Innovation in batteries and electricity storage

A global analysis based on patent data | September 2020

Europäisches Patentamt
European Patent Office
Office européen des brevets

iea
International Energy Agency

Foreword

With this report, the European Patent Office (EPO) is teaming up for the first time with the International Energy Agency (IEA) to offer key insights into patent trends in high-value inventions in the field of electricity storage. Because patents are filed many months, or even years, before products appear on the market, patent information is an early indicator of which technologies could be poised to play ground-breaking roles in the future.

As the patent office for Europe, the EPO is positioned at the forefront of technical progress. Thanks to our unique access to the world's largest collection of patent and non-patent literature, the EPO can produce cutting-edge business intelligence on the very latest technological trends. Our patent classification scheme for climate change mitigation and adaptation technologies is just one example of the high-quality, specialised data that we provide. With millions of patent documents classified across a wide variety of fields, it has become a widely-used standard for monitoring progress in green technologies across the world.

Drawing on the IEA's unparalleled expertise in the field of energy enables us to go one step further by leveraging patent information to zoom in on innovation in this strategic domain. The data produced by our two organisations are designed to address the information needs of decision makers in the public and private sectors. By providing detailed insights into emerging trends, this data will help innovators in the sector get ahead of the technology curve.

Our first joint report provides an overview of the innovation landscape in the booming electric storage industry. Specifically, we reveal that patent filings in batteries and electricity storage have soared over the past ten years, at an annual growth rate of 14% versus just 3.5% on average [i] - highlighting a burst of innovation in the sector and a global battery technology race.

The report bears testimony to the challenge that electricity storage represents for energy transition. In view of rising demand for electric mobility and a growing dependence on the renewable energy supply to mitigate climate change, considerable technological progress is being made to find ways of storing massive amounts of electricity at affordable prices.

In this context patent information proves a critical source of intelligence. I am therefore delighted that our new co-operation with the IEA will give decision-makers unparalleled data and analyses on innovative solutions to meeting the clean energy needs of industry and society as a whole.

António Campinos
President, European Patent Office

i From 2008-2018

Foreword

The relaunch of the International Energy Agency's (IEA) flagship *Energy Technology Perspectives* series earlier this year highlighted that the world's energy sector can only reach net-zero emissions through a significant and concerted push to accelerate innovation. The crisis brought about by the Covid-19 pandemic has helped to move this message higher up the policy agenda as governments have sought to boost economic growth, create jobs and reorient recovery towards clean energy transitions.

The IEA's projections for the future of global energy underscore the critical and growing importance of developing better and cheaper electricity storage. In our S*ustainable Development Scenario*, which maps out a path to meeting key international energy and climate goals, close to 10 000 gigawatt-hours of batteries across the energy system and other forms of energy storage are required worldwide by 2040 – 50 times the size of the current market. This would enable the world to meet more of its energy needs through clean electricity, the supply of which does not always match the location and time of demand.

However, energy storage – which is a critical technology – is currently not on track to achieve the levels called for in the *Sustainable Development Scenario*, both in terms of its deployment and its performance. This means that we are failing to put in place the infrastructure that will be needed for renewable energy to expand more rapidly.

Clean energy innovation policy will have a crucial role to play in reconciling these divergent trends. But for it to be effective, it needs to be based on robust data. This timely report is an excellent example of the value of reliable numbers and rigorous analysis on new technologies for which claims and counter-claims can sometimes obscure the reality. For example, it provides important statistics on countries' technological advantages that can support critical decisions about funding for energy storage projects.

This report is also notable for being the first output of a new cooperative relationship between the IEA and the European Patent Office (EPO). The EPO's expertise on patent analysis is world class, and I am delighted that by working together our two organisations are now in a stronger position to understand key energy innovation trends.

To help decision-makers guide vital public and private investments in cutting-edge technologies – whether at the laboratory stage or to overcome barriers to market uptake – measuring progress is critical. I believe that the analysis in this report, undertaken in close cooperation with the EPO, is a significant contribution to sustainable and secure clean energy transitions globally.

Dr. Fatih Birol
Executive Director
International Energy Agency

Executive summary

Today, batteries are already ubiquitous in our phones, laptops and cars, but growth in the markets for electric vehicles and stationary electricity storage will make them even more important in the future. Modern societies are increasingly dependent on reliable supplies of electricity for a wide array of uses at the location and time when it is needed. This expansion of electricity in the supply of energy has a key role to play in the clean energy transition, because electricity can be readily generated from renewable sources and produces no emissions at the point of use.

Yet electricity is unlike other fuels because almost all of the electricity we use is generated just moments beforehand. With the rising importance of electric mobility on the demand side, and of variable renewable energy sources (i.e. dependent on weather conditions) on the supply side, temporal balancing has become a key challenge. According to the Sustainable Development Scenario (SDS) of the International Energy Agency (IEA), close to 10 000 GWh of batteries across the energy system and other forms of energy storage will be required annually by 2040, compared with around 200 GWh today. To address this challenge, considerable progress is needed to find ways of storing electricity in large quantities and at a price affordable to suppliers and consumers.

Against this background, technology innovators have been devoting considerable effort to identifying commercially viable means of electricity storage in order to achieve cost-effective balancing over time. They are also seeking to expand the portfolio of end-use applications in a number of ways. In theory, storage can be paired with any energy service, including for portable electronics and their ever-expanding uses and even for heating, with improvements to heat pumps making the combination of solar and electric heating more viable for households. In the area of transport, batteries are a heavy and costly way of storing energy on board vehicles, especially trucks and aircraft, but as they become cheaper they are increasingly attracting widespread interest. As such, better energy storage technologies can open up opportunities to integrate larger quantities of renewable energy into the energy system as a whole, thus helping to replace fossil fuels in a variety of applications.

These challenges help to explain the rapid and sustained increase in electricity storage innovation documented in this report, as well as the need for further innovation over the coming years. The data presented in this report show trends in high-value inventions for which patents have been filed on an international scale. They provide insights into which countries and companies are leading the way in developing electricity storage technologies and thus may be best placed to deliver much-needed improvements in this area in the near future. The data also show not only how the types of electricity storage application attracting the most interest from companies and inventors have changed, but also which applications and technologies are gathering momentum and could be poised to play breakthrough roles in the future.

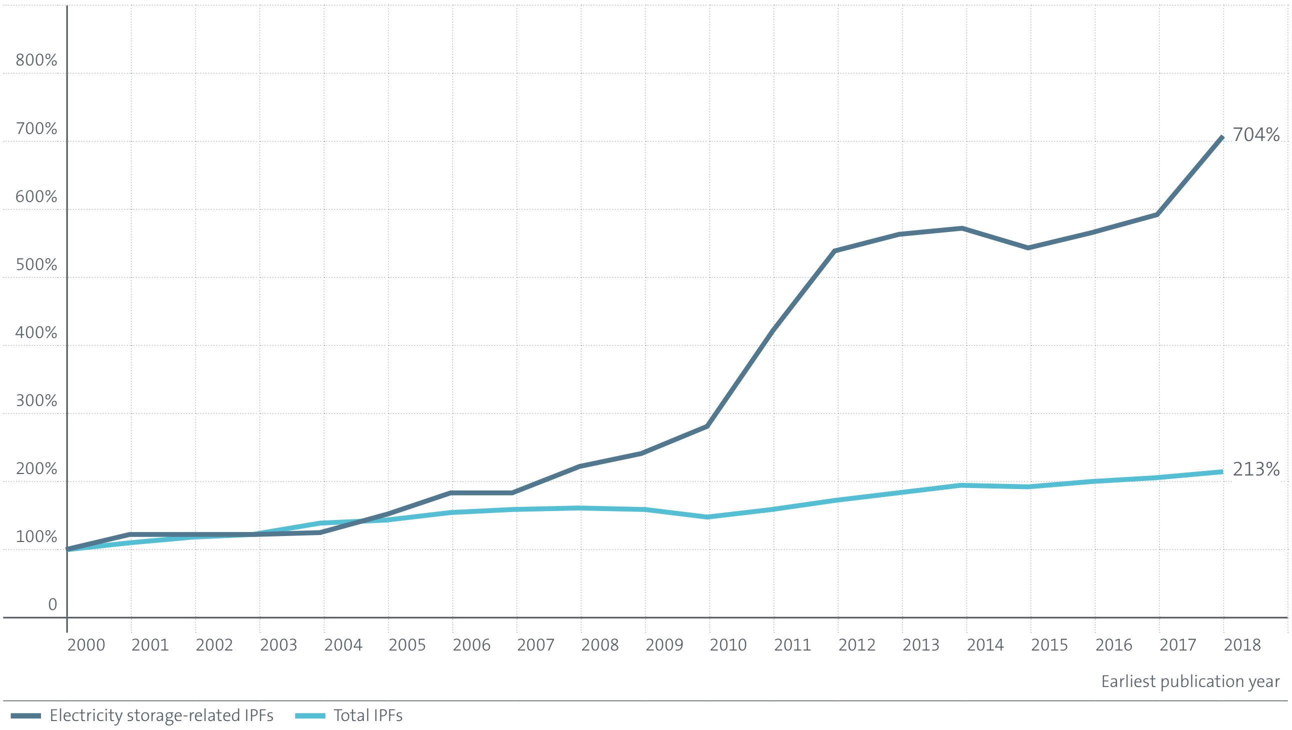
Highlight 1: *Patenting activity in electricity storage has grown much faster than patenting activity in general over the past decade, indicating a burst of innovation in this area, spearheaded by lithium-ion (Li-ion) batteries, in particular for electric vehicles.*

More than 7 000 international patent families (IPFs) related to electricity storage were published in 2018, up from 1 029 in 2000. [1] While a consistently upward trend has been observed since 2000, there has been a notable acceleration since 2005, with an annual growth rate of 14% until 2018, compared with just 3.5% on average for all technology areas across the economy (Figure E1). This reflects in small part the use of batteries in an ever-expanding array of personal devices and tools, but the findings of this report point to a much larger driver in recent years: clean energy technologies, in particular electric mobility.

1 Each IPF covers a single invention and includes patent applications filed 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.

Figure E1

Trends in electricity storage innovation, 2000-2018



Source: European Patent Office

Electrochemical inventions (i.e. batteries) account for 88% of all patenting activity in the area of electricity storage, far outweighing electrical (9%), thermal (5%) and mechanical (3%) solutions. Although all of these fields experienced rapid growth up to 2012, since this time growth in innovation has only continued in battery technology, thereby underlining the dominance of batteries in the recent electricity storage innovation landscape.

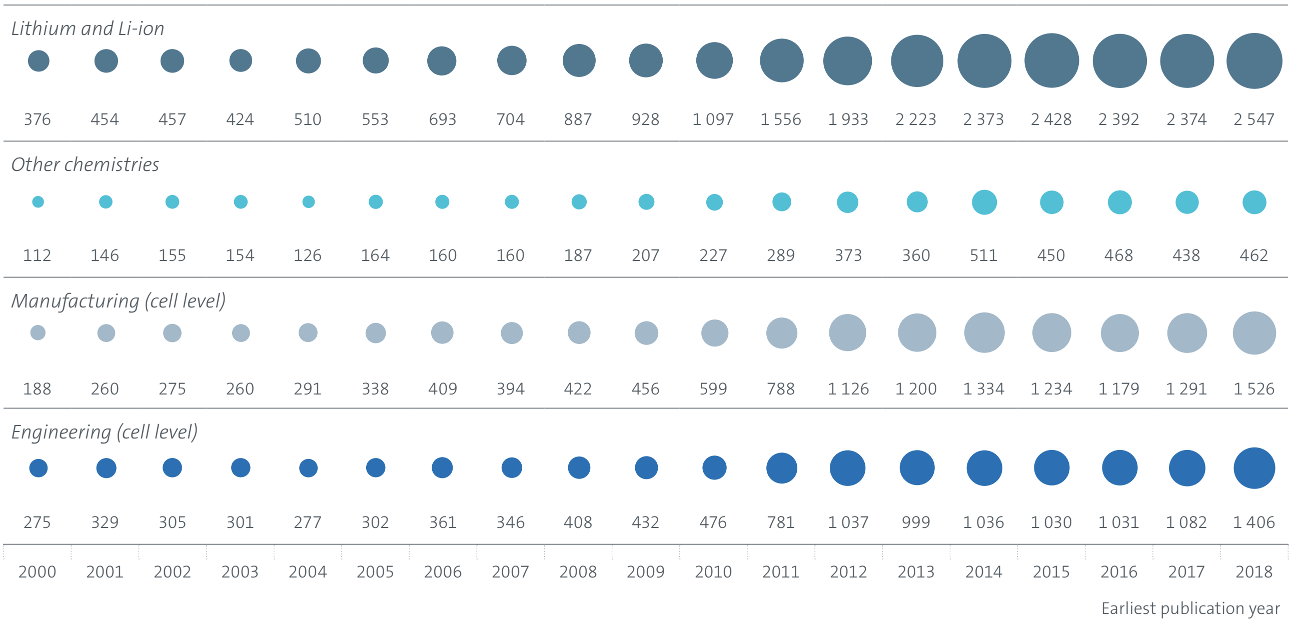
Within the area of battery technologies, patenting activity has been on the rise for most key technology variants, including lead acid, redox flow and nickel. It is Li-ion technology, however, which has been fuelling innovation in battery technologies since 2005 (Figure E2). Li-ion is currently the dominant technology for portable electronics and electric vehicles. In 2018, innovation in Li-ion cells was responsible for 45% of patenting activity related to battery cells, compared with just 7.3% for cells based on other chemistries. Around 48% were related to inventions not specific to a particular chemistry.

These trends in patenting rates coincide with price movements. Since 1995, Li-ion battery prices for consumer electronics have fallen by more than 90%. For electric vehicles, Li-ion prices have decreased by almost 90% since 2010, while for stationary applications, including electricity grid management, they have dropped by around two-thirds over the same period. These cost reductions are partly due to new chemistries, mostly adjustments to the composition of the battery cathode, as well as economies of scale in manufacturing. However, as shown clearly in the patent statistics, innovative manufacturing processes have also played a key role. Patenting activity in the manufacturing of battery cells and cell-related engineering developments has grown threefold over the last decade (Figure E2). Together, these two fields accounted for nearly half (47%) of all patenting activity related to battery cells in 2018, a clear indication of the maturity of the industry and of the strategic importance of efficient industrialisation for mass production.

Battery cells are typically assembled into battery packs that are configured to deliver the desired voltage, capacity or power for the end use in question. While different applications, such as mobility solutions and smartphones, can use the same cells, the packs differ somewhat. Therefore, patenting activity in battery packs provides insights into the target applications of innovators in this area. In recent years, patenting activity in battery packs has been rising faster than that related to battery cells. This indicates a level of technological maturity, as attention has shifted away from the basic science behind this technology and towards ways to optimise its delivery to cater for highly demanding commercial markets.

Figure E2

Number of international patent families related to battery cells, 2000-2018

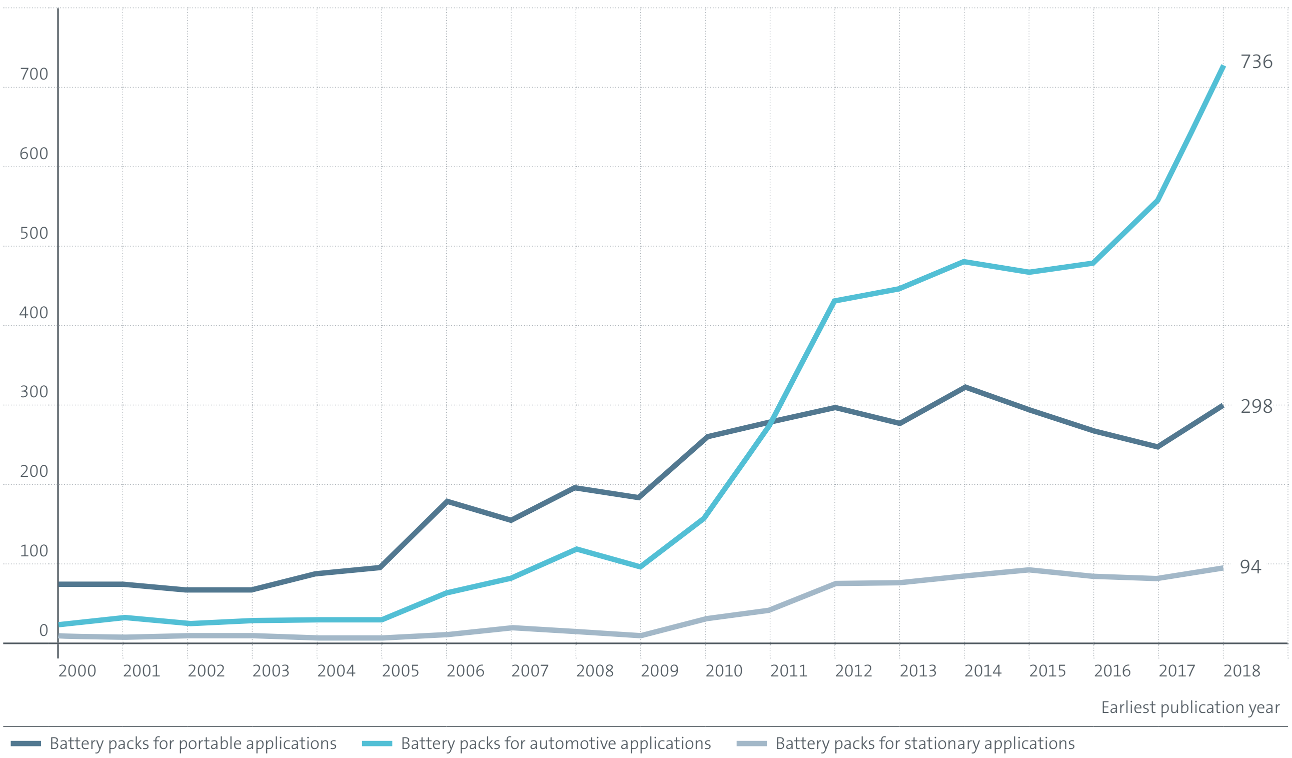


Source: European Patent Office

The data show that electric mobility has been behind the growth in inventive activity in battery packs, especially over the last decade (Figure E3). Prior to this time, from the mid-2000s to 2010, portable applications (typically in consumer electronics) were the main driver. In absolute terms, patents targeting electric vehicles overtook consumer electronics in 2011 and, while patents for portable electronic battery pack designs levelled off after this time, electric vehicle patents continued to grow with even more vigour. Innovation in stationary applications has been growing more slowly, recording just two years of accelerated growth in 2010 and 2011. However, this is still testament to the versatility of Li-ion technology and highlights the synergies between these different applications, with improvements to one application likely to have a positive effect on other applications. This is shown by the declining price trends seen for all applications. As a result, efforts to improve Li-ion technology for portable applications have had positive spillover effects on electric vehicle applications, nudging battery price and performance into an acceptable range for the first electric car buyers. For example, the Tesla Roadster, the first highway legal serial production all-electric car to use Li-ion battery cells, was launched in 2008. Over the last decade, improvements to battery packs catering for the wide range of all-electric cars and plug-in hybrid cars on the market have had positive spillover effects on stationary applications, many of which can reuse modified vehicle batteries once they have reached the end of their useful lives within vehicles.

