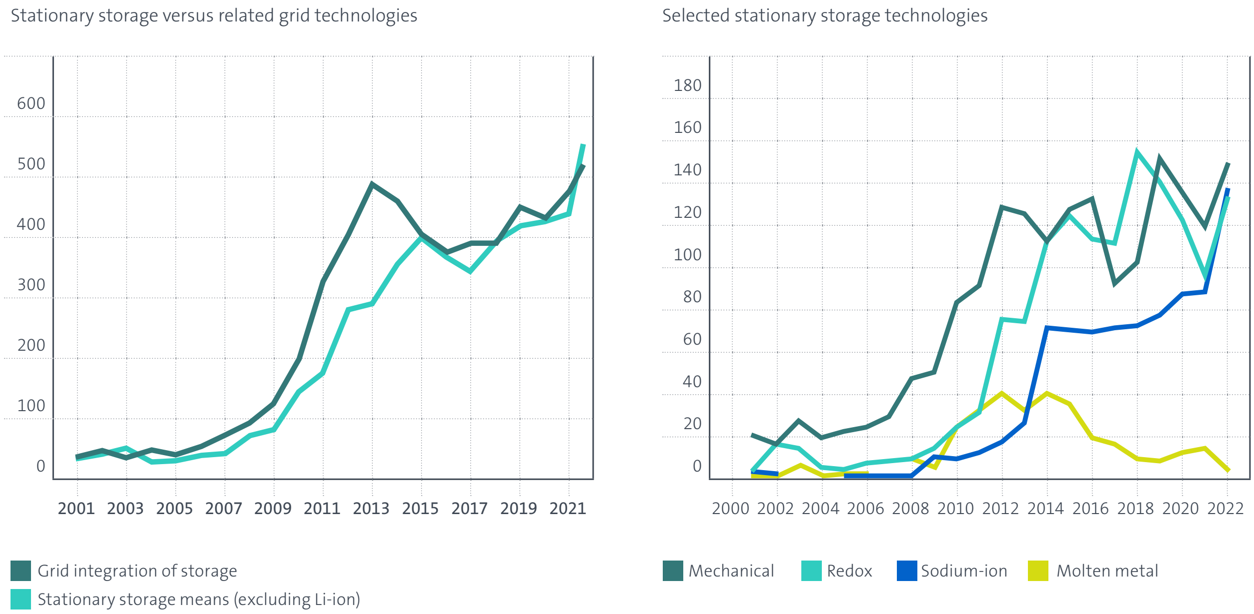
Storing energy on a large scale is increasingly important to help maintain the stability of power grids, offset the need for other costly grid expenditure (such as new transmission capacity) and reduce the need for additional power generation assets to cover peak demand. By enabling storage at times when electricity is cheap – for example when generation from solar and wind is more than can be transmitted by the local grid connection or, in some cases, exceeds demand – it can provide a valuable resource later when demand would otherwise need to be met by ramping up a fossil fuel-fired generator. There are opportunities for stationary storage operators to play an arbitrage role, limiting extreme peaks and troughs in spot prices and lowering power prices overall. However, to date most stationary storage projects have generated revenue by releasing electricity to the grid for very short periods to compensate for rapid dips in output from variable renewable generators. Without this compensation, fast changes in the magnitude of electricity supplies can threaten grid stability, which is why generators and grid operators are willing to remunerate stationary storage operators for this service. Most changes in variable renewable electricity output are readily forecastable, allowing grid operators to plan various means of accommodating them, including but not limited to stationary storage resources.

Currently, the bulk of large-scale storage is provided by pumped hydropower installations, a mature and already widely deployed technology developed to allow large generators such as nuclear power plants to operate in continuous mode even where this does not match patterns of varying electricity demand. As the variability of electricity has increased with the penetration of variable renewable resources, and forecasting and control of electricity demand has improved, smaller and more decentralised forms of storage have been commercially developed. These include utility-scale batteries and behind-the-meter batteries. Lithium-ion batteries similar to those used for EVs are the dominant technology for stationary batteries at this stage, mostly with a storage duration of around four hours. It is expected that the future market for stationary storage will be more varied, with a bigger role for short-term storage in behind-the-meter batteries in buildings and even in people's vehicles, as well as new technologies that are cheaper than lithium-ion (or sodium-ion) batteries for storage over durations longer than eight hours. While there is currently no significant market for inter-seasonal storage that can accept electricity generated in one season and dispatch it in another, for example to allow solar PV to cover more winter demand, many experts expect this to play a role in future.

This section considers technologies with the potential for cost-competitive, grid-scale long-duration energy storage (LDES), with a focus on technologies designed to store and dispatch electricity.[10] Patenting activities in these technologies have been increasing rapidly since 2005, with an average annual growth rate of IPFs of 19% up to 2022. As shown on the left-hand side of Figure 3.2.1, this has been matched by an increase in IPFs related to integrating storage solutions in power grids over the same period (average growth rate: 16.4%).

Figure 3.2.1

Patenting in selected stationary storage technologies (IPFs, 2001-2022)



Source: author's calculations

A variety of technologies are being explored to address grid-scale energy storage needs (EPO-IEA, 2020).[11] The chart on the right-hand side of Figure 3.2.1 organises them into four main categories. The first captures largely incremental progress in relatively well-known mechanical storage means suitable for grid applications, such as gravitational storage (including pumped hydropower), flywheels and pumped thermal storage, as well as some emerging technologies such as compressed air and cryogenic liquid air storage. Together, these generated the bulk of patenting activities up to 2010. They show rapid growth in IPFs until 2012, followed by a more erratic trend until 2022. Patenting activities in these technologies have been largely led by European applicants, with about 39% of IPFs over the period 2011-2022 (27% for the EU27 alone) (Figure 3.2.2).

The other three categories of stationary storage technologies have emerged much more recently. Redox flow batteries and sodium-ion batteries show an impressive acceleration in patenting activities around 2010, with average annual growth rates of 23% and 33% respectively from 2005 to 2022. These showed the steepest initial increase, with a clear lead for US applicants (28% of IPFs in 2011-2022), followed by Japanese ones (21%).

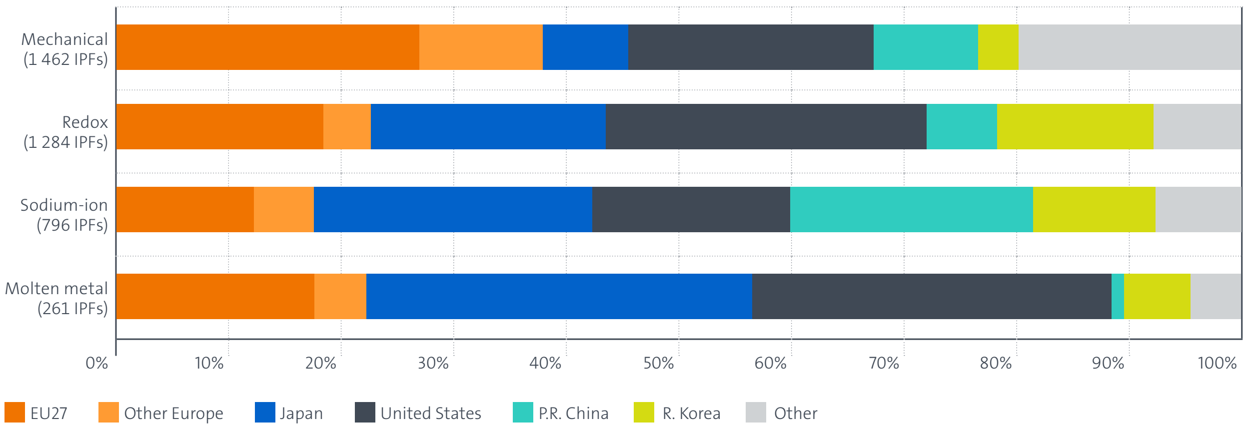
[10] It does not cover the wide range of options for storing electrical energy in the form of thermal energy for subsequent direct use in heating or cooling.

[11] A comprehensive analysis of patenting trends in batteries and energy storage technologies can be found in a previous joint study by the European Patent Office and the International Energy Agency: EPO-IEA (2020): "Innovation in batteries and energy storage. A global analysis based on patent data".

Patenting activities in sodium-ion technologies started with a lag, but have been growing even faster, at an average rate of 33.5% between 2005 and 2022. They are mainly led by Japanese and Chinese applicants, with 25% and 22% respectively of IPFs in the field over the period 2011-2022. As a result of this rapid development, patenting activities in redox flow batteries and sodium-ion batteries eventually caught up with those observed in mechanical storage. By contrast, activities in molten metal batteries, the fourth category of storage technology, are now decreasing after a brief growth in IPFs around 2010. Molten metal batteries are mainly used today in concentrating solar power plants to store the heat from the reflectors until dusk, an application that saw a great deal of development work in 2010-2020.

Figure 3.2.2

Global origin of patents in stationary storage technologies, 2011-2022

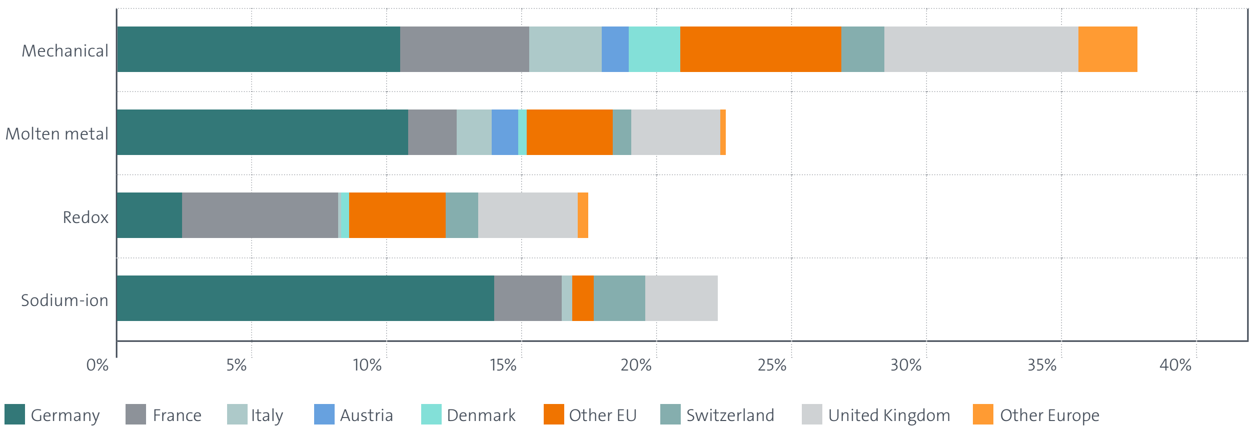


Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Figure 3.2.3

European origin of patents in stationary storage technologies, 2011-2022



Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

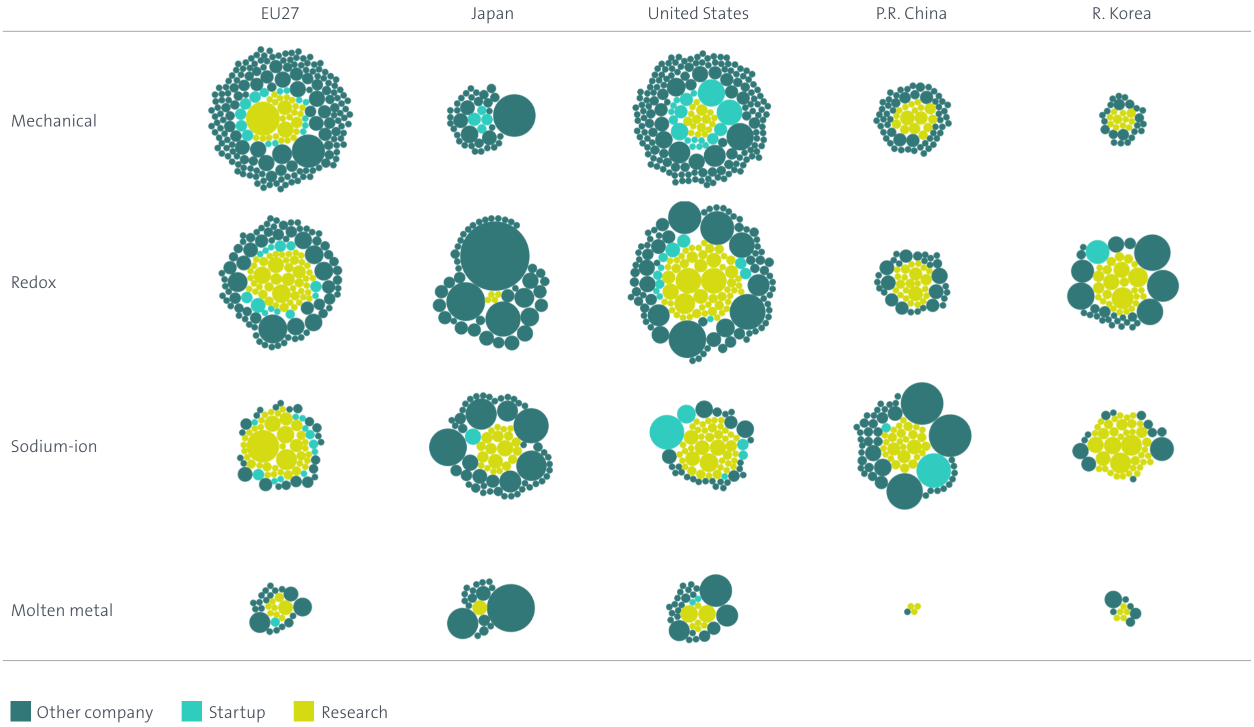
Source: author's calculations

Figure 3.2.4 provides further insights into the regional ecosystems supporting the development of these stationary storage technologies. It signals mature ecosystems – combining universities, startups and a large number of other companies with patenting activities – supporting innovation in mechanical storage means in Europe and the US, with smaller constellations of applicants in Japan, P.R. China and R. Korea.