Figure E3

Number of international patent families related to applications for battery packs, 2000-2018



Source: European Patent Office

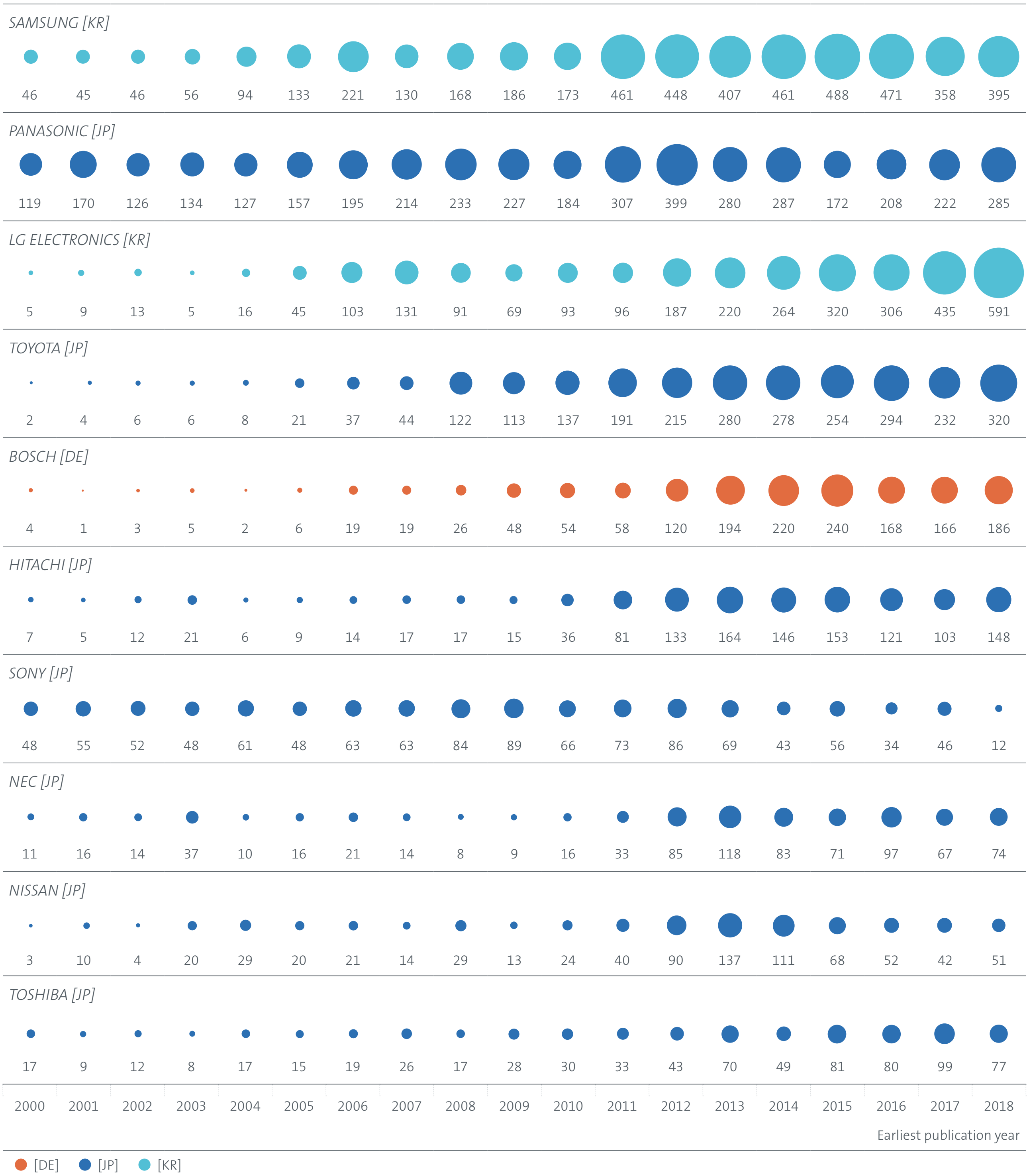
Highlight 2: *Japan and the Republic of Korea are leading the global battery technology race, pushing other countries to develop competitive advantages in specific parts of the battery value chain.*

Of the top ten global applicants behind IPFs related to batteries, nine are based in Asia (Figure E4). They include seven Japanese companies, led by Panasonic and Toyota, and two Korean companies, Samsung and LG Electronics. Bosch, a German company, is the only non-Asian applicant to feature in the ranking. From 2014-2018, Japan alone was home to the inventors of 41% of all Li-ion patenting activity.

While Japanese companies such as Panasonic and Sony are long-established leaders in this field, other top applicants have only ramped up their innovative activities in the past decade, coinciding with the increase in patenting activity related to Li-ion use in vehicles. Over this time, companies like LG Electronics, Toyota, Nissan and Bosch have rapidly increased their inventive activity in the area of batteries, with a focus on automotive applications. Samsung also has a major presence in vehicle batteries, but its patenting growth has been more focused on portable electronics.

Figure E4

Number of international patent families by top ten battery technology applicants, 2000-2018



Source: European Patent Office

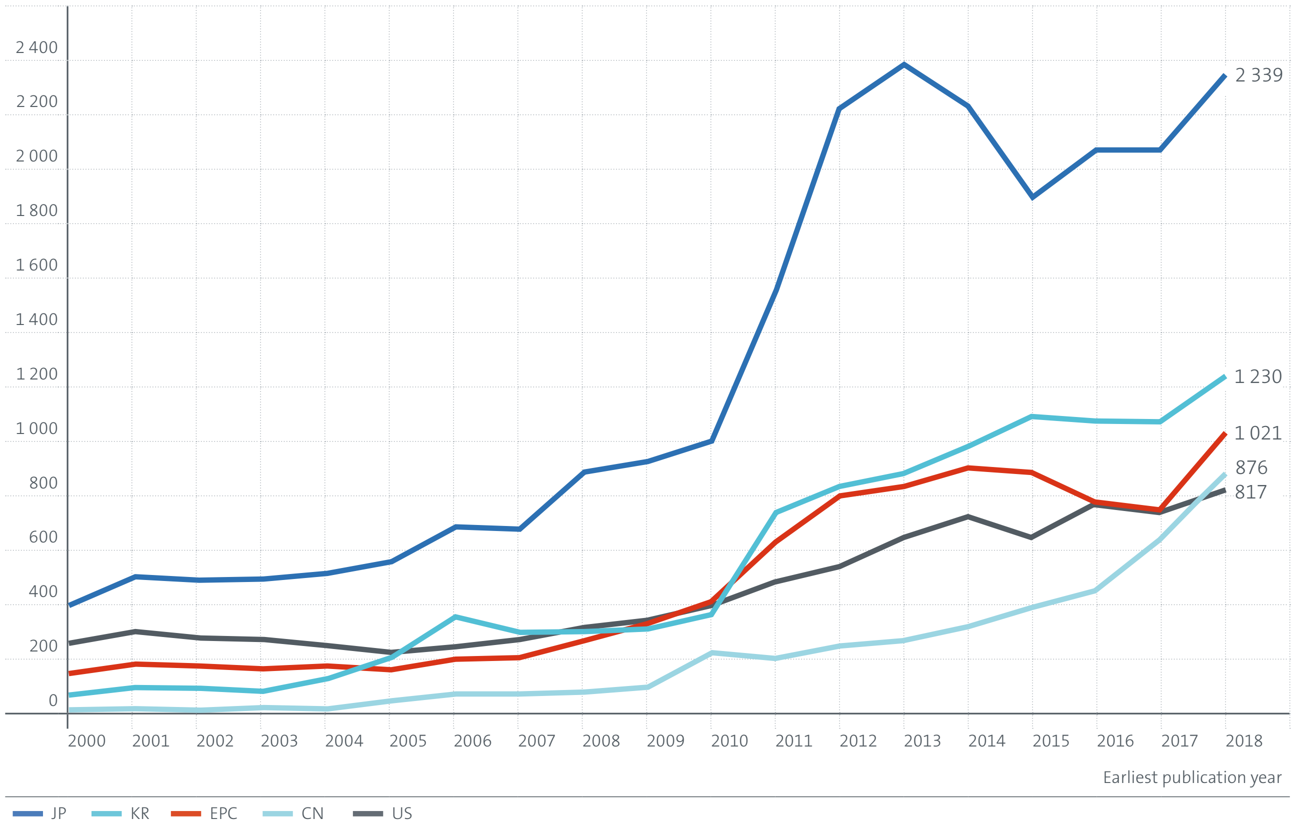
A broader analysis of the geographic origins of IPFs confirms Japan's strong leadership in battery technology (Figure E5). Japan was already paving the way worldwide in the 2000s, but further reinforced its lead at the turn of the last decade. Japanese-based companies and inventors generated more than one third of all IPFs related to batteries in 2018.

Despite trailing somewhat behind Japan, the Republic of Korea, Europe, the United States and the People's Republic of China have also contributed significantly to the global increase in battery innovation observed since the mid-2000s. This growth has been accelerating most in the Republic of Korea, which overtook Europe and the United States in 2010-2011, taking second place in the rankings after Japan in 2018. In Europe, innovation in electricity storage is dominated by Germany, which alone accounts for more than half of IPFs originating from Europe. In contrast to Japan, the Republic of Korea and China, the battery innovation ecosystems seen in Europe and the United States involve a larger proportion of IPFs from small companies and universities.

Chinese inventors are responsible for a notable national increase in electricity storage innovation over the last decade. In the field of batteries, the country (China) has almost caught up with Europe in 2018 and now makes a similar contribution to the United States. This mirrors China's contribution to electric vehicle manufacturing in recent years. In 2011, 5 000 electric cars were sold in the country, representing 11% of the global electric car market. With 1.1 million cars, Chinese sales accounted for 50% of the global market in 2019. BYD, a battery and electric vehicle manufacturer, is the leading global producer of electric buses and sells a similar number of electric cars to Tesla. By contrast, Japan's leadership in battery technology has not translated into a large domestic electric car market, representing just 2% of the global market in 2019, although Li-ion batteries are offered in some non-plug-in hybrids like the Toyota Prius. The Republic of Korea has a similar electric car market, but is a leader in stationary batteries for utility-scale power grid services and behind-the-meter applications in buildings.

Figure E5

Geographic origins of international patent families in battery technology, 2000-2018



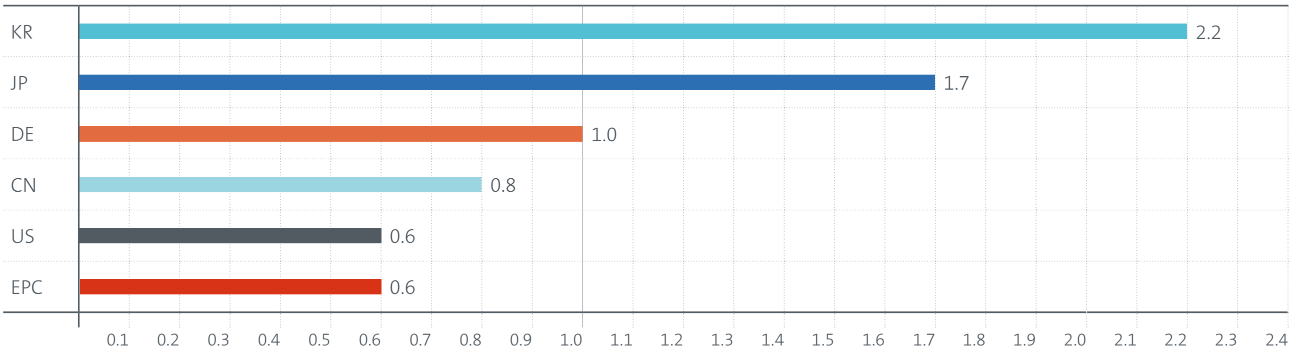
Source: European Patent Office

For governments seeking to understand their country's comparative advantage in battery technology in more detail, the revealed technological advantage (RTA) index indicates a country's specialisation in terms of battery technology innovation relative to its overall innovation capacity.[2] An RTA above one reflects a country's specialisation in a given technology. Conversely, countries with a lower RTA in a given technology face a bigger challenge in developing the technological leadership needed to add significant value to their economy in future decades. Given the level of technological detail in this report, the data provided may also reveal niches in which countries can build on their relative strengths even if their RTA is less than one at a higher level of aggregation.

For 2014-2018, this indicator reveals stark contrasts between regions leading the way in the race for innovation in battery technology (Figure E6). The Republic of Korea and Japan stand out with a very strong specialisation in this domain, while the United States, China and European countries are less specialised. Among European countries, Germany stands out with an RTA of close to one for 2014-2018, a significant rise compared with its RTA of 0.7 in 2000-2013, which was close to the average of all European countries (contracting states to the EPC).

Figure E6

Revealed technological advantage of global innovation centres related to battery technology, 2014-2018



Source: European Patent Office

Note: EPC countries means the 38 contracting states to the European Patent Convention. Germany is also reported on separately owing to its significant individual contribution to innovation in battery technology.

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

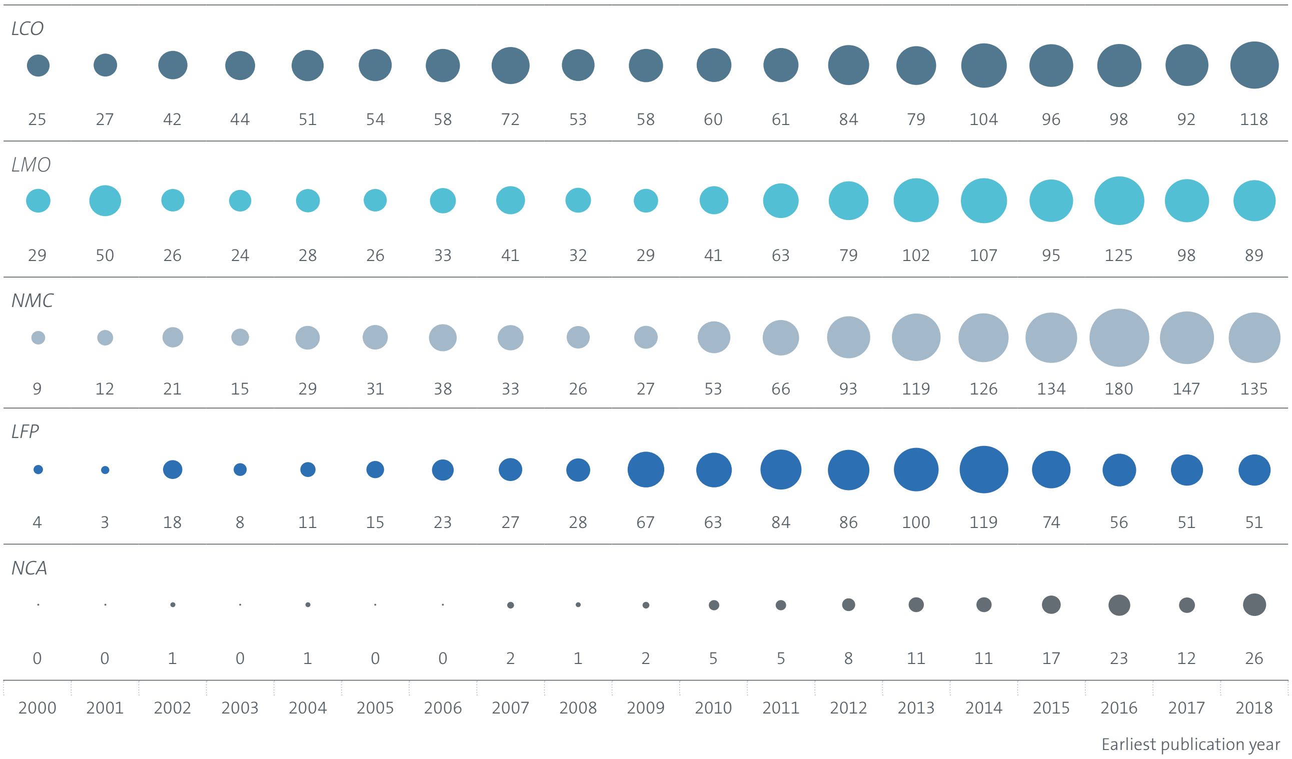
Highlight 3: *NMC cathode chemistry has seen the most innovative breakthroughs related to Li-ion batteries since the launch of mass-market electric vehicles, but potentially disruptive competitors are emerging outside the big companies and with more regional variation.*

In terms of patenting activity, Li-ion is currently the leading battery technology, accounting for 38% of all battery-related IPFs in 2010-2018. The high level of inventive activity related to Li-ion technology is due in part to the different performance criteria of different battery applications on the one hand, and to the current lack of a dominant battery cell design for each application on the other. For example, smartphones, power tools, electric cars and utility-scale stationary batteries all have different requirements and tolerances for energy and power density, durability, material costs, sensitivity and stability. While some of these features can be improved through innovation in manufacturing and engineering, innovation is primarily seen through changes to the battery cathode, anode and electrolyte, the primary elements of a battery cell through which electricity is stored and conducted.

Inventive competition has mostly been focused on Li-ion battery cathodes, as they are the limiting factor in determining energy density and cost reductions. Energy density – the amount of energy that can be stored per unit of battery volume – is very important for portable devices, for example for ensuring that smartphones still only need to be charged once a day despite the increasing energy demands of their applications. However, energy density is more important still for electric vehicles, which must match the performance and costs of internal combustion engine vehicles.