Emerging technologies such as redox flow and sodium-ion batteries show even more diverse patterns. In both cases, the US and the EU27 have comparable populations of applicants. However, the US ecosystem is larger in the case of redox batteries. It also includes applicants with a relatively large portfolio of IPFs, whereas no such large applicant emerges in the EU27. Japan stands out with a relatively low contribution by universities, but several corporate applicants with large patent portfolios in both technology fields. R. Korea's specialisation in redox batteries and P.R. China's in sodium-ion batteries likewise translates into a combination of research-oriented applicants and relatively large corporate applicants.

Figure 3.2.4

Regional ecosystems in selected stationary storage technologies (IPFs, 2011-2022)



Note: Each bubble in this chart signals a different applicant. The size of the bubbles is proportional to the number of IPFs produced by each applicant. The colours indicate the category of applicant.

Source: author's calculations

4. Smart grids

The concept of smart grids emerged around the year 2000, as experts grappled with challenges including ageing infrastructure, a lack of grid investment in the previous decade, coordination of recently liberalised power markets, and the opportunities presented by digital technologies. In 2003 the US public-private Consortium for the Electric Infrastructure to support a Digital Society (CEIDS) published recommendations that promoted the use of smart grid terminology, but there has never been a fixed definition of a smart grid. Typically, the scope of smart grid work is defined by how the smarter grid functions, rather than the technologies involved. However, it is generally agreed that smartness is related to the use of cutting-edge communications technologies, combined with much greater data acquisition, data analysis and automation of controls. Since the early 2000s the following five functions have been the main targets:

- the grid can “self-heal” after disruption
- the grid is secure against physical and cyber threats
- distributed generators can easily connect and supply end-users via the grid
- end-users can programme or allow automated control of their electricity-using equipment
- grid operators can achieve greater throughput and lower costs

While the general concept has not changed dramatically, the expectations for the roles of variable renewable energy, household solar PV, EVs and digital controls have been transformed in the past two decades. Today there is therefore more emphasis on the ways these functions, especially end-user controls, can help facilitate greater penetration of a much wider range of electricity generation options, whether distributed or not, while minimising investment in new capital-intensive assets.

In this section, patenting trends are explored in smart grids primarily in relation to the challenge of making grid operations more flexible and bidirectional. These are mainly covered in Section 4.1 and include technologies for controlling the generation, distribution and transmission of electricity, as well as controlling end-use demand. Section 4.2 looks in more detail at EV charging, which is one specific and fast-growing area of end-use demand control. Smart grid technologies designed to improve fault detection and management are discussed in Section 3.1, along with the physical grid technologies that also support expansion and enhancement of physical connections.

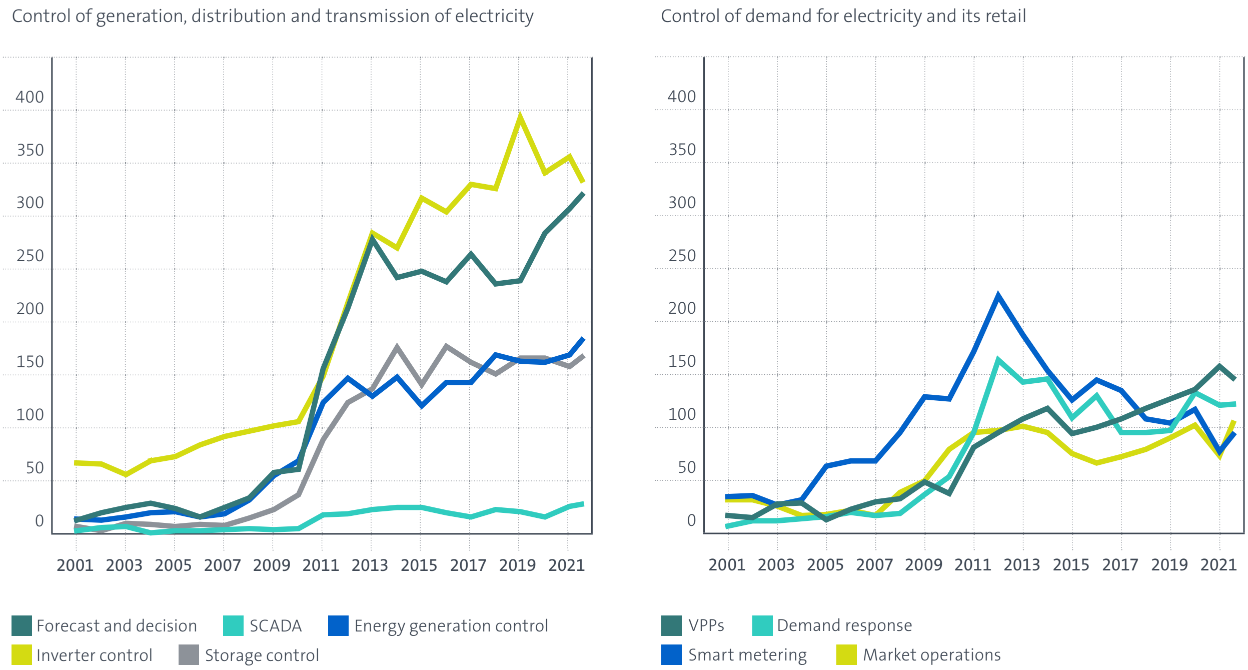
4.1. Main patenting trends in smart grid technologies

Smart grid-related patenting has been a bigger driver of the overall trend in electricity grid patenting than physical grid technologies. In particular, nearly all of the striking growth in electricity grid patenting since 2016 has been related to smart grid technologies, mostly in just one country: China.

All smart grid technologies experienced the same sharp rise in patenting over the period 2009-2013, but to different extents (Figure 4.1.1). IPFs for controlling electricity storage systems rose by around 800% and those for forecasting and grid operation decisions rose by around 700%, while those for controlling inverters rose by around 300%. IPFs for demand response (excluding EV charging, which is analysed separately in Section 4.2) rose by 700%, higher than the growth in other IPF categories in this area.

Figure 4.1.1

Growth of patenting in selected digital technologies for grids (IPFs, 2001-2022)



Source: author's calculations

In most smart grid areas, the high innovation levels reached by 2013 have been maintained to 2022. Annual patent applications are now four to five times higher than over the period 2000-2010, showing that much more effort is being devoted to improving smart grid technology around the world. While it is possible to interpret the trend of the past decade as a missed opportunity due to a lack of continued growth in patenting, it is nonetheless impressive that the R&D and market conditions have supported continued innovation at a high rate. This is cause for optimism that R&D remains worthwhile for companies and governments and there is a significant chance that a share of it will be translated into new commercial products that promote clean energy transitions.

One exception to this trend relates to patenting in the field of smart meters. Smart meter IPFs were an early frontrunner, rising faster than other smart grid fields before 2010, This was driven mainly by US and European applicants (with 39% and 26% of IPFs respectively during this period). After a peak of over 220 IPFs in 2012, smart meter patenting more than halved to below 100 IPFs per year in 2021 and 2022. One explanation for this trend is that the first government deployment regulations and targets in the area of smart grids were for smart metering.

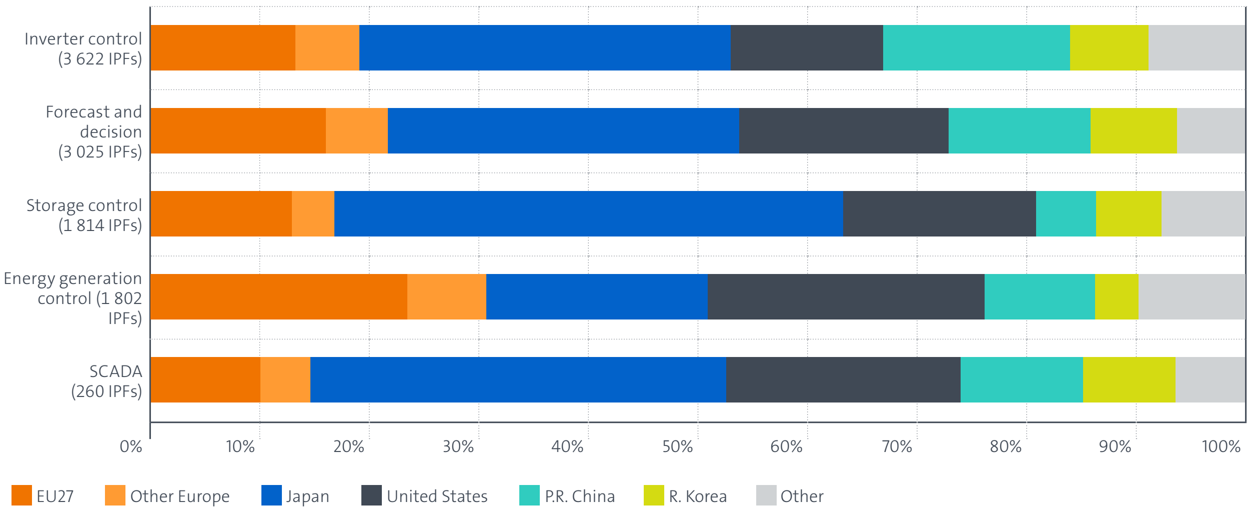
By 2005 electricity utilities were supportive of smart meters and the technology was sufficient to provide four key services: remote reading, two-way communication, support for advanced tariff and payment systems, and remote disablement and enablement of supply. Smart meter deployment does not just rely on consumer spending and competitive pricing compared with incumbents. The costs are borne directly by governments or the companies – electricity grid operators or retailers – given a mandate to install them and recoup costs from customer bills. Therefore policy intervention quickly enabled pilot projects in Europe and the United States, followed by legislation to require meter replacements to be smart.

Spain was among the first to pass such a law, in 2008. Today, penetration of smart meters is approaching 100% in many major economies and it is estimated that there are around 1.7 billion such devices installed globally (Transforma Insights, 2024). The IEA estimates that, after passing USD 10 billion as early as 2012 and growing at 14% on average between 2015 and 2021, the global market size of smart meters dipped in 2022 to USD 24 billion, an indication that new installations are reaching saturation point.

Geographically, innovation in these fields was chiefly driven by Japanese applicants, which accounted for nearly half (47%) of IPFs in storage control over the period 2011-2022, and a third or more of IPFs in inverter control (34%), SCADA (38%) and forecast and decision (32%) (Figure 4.1.2). Globally, Tokyo was the top city hub for smart grid patenting (IEA, 2024b). By contrast, the EU27 has been only a minor contributor to patenting activities in these fields, ranking third behind the US in storage control and even fourth after the US and China in inverter control and SCADA. Remote control of energy generation is the only exception, with a relatively even distribution of patenting activities between the US (25%), the EU27 (24%) and Japan (20%).

Figure 4.1.2

Global origin of patents related to control of electricity generation, storage and grids, 2011-2022

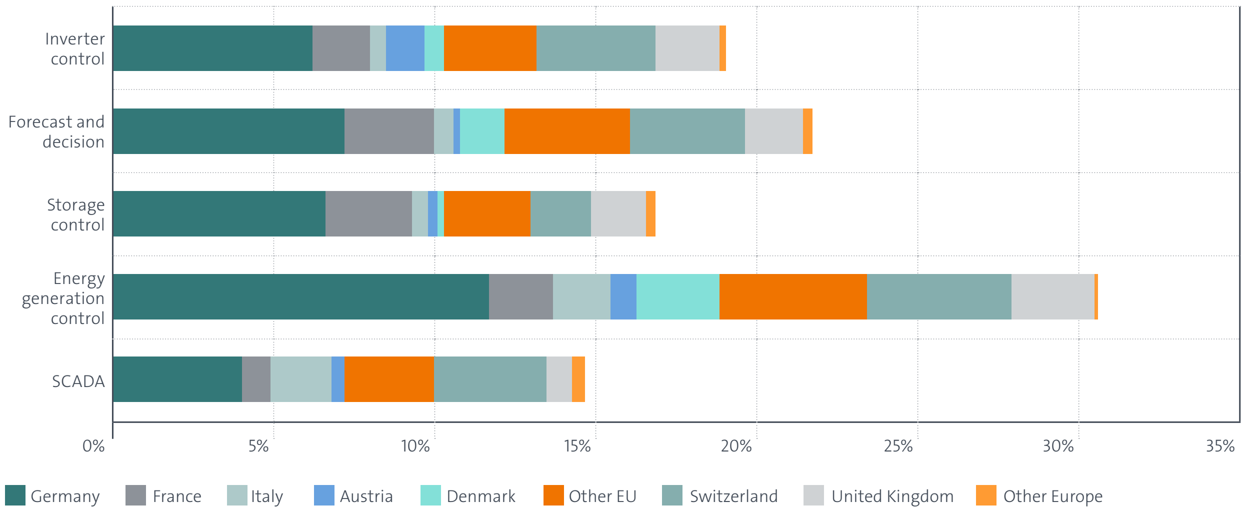


Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Figure 4.1.3

European origin of patents related to control of electricity generation, storage and grids, 2011-2022



Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

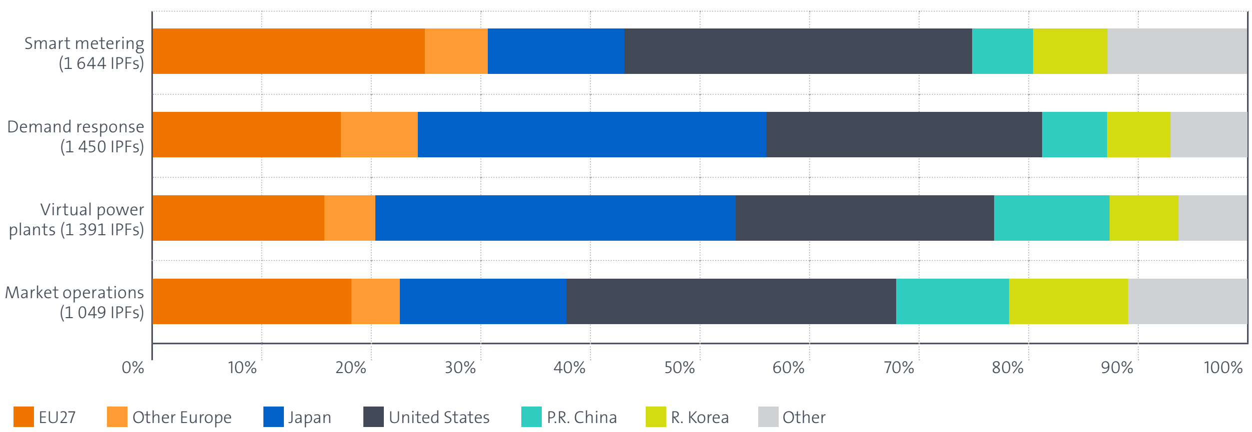
Source: author's calculations

While the surge in 2009-2013 can be observed in all smart grid applications related to the control of demand and its retail, patenting activities show divergent trajectories between those fields in the subsequent period. The number of IPFs related to VPPs kept growing up to 2022, despite a dip in 2015. After a peak in 2014, patenting activities in the other fields decreased to about 100 IPFs per year.

Japan stands out as the leading applicant region in demand response and VPPs, with about a third of all IPFs for the period 2011-2022, followed by the US and the EU27. By contrast, the US stands out with a specialisation in smart metering and market operations, where Japan shows relatively modest patenting activities.

Figure 4.1.4

Global origin of patents related to smart grid applications, 2011-2022

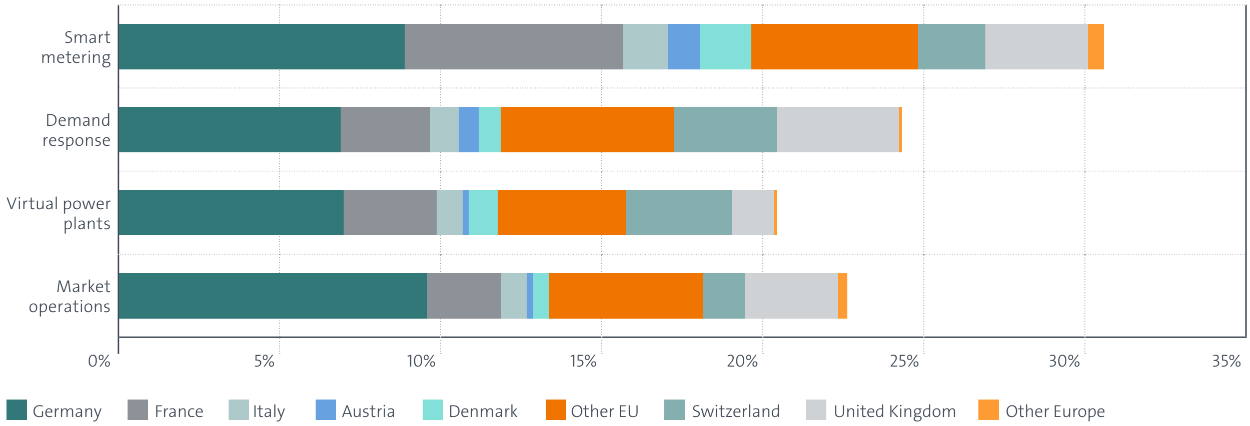


Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Figure 4.1.5

European origin of patents related to smart grid applications, 2011-2022



Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Besides Japan, the US stands out as a major applicant region in smart grid applications, with the largest share of IPFs in smart metering (32%) and market operations (30%), and the second largest share behind Japan in forecasting (19%) and VPPs (24%). While Japan is the top applicant region in demand response (with 32% of IPFs), it contributed only modestly to patenting activities in smart metering (13%) and market operations (18%). EU27 countries stand behind Japan and the US in all applications of smart grids, with shares of IPFs ranging from 16% in VPPs to 25% in smart metering, a technology pioneered by US and European applicants.

Box 7: Digital enabling technologies for smart grids

The availablity of a range of digital technologies, as well as continuous improvements to their costs and performance, triggered initial interest in the concept of smart grids in the early 2000s and underpinned its subsequent move into the mainstream of electricity grid planning. The range of technologies includes:

- data management platforms
- data transmission and reception devices, systems and protocols, including wireless communication
- cloud data storage, plus tools for writing and recalling information
- cybersecurity, including encryption, blockchain and firewalls
- AI, based on machine learning, neural networks and other advances

These techniques have applicability across a number of the challenges and technology areas covered in this report. We have identified a set of patents that relate to the general use of these digital enabling technologies to electricity grids specifically, and we highlight them here. These are in addition to the IPFs covered in the other sections of this document.

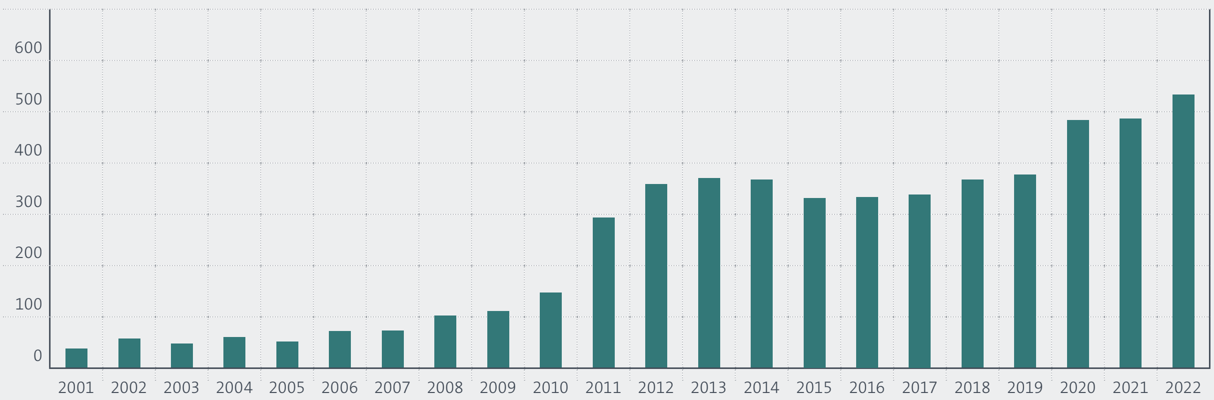
Patenting activity in digital enabling technologies for electricity grid applications has grown significantly since 2005 and steadily risen at an average annual growth rate of 15% to a new peak of over 500 IPFs in 2022 (Figure 4.1.6).