Figure E7

Number of international patent families by type of lithium-ion cathode materials, 2000-2018



Source: European Patent Office

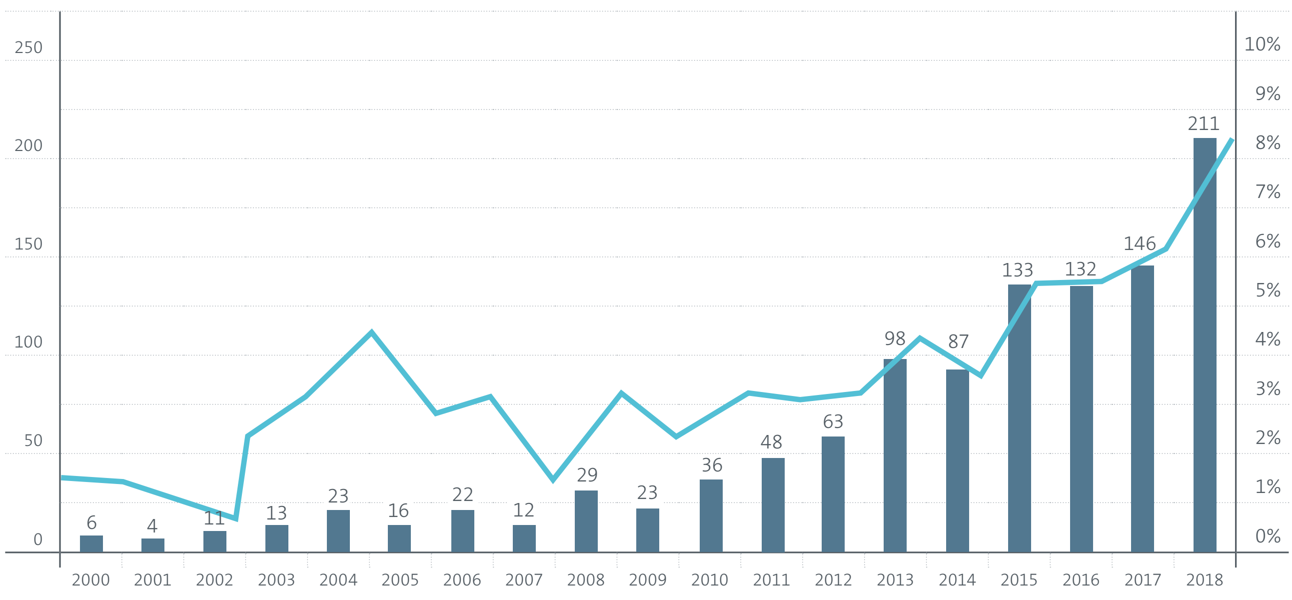
The first serial production electric cars, launched just over a decade ago, used the same cathodes as those dominating the field of consumer electronics: lithium cobalt oxide (LCO) and lithium manganese oxide (LMO). Since then, the focus has moved onto other chemistries, including NMC, lithium iron phosphate (LFP) and, more recently, lithium nickel cobalt aluminium oxide (NCA), owing to a shift in technical challenges away from maximising energy density and stability and towards improving specific energy (energy per unit mass), durability, power output, charge/discharge speed and recyclability. This trend can be seen in the patenting data (Figure E7): LCO patenting activity was double that of NMC in 2005, but overtaken by NMC in 2011, with NMC patenting activity rising by 400% between 2009 and 2018. By way of comparison, over the same period LCO patents rose by 200%. Today, NMC is generally regarded as having the best potential for electric vehicles in the near term, and researchers are continuing to work on ways to reduce the proportion of cobalt, which largely determines overall cost and sustainability.

However, NMC itself is expected to be displaced in due course, with NCA in particular increasingly in the spotlight as a promising alternative. NCA chemistry is based on the same chemistry behind NMC, and NCA batteries are already being used by Panasonic and Tesla for electric vehicles. Other companies such as Tesla and BYD are betting on improved LFP-based batteries for their vehicles. The level of patenting activity in this area remains limited, but had increased from almost zero before 2010 to levels closer to those of more established cathode chemistries by 2018.

Inventive activity is also focused on electrolytes, with efforts underway to find alternatives to the liquid or polymer gel electrolytes used in current Li-ion batteries, which pose a flammability risk. Solid-state electrolytes can provide an alternative featuring a high level of specific energy and high degree of stability, but they are currently expensive. To address the remaining technical challenges, patenting activity in this area has been growing by an average of 25% per year since 2010 (Figure E8). In 2018 it represented more than 8% of all patenting activity in Li-ion technology, compared with 3% in 2010. Thanks to progress in this domain, commercial applications of solid-state electrolytes are anticipated in the next decade.

Figure E8

IPFs related to solid-state lithium-ion technology, 2000-2018



Count of solid–state IPFs (left axis) Solid-state IPFs as share of Lithium and Li-ion (right axis)

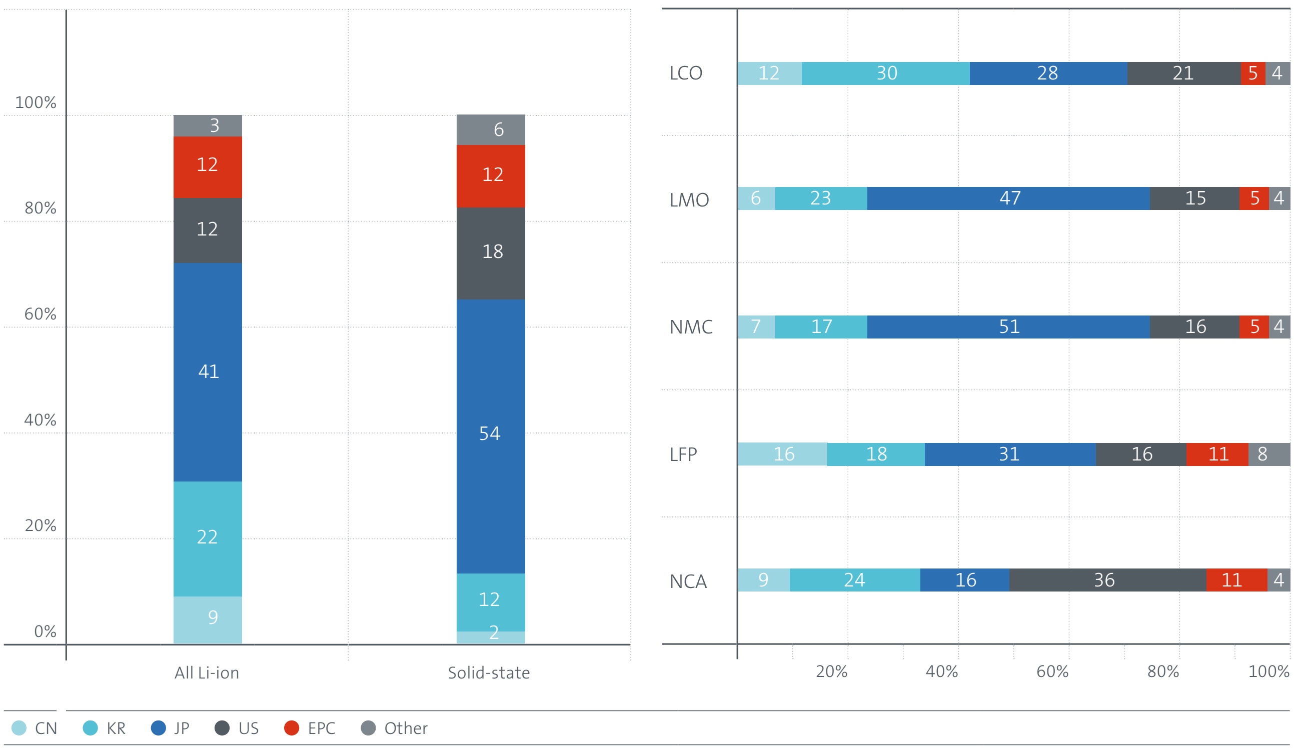
Source: European Patent Office

Looking at the geographic origins of IPFs, Japan is dominant in solid-state batteries, which accounted for 54% of its IPFs in 2014-2018 (Figure E9). The United States (18%) and the EPC contracting states (12%) also performed better in this field, with equal or larger shares of IPFs related to solid-state batteries than to Li-ion technology overall. However, this is not the case for the Republic of Korea or China, which have relatively modest shares of IPFs in the area of solid-state batteries (12% and 2%, respectively), despite accounting for 22% and 9%, respectively, of all IPFs related to Li-ion technology in 2014–2018.

At the level of cathode materials, Japan has a strong lead in terms of IPFs in the dominant fields of LMO (47%) and NMC (47%), but stands on a par with the Republic of Korea when it comes to LCO, each country accounting for around 30% of IPFs in this area (see Figure 9). However, the competition for innovation appears to be more open with regard to the emerging LFP and NCA chemistries. Responsible for 31% of IPFs related to LFP, Japan is slightly less dominant in that field, where the Republic of Korea, the United States and China are all important contributors (each accounting for around 16% of IPFs). In the case of NCA, the US is the clear leader with 36% of the related IPFs, followed by the Republic of Korea with 24% and Japan with just 16%. The share of inventions from European countries is relatively modest in all fields, but is twice as high in the emerging fields compared with the more established ones; it generated 11% of IPFs in both LFP and NCA.

Figure E9

Geographic origins of international patent families in Li-ion technology, 2014-2018

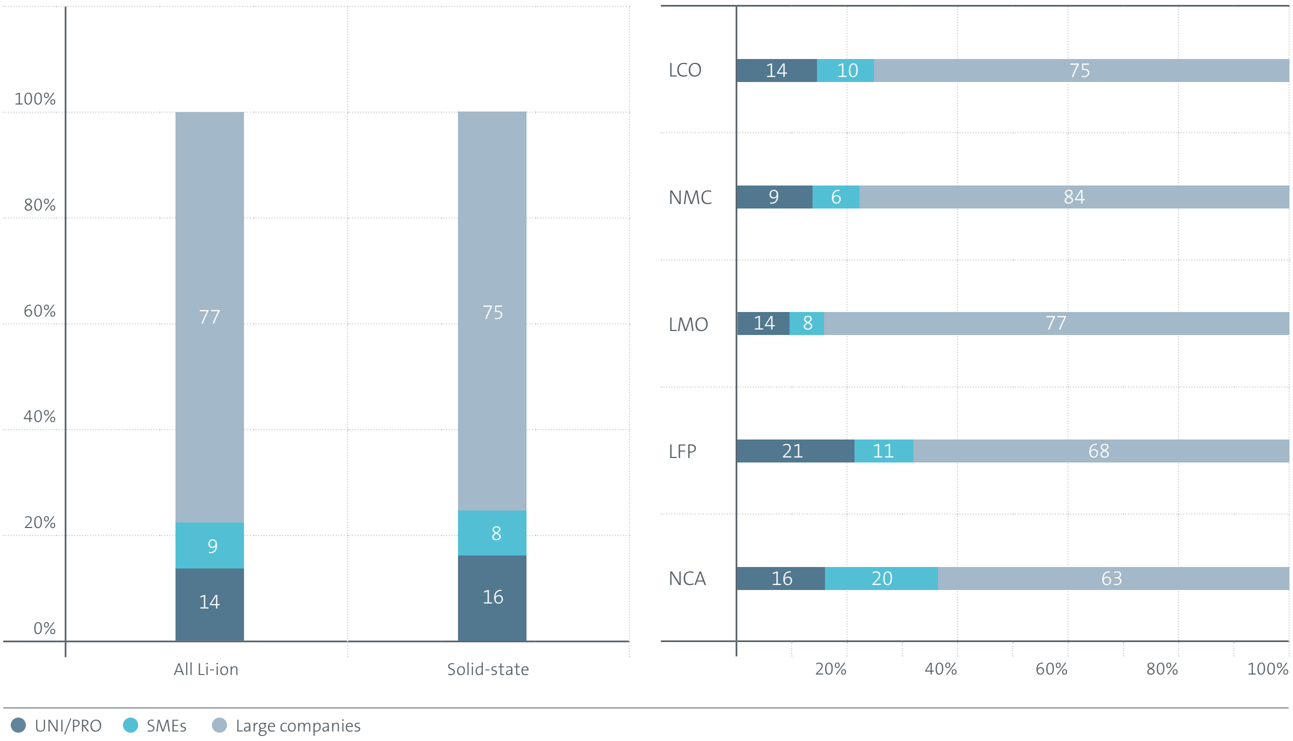


Source: European Patent Office

While 77% of innovation in Li-ion technology in general, as measured by patenting activity, arises in large companies, small and medium-sized enterprises (SMEs), universities and public research organisations (UNI/PRO) play a more important role in novel cathode chemistries such as LFP and NCA (Figure E10). With LFP accounting for 21% of IPFs from 2014-2018, universities and public research organisations are key contributors in that field. Small companies, especially in the United States, are most relevant when it comes to NCA (20%), which is the only chemistry in which their share of IPFs exceeds that of universities and public research organisations. These high shares held by small applicants provide an insight into the relative maturity of the competing options. In the early days of LCO and LMO cathodes it was universities that led the way, before large corporations, mostly in Japan, took over the development of the batteries as they started to be integrated into consumer products like camcorders in the early 1990s.

Figure E10

Applicant profiles in emerging lithium-ion technology, 2014-2018



Source: European Patent Office

Contents

List of tables and figures

Tables

Figures

List of abbreviations

BMS	battery management system(s)
CAES	compressed-air energy storage
CCUS	carbon capture, utilisation and storage
CEA	French Alternative Energies and Atomic Energy Commission
CPC	Cooperative Patent Classification
EPO	European Patent Convention
EU	European Union
GHG	greenhouse gas
GUO	global ultimate owner
IEA	International Energy Agency
IPF	international patent family
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
Li-ion	lithium-ion
LMO	lithium manganese oxide spinel
LTO	lithium titanate oxide
NCA	lithium nickel cobalt aluminium oxide
NMC	lithium nickel cobalt manganese oxide
PSH	pumped storage hydropower
R&D	research and development
RTA	revealed technological advantage
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario

Country codes

AT	Austria
CH	Switzerland
CN	People's Republic of China
DE	Germany
FR	France
GB	United Kingdom
IT	Italy
JP	Japan
KR	Republic of Korea
NL	Netherlands
SE	Sweden
US	United States
TW	Chinese Taipei

1. Introduction

1. Introduction

Modern societies depend on reliable supplies of electricity, readily available at the location and time it is needed, for everything from heating, lighting, cooking and entertainment to industrial and medical equipment and, increasingly, transport. Yet electricity is unlike other fuels that we use every day, because almost all the electricity needed is generated just moments beforehand. This is because it is expensive and difficult to store in large quantities – over the past century, storage has largely been limited to pumping water to uphill reservoirs to create a reserve supply of power for use during shortages.

As a crucial energy carrier for a low-carbon energy system, electricity has a number of key advantages: it can be readily generated from renewable sources, such as solar and wind, it does not produce any emissions at the point of use, and it is extremely versatile in its applications. In theory, it can be used for any energy service, and improvements to devices like heat pumps are making it even more competitive.

However, it also has some major drawbacks, which are currently being addressed by technology innovators. First, to make use of solar and wind power, which are key renewable energy sources for the future, the sun needs to be shining and the wind needs to be blowing, and the times at which this happens may not be well matched with demand. Second, existing ways of storing electricity – to decouple the time of generation from the time of use – are not appropriate or cost-effective for all situations. Batteries provide a flexible solution that allows electricity to be used without being connected to the power grid, but they remain a generally heavy and costly option for storing energy on board vehicles, especially trucks and aircraft.

1.1 Aim of the study

Better batteries and other energy storage technologies can open up opportunities to replace unabated fossil fuels in a variety of end-use applications and integrate more renewable energy into the energy system (International Energy Agency (IEA), 2019a; IEA, 2020a). Low-cost, reliable, responsive electricity storage with a high power output can also have a positive impact on power grid management costs and reduce the need for synchronous generators that regulate electricity frequency and are usually powered by fossil fuels.

These trends and needs help to explain the rapid and sustained increase in innovation in batteries documented by this report. Aimed at decision-makers in both the private and the public sector, this report is a unique source of intelligence on the innovation trends behind batteries, drawing on the latest information available in patent documents and the combined expertise of IEA analysts and European Patent Office (EPO) examiners.

Patent information provides robust statistical evidence of technical progress, as companies and inventors make use of the temporary exclusivity conferred by patent rights to market their innovations and, in doing so, recoup their research and development (R&D) investments. The data presented offer insights into which countries and companies are leading the way in the development of electricity storage technologies and are therefore likely to be well placed to deliver much-needed improvements in this area in the near future. In addition, the data show how the types of electricity storage application attracting the most interest from companies and inventors have changed, as well as which applications and technologies are gathering momentum and could be poised to play breakthrough roles in the future.

What's more, trends in electricity storage patenting are particularly relevant given the current circumstances. As the impact of the Covid-19 pandemic is felt across the world, with many countries facing an uncertain economic future over the next few years, governments are looking to boost scalable, clean and technology-intensive sectors (IEA 2020b). Electricity storage, and battery technology in particular, is one such technological area (IEA, 2020c). Indeed, support for electricity storage was high in the United States following the financial crisis, with the government allocating economic stimulus funds to the area in 2009-2012. Patent data can help to inform governments about their comparative advantage at different stages of a technology's value chain and shed light on innovative companies and institutions that may be in a position to contribute to economic recovery and long-term sustainable growth.

1.2 Outline of the study

Chapter 2 outlines the role played by batteries and other electricity storage technologies in the IEA's Sustainable Development Scenarios. Chapter 3 sets out the methodology used in the study to identify inventions and map them to the different fields of technology underpinning electricity storage. Chapter 4 highlights the main innovation trends in electricity storage. Batteries are examined in more detail in chapters 5 (patent applications) and 6 (global distribution of innovative activities). Chapter 7 analyses recent technology trends in lithium-ion (Li-ion) batteries, while chapter 8 looks at two other emerging storage technologies: redox flow batteries and supercapacitors.

About the European Patent Office

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

About the International Energy Agency

The International Energy Agency provides authoritative data, analysis, and recommendations across all fuels and all technologies, and helps governments develop policies for a secure and sustainable future for all. The IEA was created in 1974 and examines the full spectrum of issues including energy security, clean energy transitions, and energy efficiency. It is a global leader in understanding pathways to meeting climate goals, reducing air pollution and achieving universal energy access, in line with the United Nations Sustainable Development Goals.
Its work on energy technology innovation spans the collection of national data on public energy R&D budgets, regular technology trend analysis and policy guidance for governments. The IEA family of countries accounts for 75% of global energy consumption, and includes 30 Member countries and 8 Association countries – Brazil, P.R. China, India, Indonesia, Morocco, Singapore, South Africa, and Thailand.

2. Batteries and electricity storage in the energy transition

2. Batteries and electricity storage in the energy transition

Batteries are already ubiquitous in our phones, laptops and cars, but growth in the markets for electric vehicles and stationary electricity storage will make them even more important in the future. This expansion of stored electricity in the supply of energy has a key role to play in the clean energy transition, because it enables the use of energy that can be readily generated from renewable sources and produces no emissions at the point of use.

2.1 Energy storage in the IEA's Sustainable Development Scenario

The IEA's Sustainable Development Scenario (Box 2.1) identifies the electrification of demand coupled with a rapid decarbonisation of electricity generation as a fundamental vector of the energy transition. Yet electricity is unlike other fuels because almost all of the electricity we use is generated just moments beforehand. With the rising importance of electric mobility on the demand side, and of variable renewable energy sources (i.e. dependent on weather conditions) on the supply side, balancing electricity when and where it is needed has become a key challenge. The storage of electricity in large quantities and at an affordable cost has a key role to play in this context, not only as an enabler of demand electrification in sectors such as electrical vehicles, but also as a means for electricity networks to accommodate a higher share of low-carbon generation technologies.

BOX 2.1

The Sustainable Development Scenario

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

The Paris Agreement has the objective of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Energy production and use is the largest source of global greenhouse gas (GHG) emissions, meaning that the energy sector is crucial for achieving this objective.

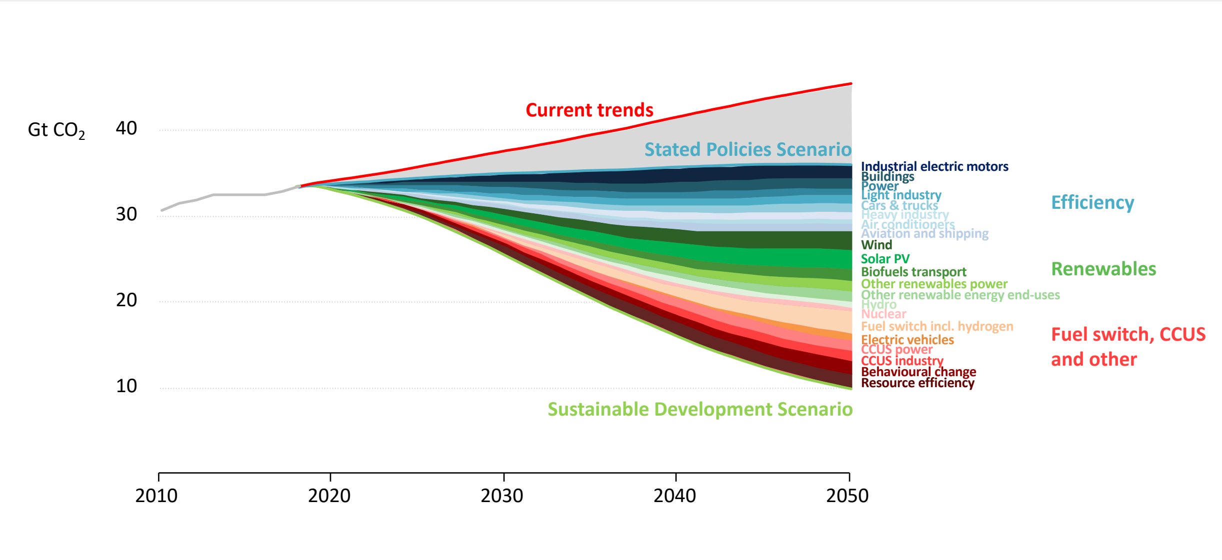
To achieve the temperature goal, the Paris Agreement calls for emissions to peak as soon as possible and reduce rapidly thereafter, leading to a balance between anthropogenic emissions by sources and removals by sinks (i.e. net-zero emissions) in the second half of this century. These conditions are all met under the SDS.

The SDS holds the increase in temperature to below 1.8°C with a 66% probability without relying on global net-negative CO_2 emissions. This is equivalent to limiting the temperature rise to 1.65°C with a 50% probability. This would result in global CO_2 emissions falling from 33 billion tonnes in 2018 to less than 10 billion tonnes by 2050, and place the world on track to achieve net-zero emissions by 2070.

Against the backdrop of this scenario, the IEA tracks the overall progress made in developing and deploying clean-energy technologies, as well as the policy framework conditions surrounding all key technologies needed to achieve the energy transition, in its annual Tracking Clean Energy Progress report (Figure 2.1). In 2020, progress in energy storage technologies was assessed as not being on course to achieve the outcomes of the SDS, following a lacklustre 2019 where grid-scale storage decreased for the first time in ten years. Electric vehicles were assessed as currently being on track – albeit starting from a low baseline and requiring continued, exponential growth over the next decade to reach an installed base of electric vehicles that is 100 times greater than today by 2040.

Figure 2.1

CO_2 emission mitigation technologies and their contribution to achieving the outcomes of the Sustainable Development Scenario



Source: IEA, World Energy Outlook 2019. Launch presentation, 2019b.

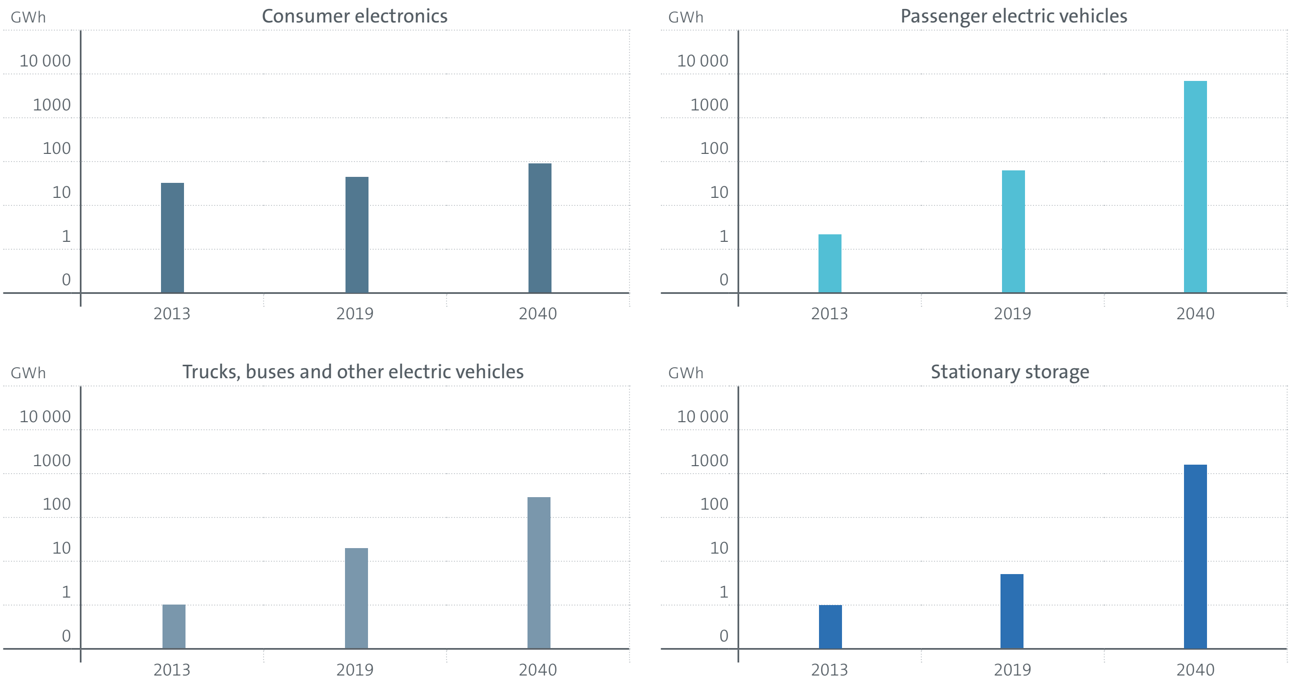
Today, the combined annual demand for batteries and other energy storage technologies that are relevant for the energy transition already stands at close to 200 GWh - with over three-quartersof these capacity additions dedicated to supplying electromobility applications (Figure 2.2).[3] Historically, consumer electronics have dominated the battery market, guiding innovation in technology design and configurations. In 2013, nearly 90% of all battery manufacturing supplied these markets. In 2017, however, electric vehicles became the largest consumers of batteries, and by 2019 their share had increased to two-thirds.

Looking ahead to 2040, the level of deployment and the range of applicability of batteries and other storage technologies expands dramatically under the SDS: nearly 10 000 GWh of batteries and other storage will be required to meet demand across all sectors. Driven by the increase in demand for flexibility to accommodate a higher share of variable renewables in the generation mix, as well as an increase in new "peak-demand" sources such as electric vehicles or electric heating and cooling, the use of energy storage in direct support of electricity grids increases 40-fold under the SDS, led by battery storage systems, which overtake all other storage technologies by 2040.

Storage and batteries in particular also play a key role in the energy transition in terms of providing access to clean energy to underserved populations. In 2020, 600 million people still have no access to electricity. According to IEA projections, renewable energy sources, in particular decentralised systems, are the cheapest way of providing access to electricity for three-quarters of those currently deprived of access. To support such deployment and use, batteries are essential. Thanks to the increasing capacities and falling costs of Li-ion batteries, stand-alone solar home systems with a solar panel as small as 50 W are an affordable way of extending the provision of basic services (lighting, mobile phone charging, fans and TV) several hours into the night in regions without reliable grid electricity, thus benefiting households and small businesses. Batteries are the key component behind new business models such as pay-as-you-go solar, where customers can lease a solar system from a provider who can control the availability of the battery as the payments are made.

Figure 2.2

Current and future demand for batteries across key applications, Sustainable Development Scenario



Source: International Energy Agency

Note: Projections from passenger electric vehicles, trucks, buses and other electric vehicles and storage are from the IEA's Sustainable Development Scenario. For consumer electronics, the historic growth rate has been extrapolated to 2040.

3 This demand estimate relates to technologies and applications within the cartography of this study, i.e. portable, automotive and stationary applications of battery types that are expected to help manage more variable electricity supply and demand, and help substitute direct use of fossil fuels with electricity-based services. Automotive applications are limited to the provision of motive force and exclude start/stop-only systems.

2.2 Batteries and electricity storage for electromobility

While electricity storage can in theory be paired with any energy service, electrification in the transport sector relies particularly heavily on continued innovation in battery technology. While electric vehicles on the road today account for a mere 1% of total vehicles (and just below 3% of annual sales), under the SDS, charging batteries in electric vehicles will become the largest single source of electricity demand, accounting for around 5% of global demand by 2050.

To support the large-scale electrification of transport under the SDS, the volume of batteries needed for passenger and commercial light-duty vehicles increases 100-fold between now and 2040, while the volume for trucks, buses and other heavy-duty vehicles increases 14-fold. In order to reach this level of adoption, continued progress is needed to reduce costs and improve the performance of batteries at both cell and pack level.

The unit cost of batteries for electric vehicles has already dropped by 85% since 2010, with industry surveys recording a sales-weighted average cost of USD 156/kWh as of 2019. As costs fall and performance increases, the average battery pack size across electric vehicle type will also increase as a means for manufacturers to extend range and improve vehicle performance. These are key steps under the SDS, which sees a shift towards larger battery capacities to support longer ranges. The average battery pack for light passenger and commercial vehicles now carries 20% more energy than in 2018, and battery electric cars in most countries are in the 50-70 kWh range. The SDS sees continued increases in battery sizes, culminating in an average pack size that is 30% larger. Meanwhile, the share of battery electric vehicles, which have larger batteries than plug-in hybrids, continues to rise under the SDS to seven out of every ten electric vehicles sold in 2040.

Li-ion variants are the mainstay of electromobility applications, and with continued innovation in blends, chemistries and designs they are likely to continue to dominate over the coming decade. The current Li-ion landscape is a mix of lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) cathodes for Li-ion batteries, with the most common chemistry and an emerging dominant design being NMC blends (see Chapter 7). Beyond unit cost reductions, the SDS is reliant on battery density continuing on an upward trajectory. Near-term developments already in the pipeline for current Li-ion technology are expected to reach cell-level energy densities of up to 325 Wh/kg and pack-level energy densities of 275 Wh/kg, both of which are close to the upper limits of current designs.

Beyond 2030, however, new technologies will be needed to follow the cost and performance trajectories set out under the SDS. These technologies are also key to facilitating the electrification of transport modes beyond cars. Despite ambitious electrification plans in the SDS however, modes of transport other than cars account for just 11% of overall battery demand in 2030, highlighting the pivotal role of electric cars in the battery market over the next decade.

Candidates with the potential to meet the high-performance battery technology requirements include lithium-metal solid-state, lithium-sulphur, sodium-ion and even lithium-air batteries, which could represent an improvement compared with Li-ion in terms of cost, density and lifecycle, as well as further benefits owing to the more widely available materials found in these types of battery than those used in Li-ion technologies. At present, there is no single technology or dominant design that can outperform current Li-ion technology in all these areas.

Once their performance has been tried and tested in the research phase, the SDS requires these new technologies to be rapidly deployed and scaled up. The pace of development will need to be faster than that experienced by Li-ion; at the same time, these new technologies will be competing with established high-performing battery technologies, a challenge that Li-ion did not face to the same extent. Established Li-ion technology will in the meantime continue to benefit from cumulative experience gained from its large-scale manufacture and a solid understanding of its long-term durability characteristics in an expanding array of real-world applications.

BOX 2.2

Does innovation in electric vehicle batteries benefit energy storage?

A key speculation for the future of energy storage is the extent to which electric vehicle technology developments can “spill over” into grid-scale batteries. Given that the market for electric vehicle batteries is already ten times greater than that for grid-scale batteries, the indirect effects of innovation and cost reductions in mobility applications could provide a significant boost.

Evidence from 2019 shows that spillover effects are already strong. Around 60% of grid-scale batteries currently consist of NMC blends – the emerging technology of choice in electric vehicles. Electric vehicle battery manufacturers aim to continually increase energy density to reduce upfront costs and increase range, but this has little impact on stationary applications. Therefore, as supply chains advance to the next higher-performing blend or chemistry, technology that may become less attractive for electric vehicles can be deployed at a lower cost for stationary applications on the grid.

The next generation of Li-ion battery technology, set to enter the market in the next five to ten years, is likely to have a low nickel content and use either NCA (which has under 10% nickel content) or NMC 811 cathodes. While these near-term developments should enable much higher energy densities, it is important to note that some electric vehicles may not necessarily be designed for the highest possible energy density. This could be the case for urban buses or delivery vehicles, where volume is less of a constraint, or for low-end electric vehicles, where affordability is more important than long driving ranges. For these applications, LFP cathodes could be a suitable alternative. These applications in turn are most likely to have performance envelopes comparable to those demanded by the power sector.

Other path dependencies can be created in electromobility that could benefit stationary applications. In China, LFP batteries were used for the majority of grid-scale installations in 2019 because the Chinese government had tightened energy density requirements for electric vehicle batteries, and the resulting manufacturing overcapacity in this relatively lower-density technology was redirected towards grid-scale applications. Manufacturers of LFP batteries also tend to be based in China, while NMC batteries are produced primarily in the Republic of Korea.

Demand for the materials used in electric vehicle batteries, in particular the availability and management of cobalt and lithium resources – has also become a central concern. These will depend on changing battery chemistries (see Chapter 7, Section 7.1). For instance, the energy density of cells with NMC cathodes rises as nickel content increases, and the current chemistry trajectory, in the light of the transition to electromobility, will naturally shift towards higher nickel and lower cobalt blends, another area in which there is continued pressure to innovate.

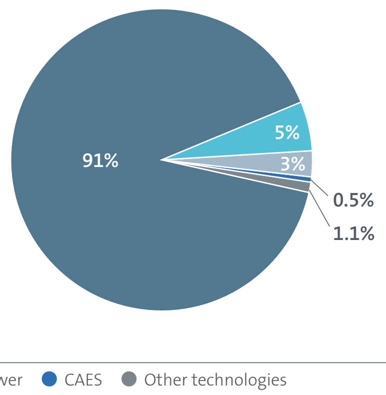
To meet battery needs under the SDS, global cobalt demand would increase three-fold, and lithium four-fold, compared with current levels. Re-purposing and re-using batteries for second-life use in a new application and developing advanced recycling strategies could therefore greatly alleviate concerns over material availability and further reduce costs in applications such as grid-scale storage and energy access provision, neither of which require the levels of performance needed for electromobility.

2.3 Batteries and electricity storage in stationary applications

The use of batteries and other technologies in energy storage applications is also rapidly expanding, albeit at a slower rate than in the field of electromobility. Globally, total storage capacity stands at just under 200 GWh – the energy volume equivalent of storing the world's electricity requirements for just six seconds. Most of this storage capacity is attributable to a single technology known as pumped storage hydropower (PSH), which accounts for over 90% of the world's storage volume, while batteries account for less than 3% (Figure 2.3). An additional 10 GWh of pumped hydropower projects are currently in the pipeline, and a number of demonstrations of large mechanical and heat storage are planned (see Section 2.4). However, there are constraints to further scaling large-scale storage from technologies like PSH or compressed-air energy storage (CAES) given the limited number of suitable sites and their nature as capital-intensive projects involving large civil engineering works with long lead times.

Figure 2.3

Installed capacity from energy storage technologies, 2019



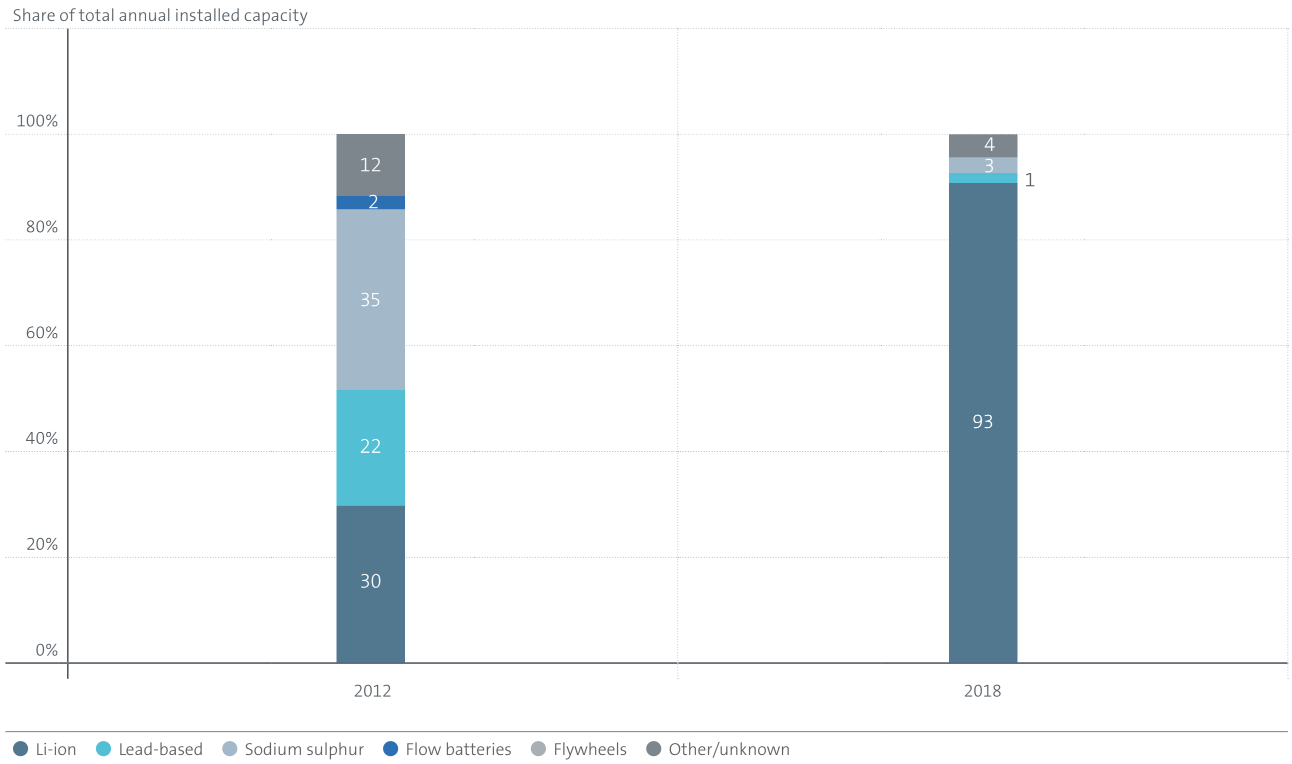
Source: International Energy Agency

In contrast, the use of batteries in stationary energy storage applications is growing exponentially: they are already being installed at an annual rate that is on a par with all other storage technologies combined. Of all the available batteries, Li-ion has quickly become the dominant design, aided by spillovers from consumer electronics and electromobility applications (see Box 2.2). Excluding PSH, variants of Li-ion technology now account for more than 90% of new energy storage installations (Figure 2.4). Other batteries make up the majority of the remaining 10%, with short-term technologies like flywheels and super-capacitors finding niche markets below 2%.