The global aggregate for these technologies exhibits a similar fast ramp-up of innovation around 2011, but less of a slowdown after 2013 than other areas. However, the aggregate trend masks a shift from patenting in the areas of data transport and data management platforms, which drove the early growth up to 2013 and was mainly led by Japan (with 38% of IPFs in this period) to growth in AI, led by China and the United States. On average, AI-related IPFs have expanded by an impressive 34% per year since 2016.

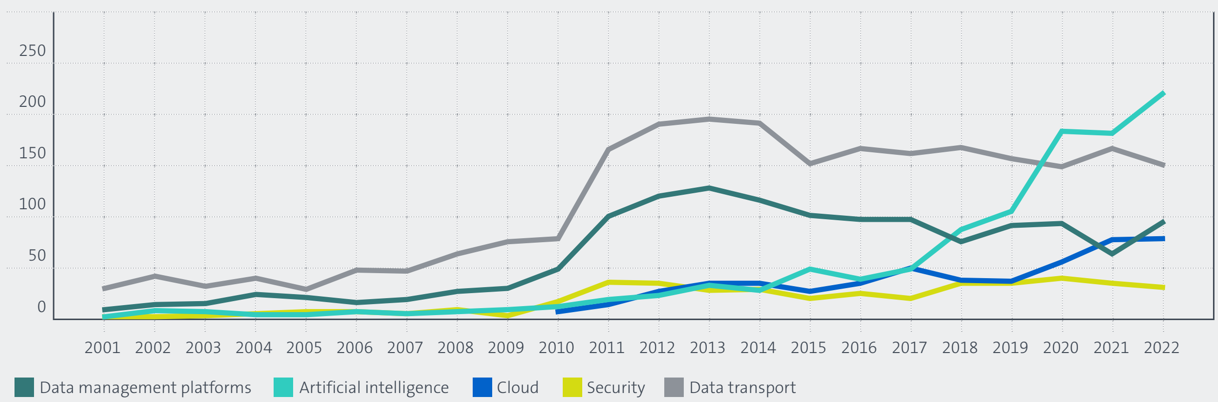
Figure 4.1.6

Patenting trends in digital enabling technologies (IPFs, 2001-2022)

All enabling technologies



Selected enabling technologies



Note: Besides the aggregated trend for all enabling digital technologies, the chart shows a selection of specific areas that generated the largest number of IPFs over the period.

Source: author's calculations

The specific grid applications of these digital enabling technologies reveal hotspots of innovation and geographical patterns. In general, it can be concluded that these tools are being applied to all three areas of grid challenges covered in this report. While they mostly intersect with the flexibilty challenge that is primarily associated with smart grid technologies, they are also being applied to the challenges of enhancing more traditional physical grid operations and protecting data.

Table 4.1.1

Impact of key enabling technologies on a subset of other fields of smart grids, 2011-2022

	Enabling technologies				
	Data transport	Data management platforms	Artificial intelligence	Cloud	Cybersecurity
Storage integration in grids	14%	16%	8%	17%	0%
Micro-grids	29%	22%	16%	27%	10%
Remote operation of generation units	12%	7%	5%	12%	4%
Outage or fault management	16%	6%	13%	15%	7%
Storage control	23%	15%	6%	13%	5%
VPPs	11%	8%	5%	10%	4%
Demand response	12%	11%	6%	9%	3%
Smart metering	11%	5%	4%	7%	8%
EV interoperability	6%	7%	4%	7%	8%
Forecast and decision	14%	21%	39%	29%	10%
Communication	4%	3%	3%	6%	37%

Note: The heat map shows the share of IPFs related to each enabling technologies that have also been identified as related to another category of smart grid technologies. Some of those may relate to two or more categories, while others may have no clearly identified relation to any of them. Percentages in the columns therefore do not add up to 100%.

Data transport-related IPFs, which were the largest single category of enabling digital technology IPFs over the period 2011-2022, targeted a range of different smart grid technology areas, with micro-grids and storage controls the largest among these (Table 4.1.5). Japan, the EU27 and the US contributed in roughly equal proportions to patenting activities in data transport, each with 20-25% of all IPFs over the period 2011-2022.

Innovation in data management platforms has a similarly cross-cutting nature. It is especially frequently present in micro-grids (targeted by 22% of IPFs related to data management platforms) and forecasting and decision technologies (21%). Patenting activity in data management platforms has been mainly led by Japan, which contributed 38% of IPFs in that field over the period 2011-2022.

AI patenting, on the other hand, has to date been more concentrated. The main area of AI-related IPFs are those supporting forecast and decision, a category that boasts 39% of AI-related IPFs and drove rapid growth in AI-related electricity grid patenting from 2000 to 2022.

AI is nonetheless applied in patents related to other areas of smart grids as well, in particular micro-grids and outage management. The US and China are the main patenting regions for these, with 24% and 23% of AI-related IPFs respectively, followed by the EU27 countries with 18%.

IPFs relating to cybersecurity respond to the challenge of protecting data for an increasingly interconnected electricity grid that communicates with several magnitudes more devices than it did just a decade ago, including appliances in people's homes. To date, cybersecurity enabling digital technologies are most associated with micro-grids and forecast and decision applications. It is noticeable that there is curently relatively litte patenting in the area of cybersecurity in relation to the integration of stationary storage, remote operation of power plants and demand response. These may be areas that governments would wish to explore to see if innovation is well-matched with the level of expected risk.

4.2. Recent trends in smart EV charging

EVs represent one of the biggest challenges to grid operators today, because they are a large new source of demand that tends to be concentrated in certain nodes within a grid and can be difficult to predict. As a major impact on electricity grids, especially in advanced economies, they are a relatively new phenomenon. In 2000, the starting year for our analysis, there were no mass-produced electric cars on the market, By 2010 there were two models, and fewer than 2 000 cars sold worldwide, mostly in the US and Europe. In 2024 around 17 million electric cars are expected to be sold, of which over 10 million will be in China (IEA, 2024a). Global electricity demand from EVs is projected to rise from 115 TWh today to around 1 000 TWh by 2030 – an amount equivalent to today's electricity demand for the whole of Japan.

If a large share of these vehicles plug in to charge at the same time, it will have very serious consequences for the stability of the grid and require much more generation capacity than would otherwise be needed, especially in the evening. The magnitude of this element in the challenge of making grid operations more flexible was not foreseen by early proponents of the smart grid concept.

Smart charging refers to a flexible and efficient approach to EV charging that goes beyond simply topping up a battery as fast as possible. It involves enhanced interoperability and communication between the vehicle, the charger and a management system, making it possible to dynamically manage charging as a function of factors such as grid utilisation, electricity prices and mobility needs. As the electric car market keeps expanding, smart charging is emerging as a critical application in smart grid technologies. It helps mitigate the massive strain put on grid infrastructure by the need to charge increasingly large fleets of EVs. It can also transform these EVs into an asset for the grid, by turning their batteries into flexible storage means capable of sending power back to the grid.