The SDS sees a step change in the need for flexibility – power systems need to be able to maintain the required balance of electricity supply and demand in the face of uncertainty and variability in both supply and demand. As time goes on, many countries will experience a need to source more flexibility. By 2040, for instance, European Union (EU) countries on average will require enough flexibility to accommodate a share of wind and solar power equivalent to that of the global leader among major economies, Denmark.

Figure 2.4

Energy storage technology mix excluding pumped hydropower storage, 2012-2018



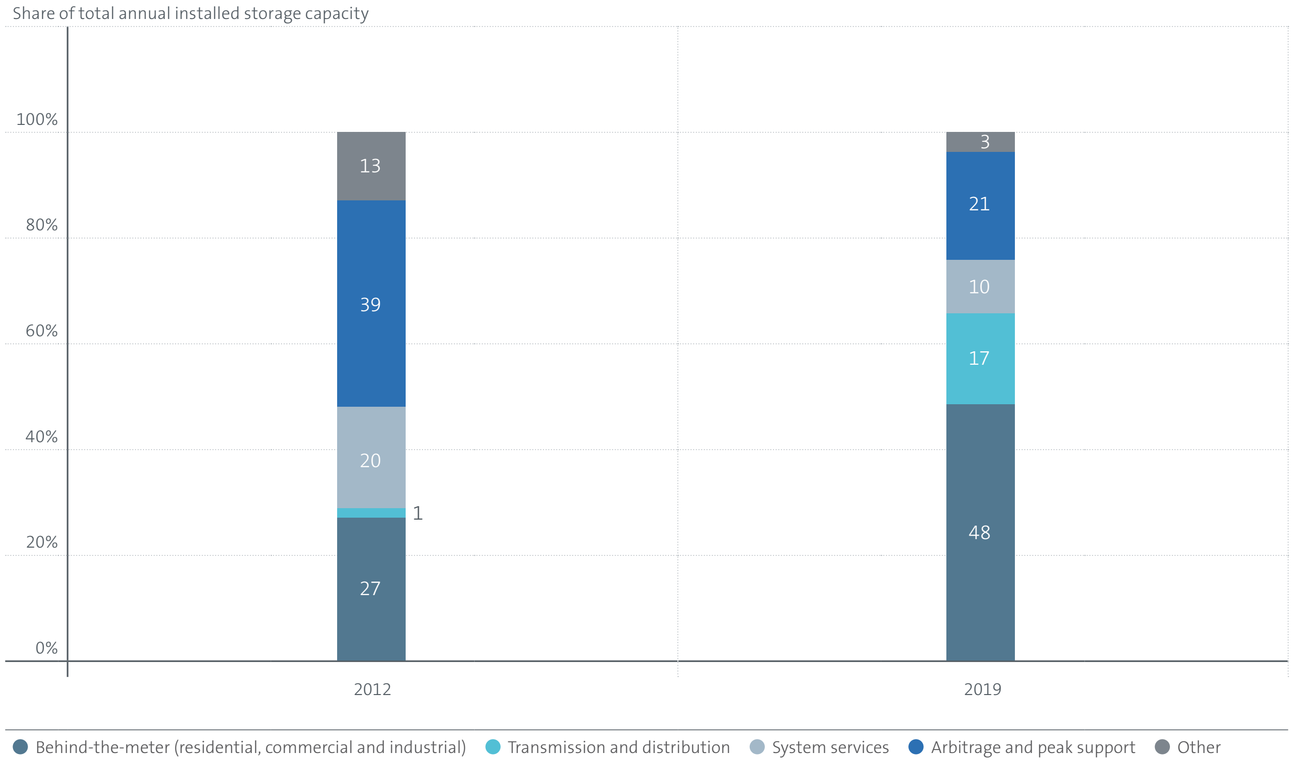
Source: International Energy Agency

Under the SDS, battery storage becomes a key provider of this flexibility, reaching a capacity of 550 GW by 2040, up from 6 GW in 2019. This increase in capacity is related to the rise of variable renewable energy capacity: today, the vast majority of utility-scale battery installations are paired with solar PV and wind power. More crucially, however, batteries are supported by market design that rewards an expanding range of services that batteries can provide. In 2012, the vast majority of storage was used for a small number of services (Figure 2.5), mainly energy arbitrage on the grid or in the residential and commercial sector (shifting energy demand or supply in bulk from high- or low-demand periods).

As markets, products and services have diversified – owing largely to the rise of variable renewables – the range of services has increased. Under the SDS this range increases even further to cater for the growing need for new flexibility products, such as frequency and voltage regulation, inertial response and grid deferral, which are expanding to more markets. In turn, this drives technology innovation, as the power, energy, storage duration and lifecycle required by each of these services vary substantially.

Figure 2.5

Applications of energy storage technologies, 2012-2019



Source: International Energy Agency

This versatility of services and revenue streams, combined with the modularity of batteries, short lead times, wide range of applicability, economies of scale and overall technological progress, underpins the explosive growth in the battery market under the SDS. Other storage technologies, however, are also required for the energy transition (see Section 2.3). For instance, despite a growing shortage of suitable sites in some regions, the installed capacity of PSH increases by two-thirds by 2040, driven by more innovative designs that open up new locations and build on existing reservoir hydropower projects. Nevertheless, the very rapid growth in battery storage means that batteries overtake total PSH capacity by 2040.

To support this growth in battery storage, innovation in batteries alone is not enough. Battery systems are supported by a range of technologies, which currently account for over half of the total battery system costs. These include "balance-of-system" components such as housing, ventilation, monitors and controls, energy management systems as well as safety equipment such as thermal management and fire suppression, a power conversion system (a bidirectional inverter for battery charging and discharging), and other power equipment such as transformers and switchgear. In order to reach the goals set out under the SDS, the cost of these relatively mature technologies would need to drop to less than half the current levels by 2040.

2.4 Other roles of batteries and storage in the energy transition

As countries reach very high shares of renewables, the need for flexibility will shift towards longer time periods (several days or weeks) during which systems are over- or under-supplied. The SDS sees the EU, for instance, reaching on average this phase by 2050. For applications with longer storage durations, technologies other than Li-ion batteries are increasingly attracting interest. These include sodium-sulphur batteries, which are well suited to delivering power over long periods of time, or flow batteries, which, in contrast to other batteries, allow the volume of energy stored to be sized independently and at a relatively low cost.

Other long-term storage technologies, such as CAES, are also seeing a resurgence of interest. While there are only two plants in place today, the more recent of which was fully constructed in 1991, key demonstrations of newer designs (e.g. adiabatic or near-adiabatic) began in 2019. There have also been recent key demonstrations of long-term thermal and mechanical storage.

As the share of electric vehicles increases, managing electric vehicle charging patterns will be key to encouraging charging during periods when the share of wind and solar power on the grid is high or overall demand is low. By 2030, the average evening peak demand could rise to as high as 4-10% in the main electric vehicle markets (China, the EU and the US), assuming unmanaged charging. However, continued innovation in managing battery technology and charging systems could enable the integration of electric vehicles into the grid and substantially help to balance systems with high shares of wind and solar power.

By 2030, technically 16 000 GWh of energy, equivalent to around 100 times the current global storage capacity, could be stored in electric vehicle batteries globally under the SDS. These roaming batteries, when plugged into the grid, could actively provide energy at suitable times via smart charging (V1G) or vehicle-to-grid solutions (V2G). Without technical innovations on a number of fronts – including on battery cycling, controls, ancillary charging equipment and digital platforms – both V1G and V2G could negatively affect battery lifetimes and performance.

Assuming market designs evolve to reward these services, under the SDS batteries supporting V1G and V2G technology could provide around 600 GW of flexible capacity globally by 2030 across China, the US, the EU and India. This would have the knock-on effect of compensating for periods of low wind and solar power at peak times, allowing higher capacities of variable renewables to be accommodated, and reducing upstream power generation and network infrastructure needs.

3. Methodology

3. Methodology

This study covers all the main technologies being developed for storing electricity and seeks to identify and compare trends in their patenting activity, including the profiles of their inventors and their intended applications.

More specifically, the boundaries of the scope have been established to account for technical progress in improving the performance or reducing the cost of devices that could facilitate the storage of electrical energy in electrochemical, thermal, potential, kinetic or electrical form over durations ranging from under a second to more than a year, such that this energy could then be discharged to meet consumer demand for any electricity-based service. To ensure comparability between the technologies studied, the chemical storage of electrical energy as hydrogen by splitting water molecules has been excluded from the study, because it is not possible to isolate hydrogen-related technologies that are primarily intended for electricity storage from other hydrogen-related technologies.[4] However, hydrogen is another important area in energy technology innovation that deserves separate consideration, including for shifting the time, place and means of consumption of electrical energy.

4 Technologies related to the production, storage, conversion and use of hydrogen straddle the boundaries of the scope, considering, for example, that much of the relevant set of technologies can be applied to hydrogen that is neither produced from electrical energy nor reconverted to electricity after storage. It is therefore not appropriate to directly compare progress in a given hydrogen technology with other storage options because at least three separate technologies (electrolyser, hydrogen storage medium and fuel cell) must be combined to replicate the round-trip performed by, for example, a battery.

The stated scope is used to systematically map technology areas to patent data, resulting in a cartography for categorising relevant patents and technology applications (Figure 3.1). This cartography, presented in detail in Annex B, covers the four categories of storage technology, namely electrochemical storage (i.e. batteries), electrical storage (e.g. supercapacitors), mechanical storage (e.g. PSH, flywheels) and thermal storage (restricted to technologies that use heat to store and retrieve electricity). Each of these main categories is further subdivided to ensure that the cartography is comprehensive and enable an analysis at the most granular level possible. For example, mechanical storage types include flywheels and PSH in general, as well as pumped hydropower specifically used for seawater applications.

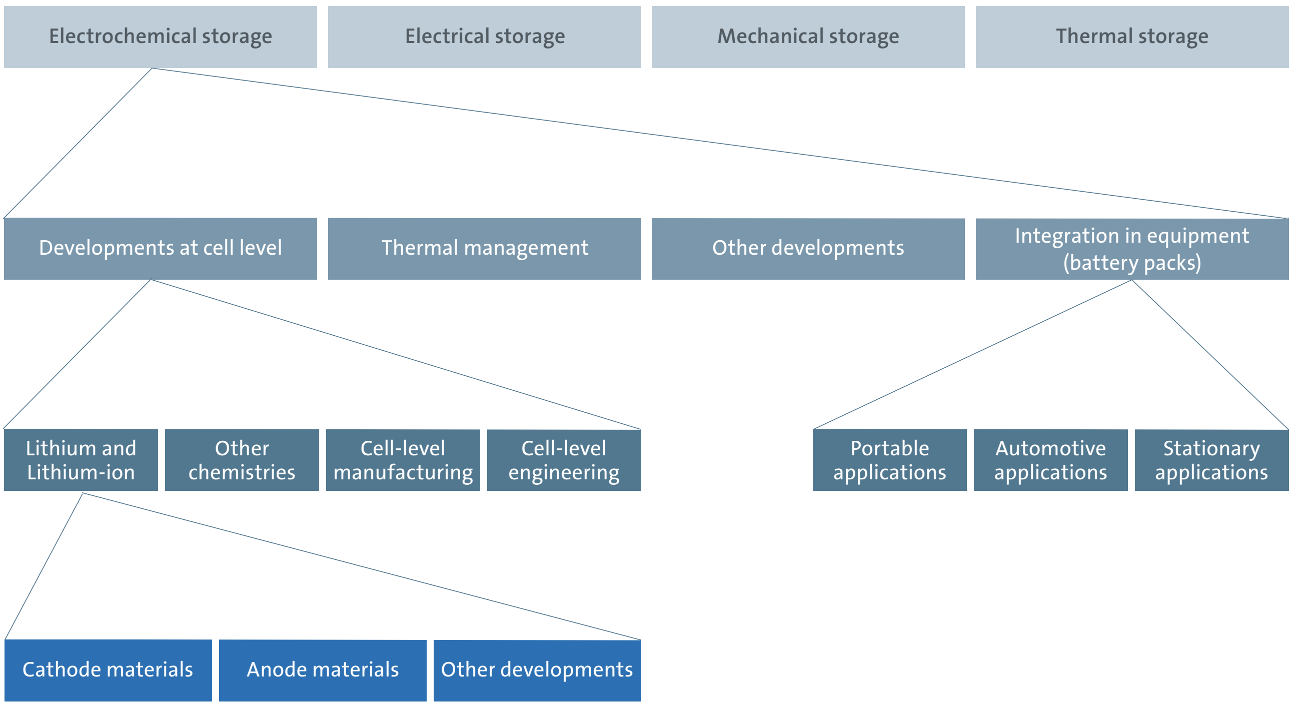
Particular attention has been paid to electrochemical storage, which is the main focus of this study. The cartography accounts for technology developments at the level of the battery cells, distinguishing between different chemistries and materials (in particular in the case of Li-ion cells), as well as for innovation in manufacturing and the integration of battery packs in different fields of application, such as portable, automotive and stationary. Thereby, automotive applications are limited to the provision of motive force and exclude start/stop-only systems.

Patent applications related to the various parts of the electricity storage cartography were identified on the basis of expert knowledge from the EPO and the IEA, together with a review of scientific publications and studies published by various consultants and institutions. This knowledge has been built up over many years by a network of EPO and IEA specialists working in the core electricity storage technology fields.

Details of the methodology used to identify relevant patent applications and map them to the cartography fields can be found in Annex B.

Figure 3.1

Overview of the cartography



Source: European Patent Office

The patent analysis in this report is based on the concept of international patent families (IPFs), each of which represents a unique invention and includes patent applications filed and published in at least two countries.[5] IPFs are a reliable and neutral proxy for inventive activity because they provide a degree of control for patent quality and value by only representing inventions deemed important enough by the inventor to seek protection internationally. A relatively small percentage of applications actually meet this threshold. This concept enables a comparison of the innovative activities of countries and companies internationally, since it creates a sufficiently homogeneous population of patent families that can be directly compared with one another, thereby reducing the national biases that often arise when comparing patent applications across different national patent offices.

In addition, unlike patent applications that have only been filed at one office, almost all IPFs are classified according to the Cooperative Patent Classification (CPC) scheme, which means that only one scheme is needed to identify relevant inventions and assign them to the different technologies within the cartography, irrespective of where the applications are filed. Each IPF identified as relevant to electricity storage technologies is assigned to one or more sectors – or fields of the cartography – as commonly understood by non-specialists.[6] The analysis covers the period 2000-2018. The date attributed to a given IPF always refers to the year of the earliest publication within the IPF. The geographic distribution of IPFs is calculated using information about the origin of the inventors disclosed in the patent applications. Where multiple inventors were indicated on patent document within a family, each inventor was assigned a fraction of the patent family.

Where necessary, the dataset was further enriched with bibliographic patent data from PATSTAT, the EPO's worldwide patent statistical database, as well as from internal databases, providing additional information, for example, on the names and addresses of applicants and inventors (see Annex B). In addition, information was retrieved from the Bureau van Dijk ORBIS (2019 version) database, which was used to harmonise and consolidate applicant names and identify their type and age:

- *Applicant name:* After harmonisation, each applicant name was consolidated at the level of the global ultimate owner (GUO) according to the latest company data available in ORBIS.
- *Applicant type:* On the basis of the company's financials and number of employees, a distinction was made between (a) large and very large companies, and (b) small and medium-sized enterprises (SMEs), including individual inventors. All IPFs in which at least one applicant is a university or public research organisation were assigned to the university/public research organisation category.
- *Applicant age:* Company applicants were grouped into companies less than ten years old, those aged between 10 and 20 years, and those older than 20 years on the earliest publication date of the invention. The age was calculated on the basis of the date on which the unconsolidated entity was established.

5 An IPF is defined as a patent family that includes a published international patent application, a published patent application at a regional patent office, or published patent applications at two or more national patent offices. The regional patent offices are the African Intellectual Property Organization, the African Regional Intellectual Property Organization, the Eurasian Patent Organization, the EPO and the Patent Office of the Cooperation Council for the Arab States of the Gulf.

6 There is a strong but not perfect overlap between the cartography that has been prepared for the study and Y0260 Section of EPO's Y02E tagging scheme for energy technology related to climate change mitigation. The Y02E60 Section aims at providing a high level measure of patenting activities in all technologies related to any form of energy storage that is relevant for the energy sector, including hydrogen (Y02E60/3) and fuel cells (Y02E60/5). By contrast, the cartography prepared for the study focuses only on technology that is directly relevant to the storage of electricity, and it aims to provide a detailed picture of the innovation trends in battery technology. Accordingly, the scope of the study excludes hydrogen (which is obtainable also by chemical routes) and fuel cells (rather an energy conversion technology) while providing a higher level of granularity than the Y02E in the case of batteries. For the same reason, the patent applications related to thermal and mechanical storage that have been considered for the study are only those that enable the saving of electrical energy, and therefore represent only a subset of all the thermal and mechanical energy storage technologies that are covered by the Y02E60/14 (thermal) and Y02E60/16 (mechanical) Sections of the Y02E scheme.