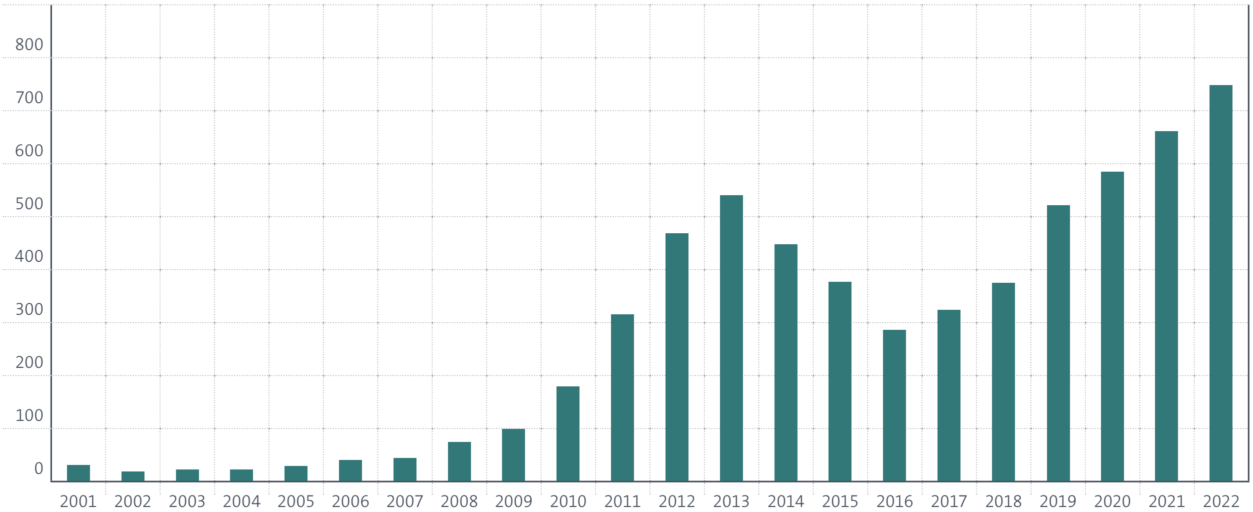
Like most technology fields related to smart grids, smart EV charging experienced a surge of patenting activities over the period 2009-2013, with a 7.4-fold increase in the annual number of IPFs between 2008 and 2013 (Figure 4.2.1).

Smart EV charging shows the most dramatic example of the 2013 peak in patenting among all electricity grid technologies. The number of IPFs nearly halved between 2014 and 2016 before picking up again at a brisk pace thereafter of 17% per annum on average. These trends can be observed in all main subfields of smart EV charging. One possible explanation is that the period 2010-2013 was when the first commercial electric cars arrived on the market and there was a rapid period of standardisation of charging interfaces, power ratings and software protocols. The data are consistent with a rush by technology developers to quickly patent their intellectual property with the dual aim of enshrining their preferred technologies in the emerging technical standards and protecting their intellectual property so licensing income could become a revenue stream once standards had been adopted. If this is indeed the case, the smoother annual IPF growth rate of 21% for the full period 2005-2022 may be more reflective of the innovation efforts related to smart EV charging. Since growth in IPFs resumed in 2017, remote or cooperative charging has been the most dynamic area of activity, reflecting efforts to integrate dispersed fleet of EVs into individual VPPs.

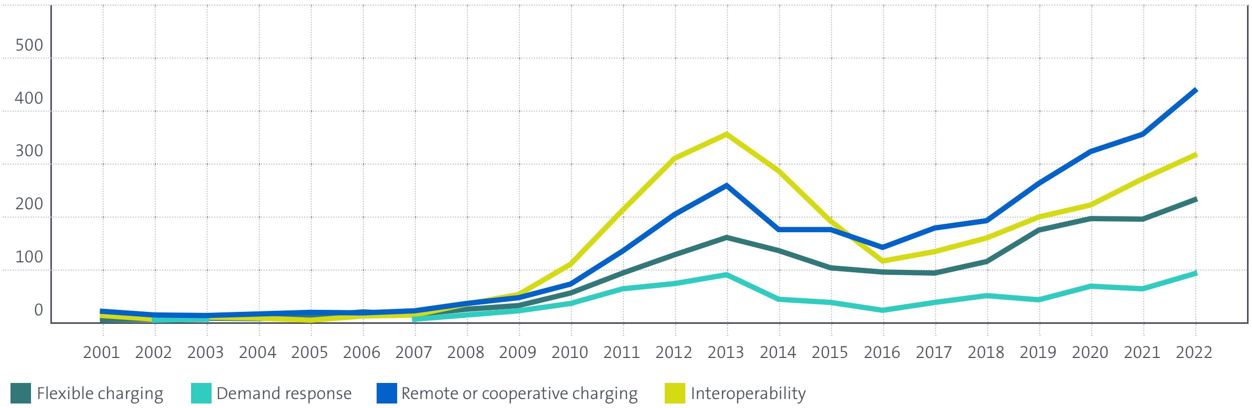
Figure 4.2.1

Growth of patenting in smart EV charging, 2001-2022

All IPFs in smart EV charging



IPFs in specific smart EV charging technologies



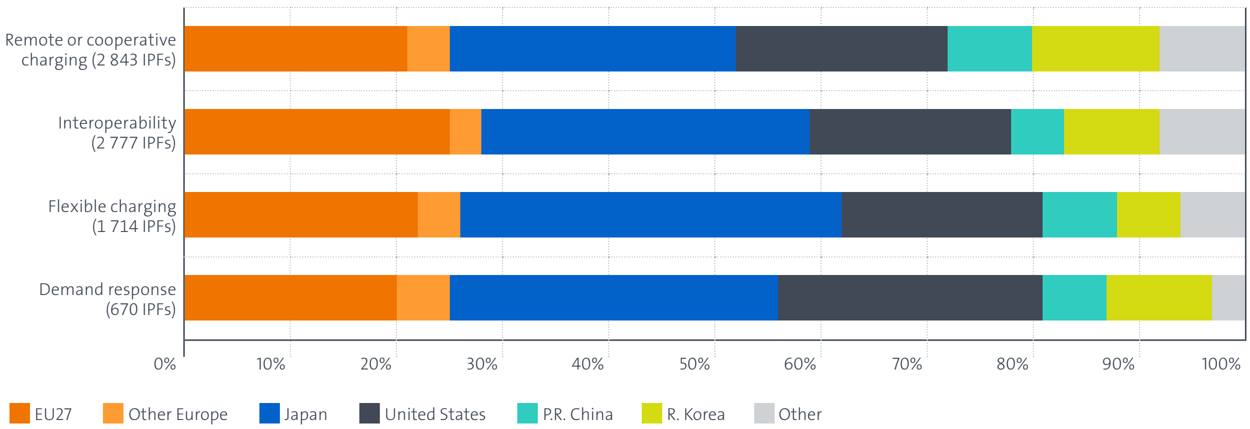
Note: Some of the IPFs in the chart below may be relevant to more than one subcategory of smart EV charging technologies. Where this is so, they are reported under each subcategory.