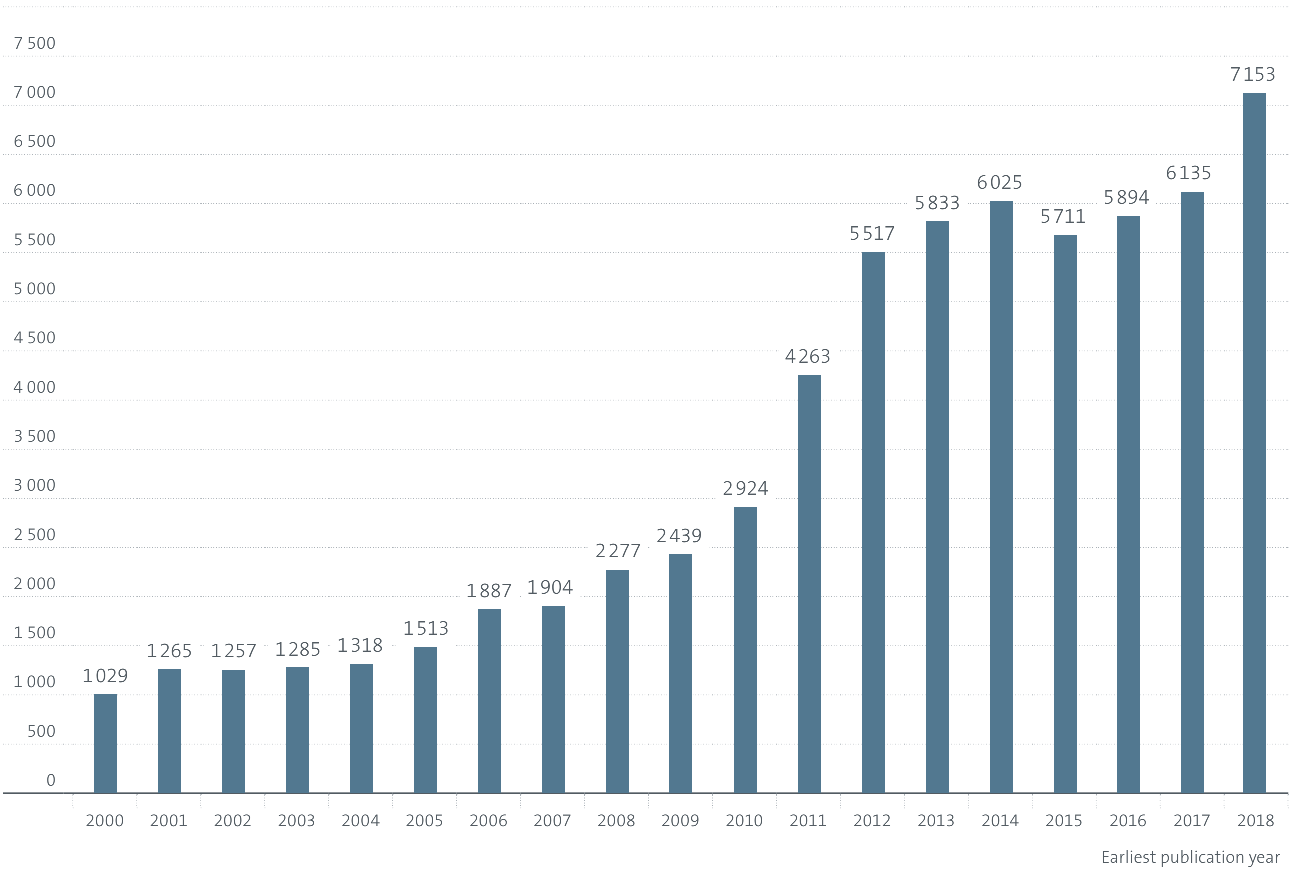
4. Main patenting trends in electricity storage

4. Main patenting trends in electricity storage

This chapter presents the major trends in electricity storage innovation between 2000 and 2018. The unit of observation is the IPF, which represents a unique invention and includes patent applications filed at two or more patent offices.

Figure 4.1

Number of IPFs related to electricity storage, 2000-2018



Source: European Patent Office

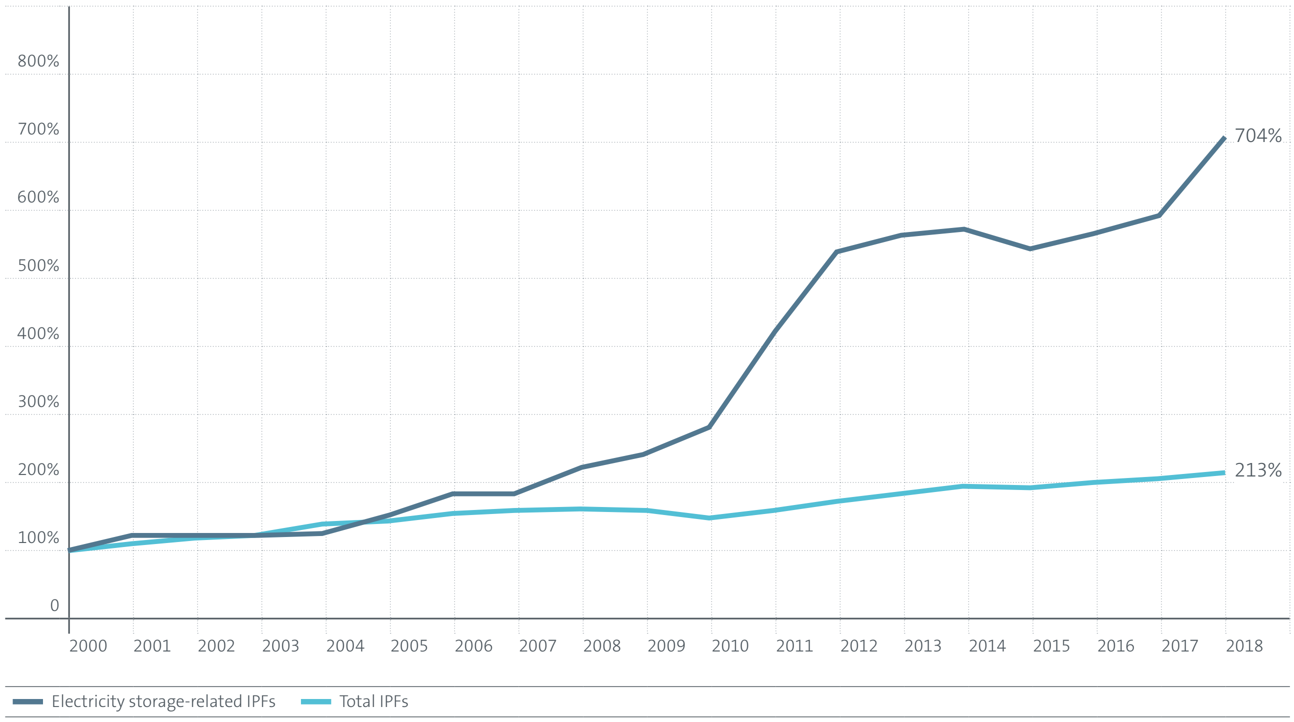
4.1 Rapid growth in electricity storage patenting activity over the past decade

Between 2000 and 2018 more than 65 000 IPFs in the area of electricity storage were filed at patent offices worldwide (Figure 4.1). The annual number of IPFs has been growing nearly exponentially, increasing from around 1 000 in 2 000 to over 5 800 in 2013. With an annual growth rate of 14% after 2005, this growth clearly outpaced the average annual growth rate (3.5%) of IPFs in all technology fields (Figure 4.2).

The growth rate has not, however, been constant. The number of IPFs in electricity storage increased exponentially until 2012 before plateauing in subsequent years. A further growth impulse can be observed in 2018, with an increase of 16.6% recorded. Future work including more recent observations will provide an indication of whether this represents a structural change.[7] Overall, the annual number of IPFs related to electricity storage increased sevenfold from 2000-2018, whereas the total number of IPFs per year in all sectors merely doubled during the same period.

Figure 4.2

Innovation trends in electricity storage, 2000-2018 (base 100% in 2000)



Source: European Patent Office

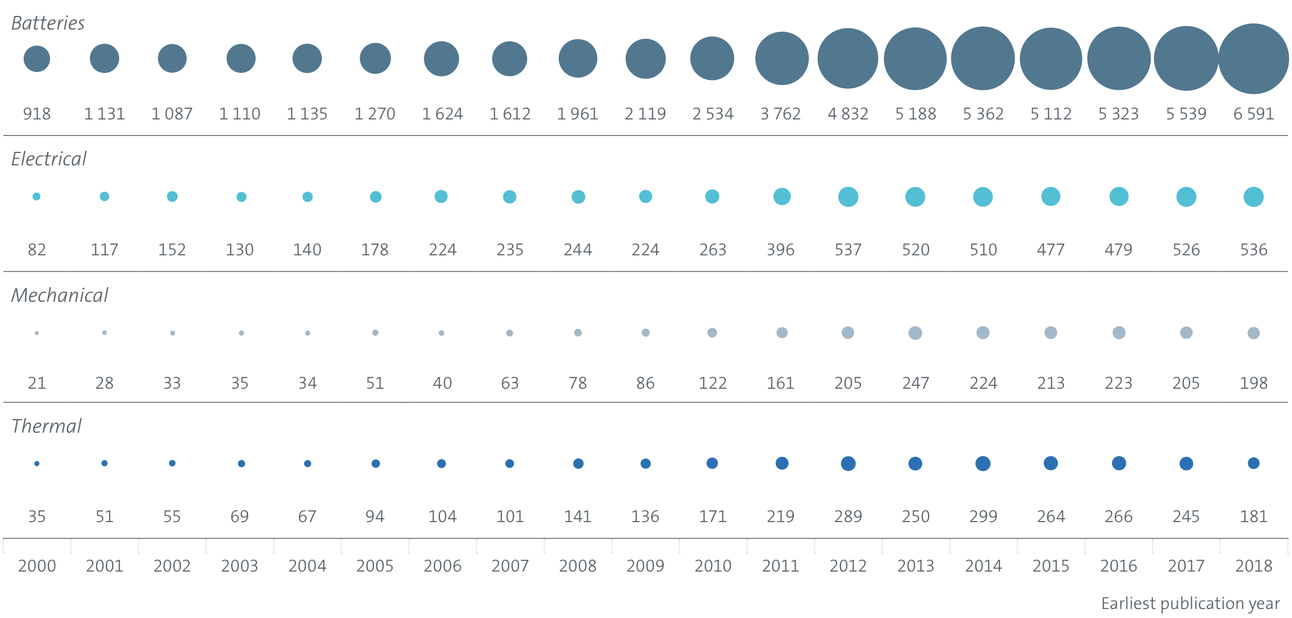
7 Owing to publication lags more recent data are not available. However, future work could apply nowcasting techniques to estimate recent trends on the basis of partial data. See, for example, IEA (2019c).

Innovation in electricity storage has been heavily dominated by progress in electrochemical technologies, i.e. batteries, which accounted for nine out of ten IPFs related to electricity storage between 2000 and 2018 (Figure 4.3). The second most important category, electrical storage, accounted for another 9% of all IPFs in electricity storage over the same period. This category includes superconducting magnetic energy storage systems and supercapacitors, which, featuring limited energy density but higher rates of power density and efficiency than batteries, are used for very fast charging and discharging applications in electric vehicles or grid management.

The remaining two categories of electricity storage technologies - thermal storage and mechanical storage technologies - account for just 5% and 3%, respectively, of all IPFs related to electricity storage.[8] Mechanical energy storage combines several storage principles such as the potential energy of water in PSH, the compression of air in CAES, the rotational energy of mass in flywheels and the stored energy in cryogenic liquids. For the purpose of this study, thermal energy storage is defined as technologies that use heat to store and retrieve electricity. The main principles underlying mechanical and thermal storage are well known, and the corresponding fields of technology are relatively mature compared with batteries and electrical storage solutions. As a result, technical progress in these fields mainly consists of incremental innovation, which may explain the relatively low numbers of IPFs documented.

Figure 4.3

Number of IPFs related to electricity storage by technology, 2000-2018



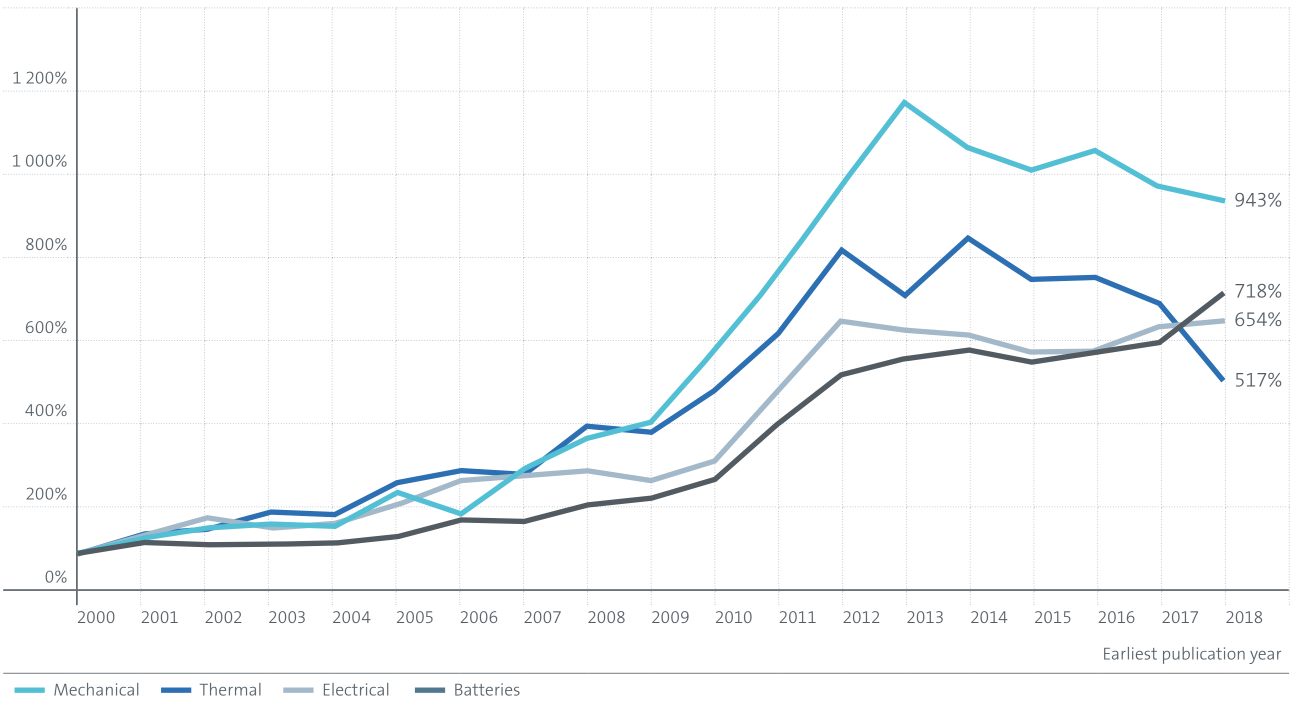
Source: European Patent Office

8 The shares add up to more than 100%, since an invention can fall within a range of different technology areas. Patent applications that are relevant to different fields are therefore assigned to each of these fields.

Although starting from very different bases, all fields experienced strong growth in the number of IPFs per year until around 2012, with increases of between 400% (batteries) and more than 1 000% (mechanical storage) recorded compared with the 2000 level (Figure 4.4). Since this time, however, all fields except batteries have been stagnating or even decreasing, thereby losing relative shares. Only the electrical storage technology area of batteries reached a new high in 2018, thereby reinforcing its top position in the field of electricity storage innovation. It is worth reiterating here, as shown in Figure 4.2, that no similar stagnation or decrease has been seen for IPFs related to technology fields in general in recent years.

Figure 4.4

Innovation trends in electricity storage by technology, 2000-2018 (base 100% in 2000)



Source: European Patent Office

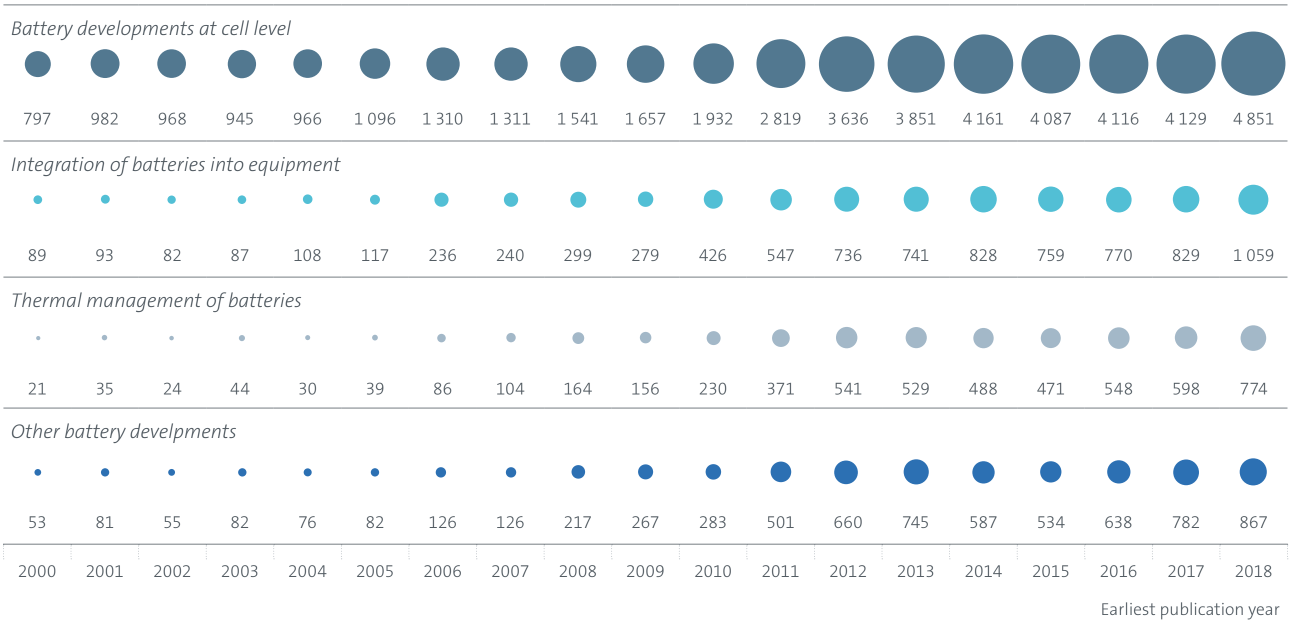
4.2 The rise of innovation in batteries

Within the area of battery technologies, technical developments since 2000 have mainly been fuelled by innovation at the level of battery cells (Figure 4.5). After stagnating at around 4 100 IPFs per year between 2014 and 2017, the number of IPFs related to cells increased to 4 851 (+17.5%) in 2018, representing almost three-quarters of all battery-related developments during that year. Other remarkable developments include technical progress made since 2000 in the thermal management of batteries and their integration into equipment, which are both key to facilitating battery use in new industrial applications. Recent efforts to accelerate their development are testament to the increasing range of applications of modern batteries.