Source: author's calculations

Japan has had a consistent lead in all segments of smart EV charging technologies, with about one- third of all IPFs over the period 2011-2022 (Figure 4.2.2). The EU27 and the US follow, each with roughly 20% of global patenting activities, and a relative advantage in interoperability for the EU (25%) and demand response for the US (25%). Within the EU, Germany alone accounts for half or more of patenting activities in all segments, far ahead of France and the United Kingdom (Figure 4.2.3). Interestingly, P.R. China has made only a modest contribution to patenting activities in these fields, despite its strong lead in the deployment and manufacturing of electric vehicles. With a 6% to 8% share of global IPFs in the different subfields of smart EV charging technologies, it is positioned behind R. Korea in all except flexible charging.

Figure 4.2.2

Global origin of patents related to smart EV charging, 2011-2022

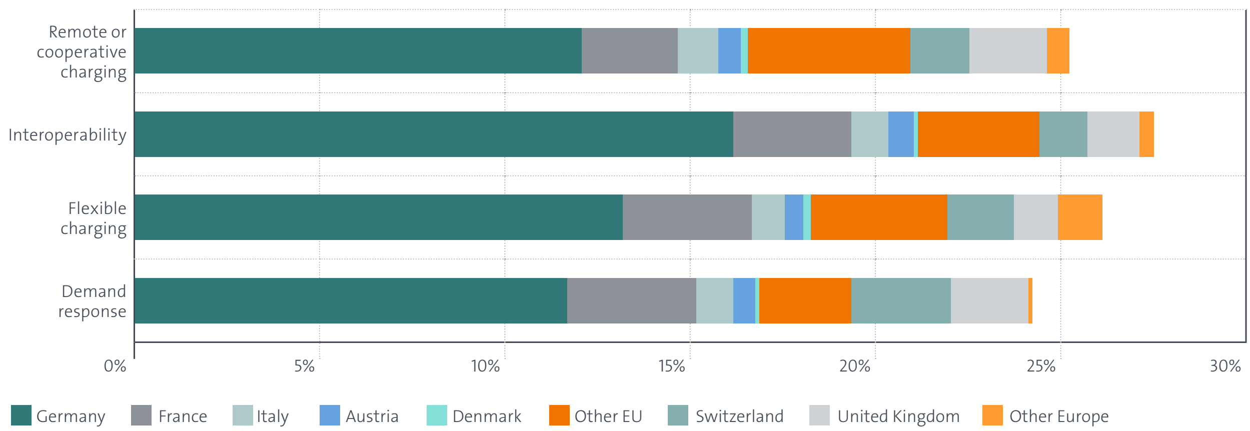


Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Figure 4.2.3

European origins of patents related to smart EV charging, 2011-2022



Note: For each technology field, the individual country shares of all IPFs are reported in the chart for the top three countries in the field.

Source: author's calculations

Box 8: Smart EV charging patent applications shift from from suppliers to OEMs

Patenting trends in smart EV battery charging show two distinct phases (Figure 4.2.1). The first is of strong growth from 2009 to 2013, followed by a decline in patenting activities to 2016. The second is a period of rapid growth starting in 2017 and extending until 2022.

While the distribution of patenting activities between regions and technologies does not differ much between these periods, the profile of the main applicants has shifted significantly.

Figure 4.2.4

Top 10 OEMs and equipment suppliers in smart grids for transport (IPFs, 2011-2022)

		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
OEM	Toyota (JP)	21	42	48	24	30	13	5	23	39	31	42	118
	Honda (JP)	4	8	14	6	7	2	10	16	32	63	59	28
	Ford Motor (US)	5	3	6	5	16	17	27	18	25	19	19	21
	Hyundai (KR)	1	4		2	9	15	17	18	11	29	22	40
	Kia (KR)	1	3		1	3	3	5	13	10	29	22	40
	General Motors (US)	11	14	10	8	5	2	2	9	7	8	4	9
	Nissan (KR)	3	7	10	19	6	1	3	2	2	5	4	6
	BMW (DE)	4	2	1	5	4	3	8	14	6	4	5	8
	Audi (DE)	2	2	3	4	1		2	12	14	5	5	7
	Volkswagen (DE)			4	3	4	5	3	3	3	5	8	4
Equipment suppliers	Panasonic (JP)	18	24	28	30	13	5	3	1	11	18	32	23
	Siemens (DE)	11	27	18	15	10	7	7	4	11	6	11	9
	LG Electronics (KR)	5	2	7	5	8	11	7	7	12	14	14	7
	Samsung Electronics (KR)	1	3	6	10	7	3	4	4	8	13	15	13
	Bosch (DE)	5	4	7	10	5	10	4	7	7	5	6	9
	Denso (JP)	8	23	6	8	6	2	3		5	9	3	2
	Hitachi (JP)	6	12	13	9	3	1	2	6	8	7	2	4
	Mitsubishi Electric (JP)	1	8	6	9	4	6	7	1	8	4	8	2
	General Electric (US)	1	32	13	4	3	4	1	2	1	1		
	Qualcomm (US)	2	6	3	11	15	9	4	1	3	1		

EU27 | Japan | R. Korea | United States

Source: author's calculations

Figure 4.2.4 shows the trend in patenting activties by the top ten original equipment manufacturers (OEMs) and equipment suppliers over the period 2011-2022. It shows a strong presence of Japanese companies in both categories: Toyota and Honda top the ranking of OEMs, with Nissan also featuring in the top ten; the list of equipment suppliers features Panasonic in first place, as well as Denso, Hitachi and Mitsubishi Electric. The rest of the ranking consists of five German companies, four US companies, and four Korean ones. No Chinese applicant features.

Figure 4.2.5

Top 10 OEMs versus equipment suppliers by segment of transport technologies (IPFs, 2011-2015 versus 2018-2022)

Source: author's calculations

Interestingly, the trajectories of OEMs and equipment suppliers diverge significantly over time. Indeed, the number of IPFs posted by equipment suppliers tend to decline, whereas a subset of leading OEMs (Toyota, Honda, Ford, Hyundai, Kia and to a lesser extent BMW and Audi) significantly increased their patenting activities after 2017. This is even more clearly visible in Figure 4.2.5. By comparing the aggregated patenting activities of OEMs and equipment suppliers over two five-year periods, this Figure highlights the shift in innovation activties away from suppliers and towards OEMs in all segments of smart EV charging technologies. This demonstrates how OEMs have made these technologies a strategic priority in recent years.

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