A closer analysis of the subset of IPFs related to battery cells is particularly informative and uncovers key dynamics in the industry (Figure 4.6). Patenting activity has been on the rise for most key cell chemistries, including lead acid, redox flow and nickel batteries. It is Li-ion technology, however, which has been fuelling innovation in battery technologies since 2005. Li-ion is currently the dominant technology for portable electronics and electric vehicles. In 2018, innovation in this field was responsible for 45% of patenting activity related to battery cells, compared with just 7.3% for cells based on other chemistries. The remaining 48% were related to inventions not specific to a particular chemistry.

Figure 4.5

Number of IPFs related to battery technologies, 2000-2018



Source: European Patent Office

BOX 4.1

Battery management systems

Battery management systems (BMS) manage the operational behaviour of a battery and integrate it into the equipment that charges it or uses its output. They play an essential role in maximising a battery's lifetime, for example by regulating its temperature to stop overheating and by distributing the charge evenly across the cells to avoid damage caused by undercharging or overcharging individual cells. They also ensure that the battery does not operate outside its safe current, voltage and temperature boundaries. Advanced BMS have systems that monitor the status of the cells and can communicate performance and maintenance-related information to the user. A modern BMS can extend the lifetime of a Li-ion cell by 9-17.5% and can recover capacity lost during rest periods by 11-19.5% (Motaqi and Mosavi, 2020).

While BMS are essential for all applications of modern batteries in energy systems, they are of particular importance for hybrid electric vehicles, including plug-in hybrid electric vehicles and fuel cell electric vehicles. This is because they co-ordinate the contributions from different energy sources and make the battery reactive to sudden changes in charge and discharge cycles during journeys, such as steady accelerations, bursts of power and regenerative braking. They also manage the charging of the vehicle by communicating rapidly with the charging station about the battery charge status.

For batteries installed in buildings, such as those that enable residents to use more output from rooftop solar systems, BMS are critical to ensuring operational flexibility. However, to optimise the interaction of the battery with the electricity grid and power market, sensors and advanced analytics are needed. Battery status diagnosis and operational forecasting are most valuable when real-time data are available on the behaviour of the building, PV system and occupants.

In 2018 the global BMS market size was valued at USD 3.61 billion, and it is projected to expand to over USD 12 billion by 2025 at a compound annual growth rate of 19% according to a report by Grand View Research (2019). This growth is supported by the growing share of variable renewable energy sources in electricity systems and electric vehicles in the car fleet.

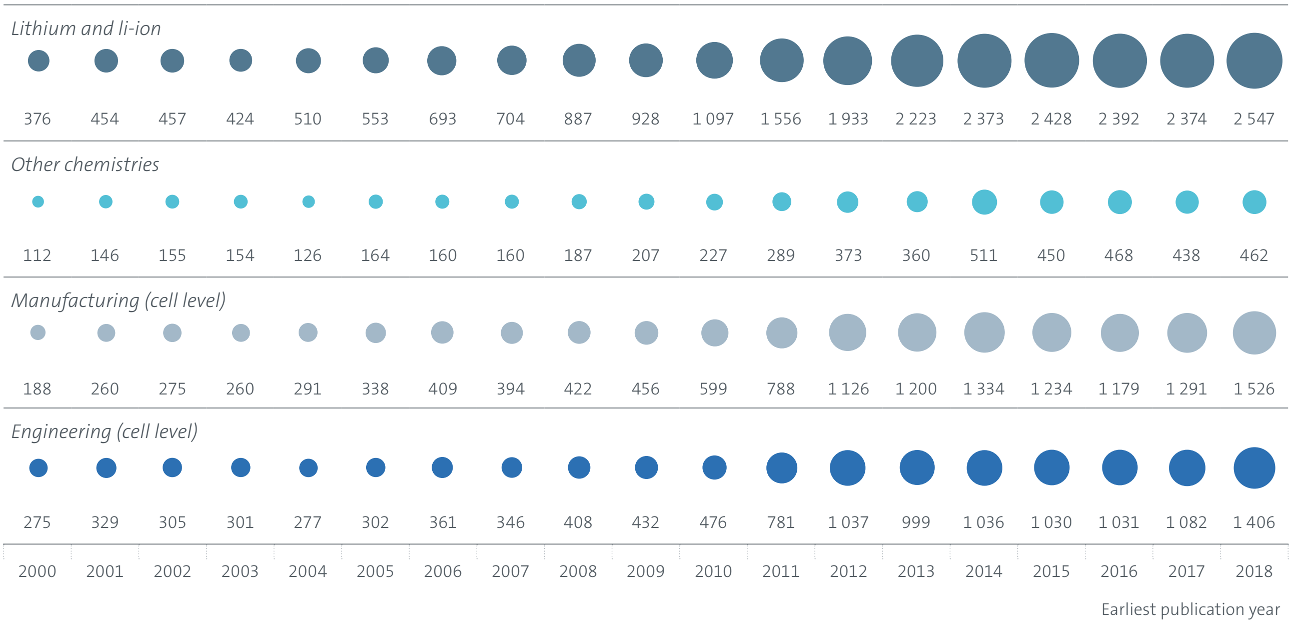
Although BMS in use today are much more advanced than a decade ago, continued innovation will play a central role in the future contribution of batteries to the clean energy transition. For example, advancements in semiconductors could lead to more compact power stages and smaller, lighter mechanical parts that would make it easier to integrate the BMS into smaller mobile and portable applications. Software-based instead of hardware-based solutions to certain functionalities could further reduce mass and volume. Modular BMS will ease scalability and reduce the need for wiring and harnesses.

These trends in patenting rates coincide with price movements. Since 1995, Li-ion battery prices for consumer electronics have fallen by more than 90% (IEA, 2020b). For electric vehicles, Li-ion prices have declined by almost 90% since 2010 alone, and for stationary applications, including electricity grid management, they have dropped by around two-thirds. These cost reductions are in part due to new chemistries, mostly adjustments to the composition of the battery cathode, as well as economies of scale in manufacturing. However, as the patent statistics clearly show, innovative manufacturing practices have also played a key role. Patenting activity related to the manufacturing of battery cells and cell-related engineering developments has grown threefold over the last decade, increasing from less than 500 IPFs in 2009 to more than 1 500 and 1 400 IPFs, respectively, in 2018. Together, these two fields accounted for nearly half of all patenting activity related to battery cells in 2018, a clear indication of the maturity of the industry and of the strategic importance of efficient industrialisation for mass production.

Battery cells are typically produced as a commodity, designed to be assembled into battery packs that are configured to deliver the desired characteristics for the end use in question. Different applications, such as mobility solutions and smartphones, can often use the same cell technology; however, the packs usually differ somewhat. Therefore, patenting activity related to battery packs provides insights into how batteries are integrated into target applications. Patenting activity related to battery packs increased from less than 100 IPFs in 2003 to more than 1 000 in 2018, marking an even faster increase than that seen for battery cells. This indicates a level of technological maturity, as attention has shifted away from developments at the cell level and towards ways to optimise use in applications in highly demanding commercial markets such as the automotive sector.

Figure 4.6

Number of IPFs related to battery cells, 2000-2018



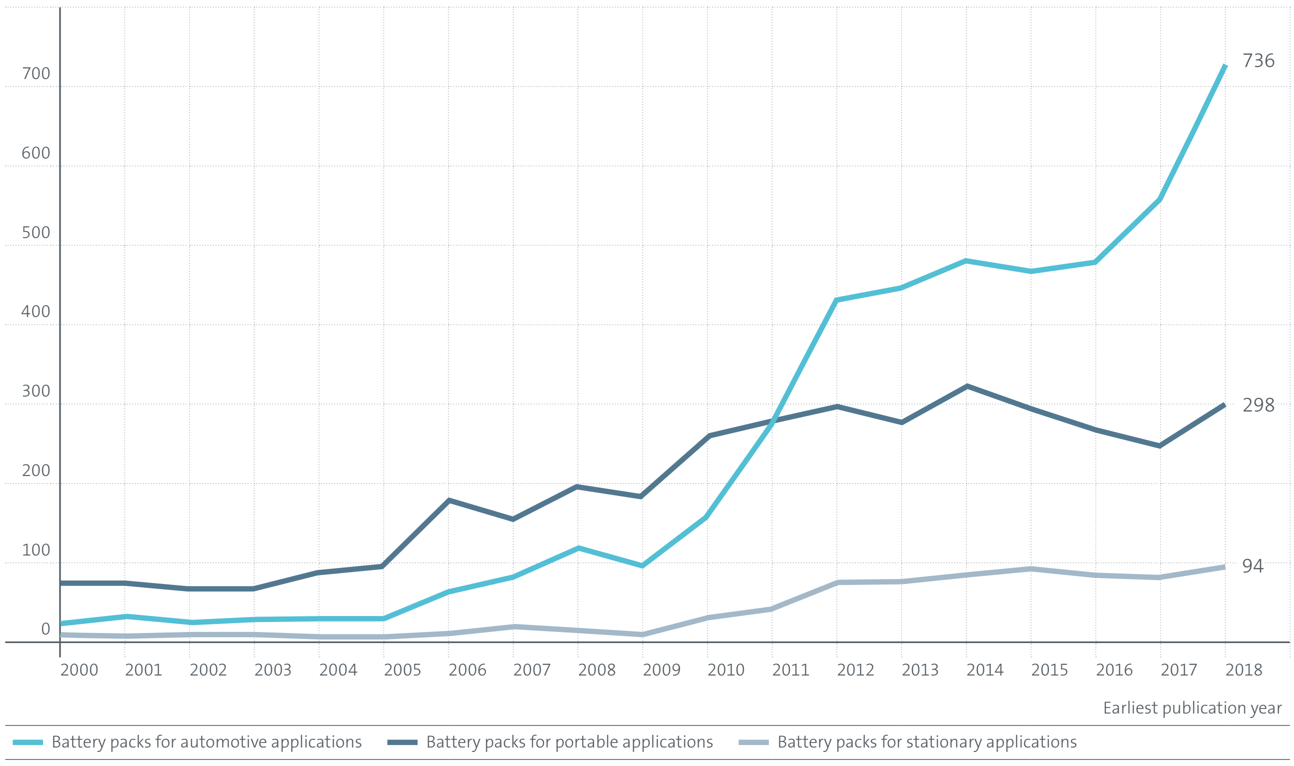
Source: European Patent Office

The data in Figure 4.7 show that the automotive sector is behind the growth in inventive activity related to battery packs, especially after 2009. Inventive activity in this area surpassed that related to the integration of batteries into portable applications (typically in consumer electronics) in 2011, which had been the leading application area up until that point. Innovative activity related to electric vehicles resumed its growth course in 2017-2018, with 736 IPFs recorded. However, developments in portable electronic battery pack designs and stationary applications, which has always been the smallest of the three application areas, have largely stagnated.

Although the automotive application area has dominated inventive activity over the last decade, other application areas will also benefit from technical developments. For example, improvements to battery packs for the wide range of all-electric and plug-in hybrid cars on the market have had positive spillover effects on stationary applications in particular, many of which are able to reuse modified vehicle batteries once they have reached the end of their useful lives in the vehicle in question. Li-ion is the dominant battery technology in all three application areas, thus enabling technology spillovers from one area to another. Such spillover effects were observed, for example, when improvements to Li-ion technology for portable applications helped to bring battery prices and performance in electric vehicle applications within an acceptable range for the first electric car buyers. With electric vehicle applications becoming industrialised, such spillovers can now be seen between automotive and stationary applications.

Figure 4.7

Number of IPFs related to applications for battery packs, 2000-2018



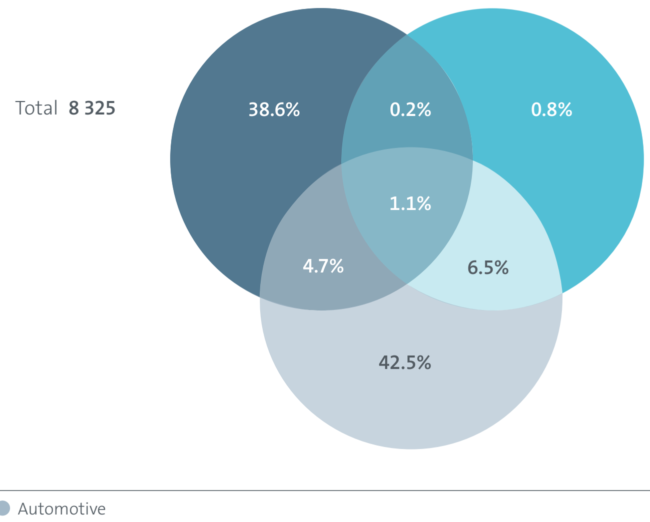
Source: European Patent Office

This phenomenon is illustrated by Figure 4.8, which shows that 22% of IPFs related to battery packs for automotive applications can also be used in the other two application areas. While spillovers between automotive and portable applications are relatively modest, they are particularly strong between automotive and stationary applications, with nearly 90% of IPFs related to battery packs for stationary applications also relevant for automotive applications.

Further work on spillovers could draw on citation data to identify the extent to which innovators build "on the shoulders of giants" in other technology fields. This has policy implications since a risk-averse policymaker may choose to incentivise the development of those technologies with a wide variety of applications.

Figure 4.8

Overlap between application areas for battery packs, 2000-2018



Source: European Patent Office

BOX 4.2

Recycling and reusing lithium-ion batteries

As the numbers of electric vehicles of all types and storage systems on the grid increases, so does the need to develop reuse and recycling technologies, strategies and value chains. So far, economic viability and market incentives for reuse and recycling have been limited because of generally low raw material prices, small volumes of spent electric vehicle batteries, and a paucity of normative measures. Under the SDS, however, around 120 GWh/year of Li-ion batteries would be available for recycling by 2030, equivalent to around 4.5% of battery demand.

In recycling terms, Li-ion can be a misnomer. Only a small proportion of a battery pack is made up by the active materials themselves, and of those a relatively small share are critical materials such as lithium and cobalt. In an NMC 622 battery, for instance, lithium is around 11% of the total cathode weight, while cobalt is around 18% (Figure 4.9). Li-ion batteries have a large variety of designs and cathode types with different material compositions, and the components can vary among manufacturers of the same cathode type. As with the primary demand for materials itself, the attractiveness of recycling Li-ion materials and components will hinge on the mix of chemistries, as well as on the emergence of fundamentally different technologies such as lithium-air or solid-state batteries.

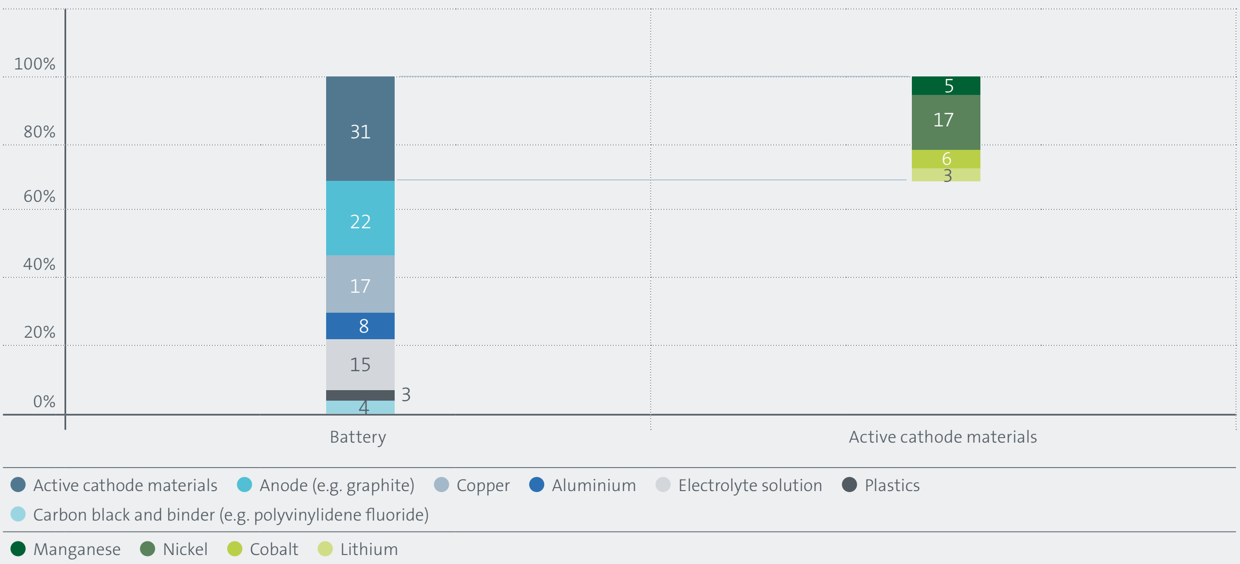
Li-ion batteries are also relatively compact, complex devices, constructed to not be disassembled and generally without recycling built in. In contrast to other batteries, larger battery packs such as those supplying electric vehicles can contain thousands of cells, as well as sensors, safety devices, thermal management and other circuitry that controls battery operation, all of which increase complexity further. Lead acid batteries, for instance, are easily disassembled. Lead is around two-thirds of battery weight and readily separated and extracted. Nearly 100% of lead is recycled in current systems.

Two mainstream recycling strategies are in use today. Pyrometallurgy (smelting) facilities use high-temperature processes to recover copper, nickel and cobalt. Organic compounds, plastics, as well as lithium and aluminium are not recoverable. Hydrometallurgic methods, also known as chemical leaching, are less capital- and energy-intensive, and are able to recover lithium, but can rely on large volumes of environmentally harmful chemicals in the leaching process.

Direct recycling methods that do not use leaching agents promise not only improvements in recycling, but also the possibility of a faster route to re-purposing batteries for other applications. These methods vary, but generally rely on physically separating battery components, for example through crushing the cell and recovering materials based on density. Automation and robotic procedures for sorting, disassembling and recovering valuable materials from Li-ion batteries also promise increased efficiencies.

Figure 4.9

Lithium-ion battery and cathode component distribution by weight, example of an NMC 622 cathode material



Data from Argonne National Laboratory

Current recycling facilities using pyrometallurgy and hydrometallurgy can, depending on location, add a greenhouse gas footprint to an electric vehicle battery (of about 10%), compared with a battery manufactured from primary raw materials. Research points towards a net benefit when considering non-greenhouse gas indicators such as ecotoxicity. Energy efficiency measures, new, innovative recycling processes using less energy, and adequate sorting and separation of battery pieces that need recycling or that can be directly repurposed or repackaged into new batteries will also be needed to reduce the greenhouse gas footprint of recycling.

Battery reuse in second-life applications is also a fundamental strategy under the SDS. Storage applications in particular can benefit from the extended lifetime of batteries that are no longer suited for automotive applications: the reduction in energy storage capacity in a battery that would reduce the range of an electric vehicle would not prevent the battery from being useful in stationary applications.

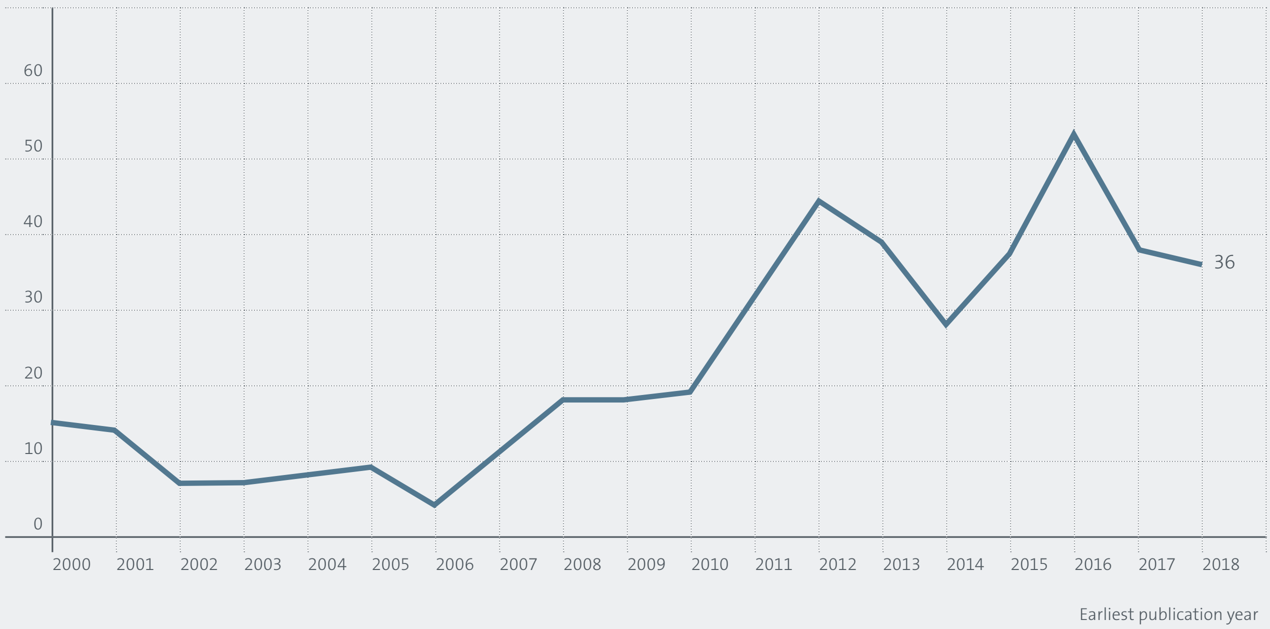
The availability of second-use batteries and further balance of system cost reductions would give a further boost to the competitiveness of battery storage. In a scenario in which the technical potential for second use is fully utilised, cost reductions would lead to batteries being 70% less expensive than today by 2040, and around 540 GW of battery storage deployed by 2040.

To date, however, experiences creating a value chain for battery reuse are scarce. New battery manufacturing continues to enjoy strong economies of scale and overall efficiency improvements, creating disincentives for repurposing existing batteries, and the value chain is technically complex. Nevertheless, an industry is emerging of OEMs, electric utilities and third parties, and including a number of smaller, emerging companies. Patenting activity related to battery recycling remained at relative low levels with a total of 436 IPFs between 2000 and 2018. This trend was closely aligned with the developments in battery technologies (see Figure 4.10). At around 10 throughout the early 2000s, the number of IPFs grew to more than 40 by 2012 and remained at around this level until 2018.

As the volume of Li-ion batteries continues to grow in the SDS, material prices could increase and become more volatile, and further pressure to improve environmental performance could materialise. This could make materials recovered through recycling more competitive and tap into that technically recoverable potential, which would in turn reduce demand for raw materials, greenhouse gas emissions and impacts from mining and processing materials.

Figure 4.10

IPFs in battery recycling technologies, 2000-2018



Source: European Patent Office

5. Battery technology applicants

5. Battery technology applicants

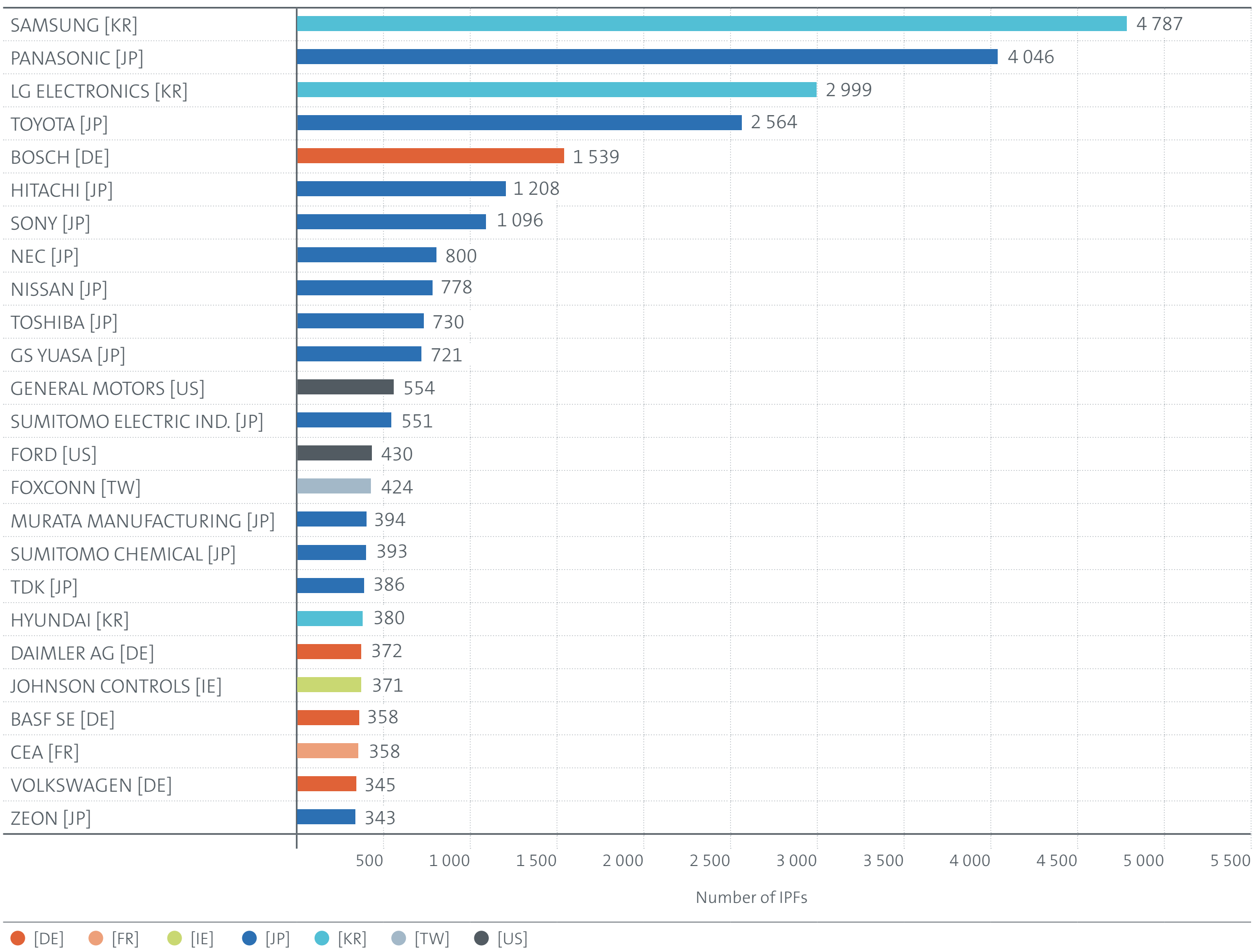
This chapter focuses on the origins of IPFs related to battery technology, drawing on company-level data. The first two Sections describe the top players in the field and their respective specialisations, as well as the overall distribution of applicants by size or age of IPFs in the field of battery innovation. The third Section analyses the geographic locations of innovative activities on the basis of the inventors' countries.

5.1 Top applicants

Innovation in battery technology is strongly dominated by applicants in Asia, with Japanese companies at the forefront. As shown in Figure 5.1, Asian companies account for nine of the top ten global applicants behind IPFs related to batteries, and for two-thirds of the top 25. They include thirteen Japanese companies, led by Panasonic and Toyota, three Korean companies (Samsung, LG and Hyundai), and Foxconn from Chinese Taipei. The remaining eight applicants in the top 25 consist of four German companies (Bosch, Daimler AG, BASF and Volkswagen), two US companies (Ford and General Motors), the French Alternative Energies and Atomic Energy Commission (CEA) and Ireland-based Johnson Controls. Four applicants alone (Samsung, Panasonic, LG and Toyota) generated half of the IPFs originating from the top 25 applicants in 2000-2018.

Figure 5.1

Top 25 applicants in battery technology, 2000-2018

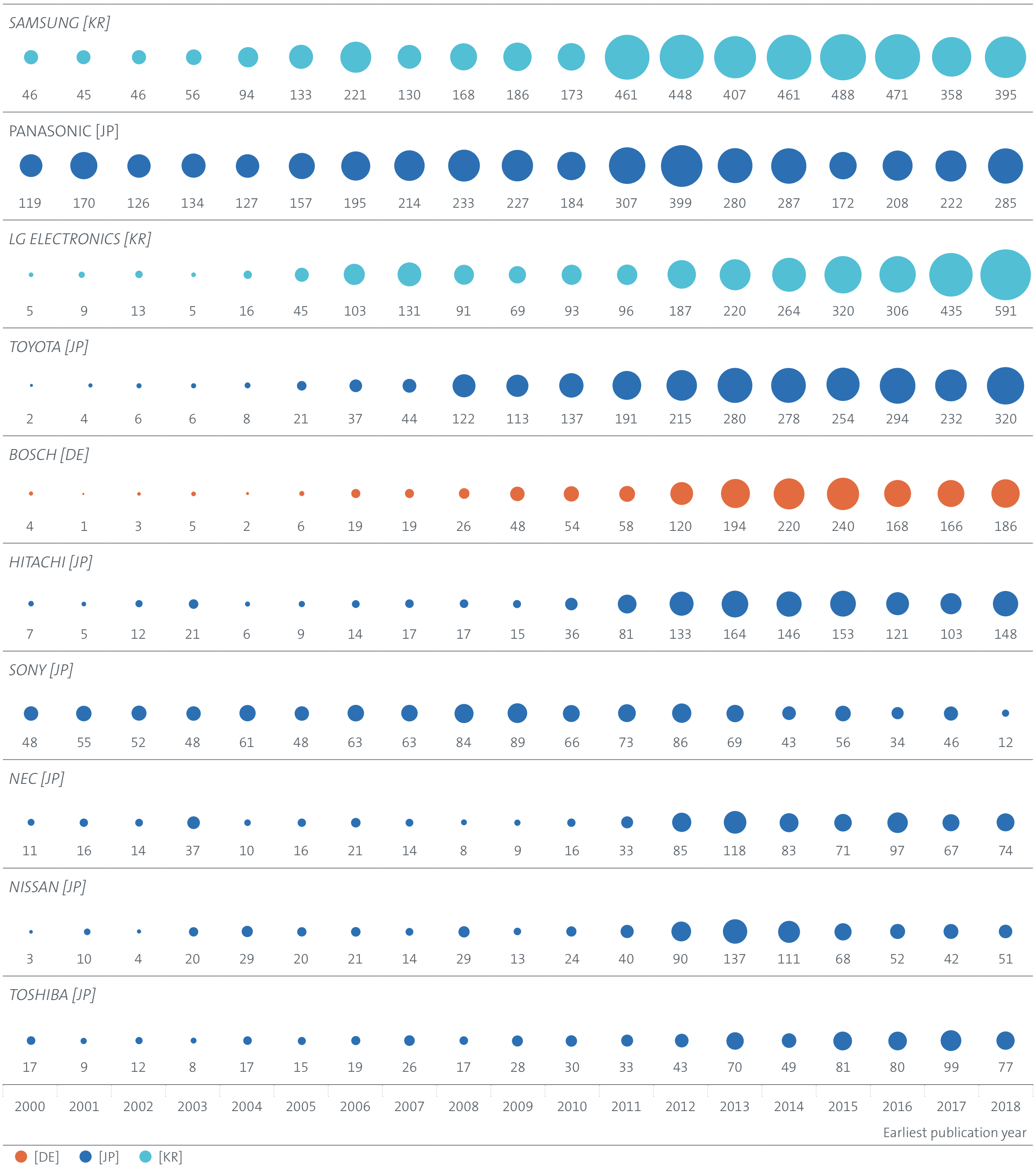


Source: European Patent Office

While Japanese companies such as Panasonic and Sony, alongside the Korean company Samsung, are long-established leaders in this field, some of the other applicants on this list have only ramped up their innovation activities over the past decade, coinciding with the expansion of patenting activity related to Li-ion use in vehicles (Figure 5.2). Companies like LG Electronics, Toyota, Nissan and Bosch have rapidly increased their battery-related inventive activity, with a focus on automotive applications. Samsung also has a major presence in the area of vehicle batteries, but its patenting growth has been largely driven by portable electronics.

Figure 5.2

Trends in battery technologies by top ten applicants, 2000-2018



Source: European Patent Office

Table 5.1 indicates the top applicants' respective shares in the different sub-fields of battery technology. Samsung, Panasonic and LG Electronics come out on top in almost all areas. Samsung is leading the way in cell-level innovation, accounting for 9.1% of all IPFs in this field, and is responsible for 8.7% of IPFs in cell manufacturing and 11.9% of IPFs in cell engineering. It is also very active in innovation in battery integration (8.7%) and shows a strong specialisation in lithium technologies compared with other chemistries. Like Samsung, LG Electronics is mainly focused on Li-ion chemistry, with a relative specialisation in the manufacturing of cells (7.4%) and their integration into equipment such as battery packs (7.2%). Panasonic has a more diverse and balanced portfolio, with relatively strong positions in both Li-ion and other chemistries (7.1% of IPFs in both cases).

Other companies have more specialised patent portfolios. For example, Bosch's strengths are not in developments at the cell level, but rather in thermal management and integration-related technologies (battery packs). Toyota holds similar positions in those fields, but also has a strong patent portfolio in cell manufacturing. GS Yuasa and Sumitomo Electric Industries, both Japanese companies, tend to specialise in alternative chemistries to Li-ion. As an indication of the growing importance of finding innovative ways of producing these batteries, Foxconn, a Taiwanese company that does not have a strong presence in the field of battery cells, nonetheless shows a strong technology specialisation in the area of integration into battery packs for final applications.

The diversity of specialisation profiles in the area of battery technologies opens up opportunities for R&D co-operation between different companies, between companies and universities, and between companies and public research organisations. Using information contained in patent applications, it is possible to identify several examples of IPFs with co-applicants, including foreign companies. For example, Bosch and Samsung have co-filed applications for more than 600 IPFs. Between 2008 and 2012 the two companies operated a joint venture, SB LiMotive, which specialised in developing and manufacturing Li-ion batteries for use in hybrid vehicles, plug-in hybrid vehicles and electric vehicles. R&D partnerships focused on the automotive sector can also be observed at national level. For example, there have been partnerships between Korean car manufacturers KIA and Hyundai, as well as between Japanese companies Panasonic and Toyota, and GS Yuasa and Honda.

It is also interesting to take note of the collaborative efforts between companies and universities or public research organisations. For example, co-applications by Foxconn and Tsinghua University in China, or by Toyota and the Japanese National Institute of Advanced Industrial Science and Technology, are proof of co-operation between public research organisations and companies. With policy incentives encouraging public–private co-operation in place in many countries, it is worth looking further at the benefits of such co-operation.

Table 5.1

Technology profiles of the top 15 applicants in battery technology, 2010-2018

	IPFs related to batteries				IPFs related to battery cells			
	Developments at cell level	Thermal management	Integration into equipment	Other battery developments	Lithium and Li-ion	Other chemistries	Engineering	Manufacturing
SAMSUNG [KR]	9.1%	5.9%	8.7%	5.1%	8.9%	2.9%	11.9%	8.7%
PANASONIC [JP]	7.0%	6.1%	6.2%	8.0%	7.1%	7.1%	6.6%	7.5%
LG ELECTRONICS [KR]	5.6%	6.9%	7.2%	3.0%	6.8%	1.0%	4.1%	7.4%
TOYOTA [JP]	4.3%	5.7%	3.7%	4.9%	4.7%	3.7%	3.1%	6.1%
BOSCH [DE]	2.3%	5.2%	4.7%	3.9%	2.6%	0.9%	2.4%	2.0%
HITACHI [JP]	2.1%	1.7%	1.3%	3.1%	2.3%	1.6%	1.7%	1.8%
SONY [JP]	2.0%	0.6%	1.7%	1.9%	2.8%	0.9%	1.1%	2.2%
NEC [JP]	1.4%	0.4%	0.9%	1.8%	2.0%	0.2%	0.8%	1.9%
NISSAN [JP]	1.4%	1.5%	1.4%	1.1%	1.7%	0.3%	1.0%	2.1%
TOSHIBA [JP]	1.3%	1.0%	1.7%	1.7%	1.7%	0.3%	0.9%	0.9%
GS YUASA [JP]	1.4%	1.0%	1.1%	1.0%	1.0%	2.7%	1.5%	1.3%
GENERAL MOTORS [US]	0.7%	2.8%	1.0%	1.7%	0.9%	0.5%	0.4%	0.9%
SUMITOMO EL. IND. [JP]	0.9%	0.8%	1.5%	1.1%	0.4%	3.0%	1.3%	0.6%
FORD [US]	0.3%	3.8%	2.3%	1.2%	0.2%	0.1%	0.7%	0.2%
FOXCONN [TW]	0.3%	0.1%	3.2%	0.8%	0.3%	0.1%	0.2%	0.3%

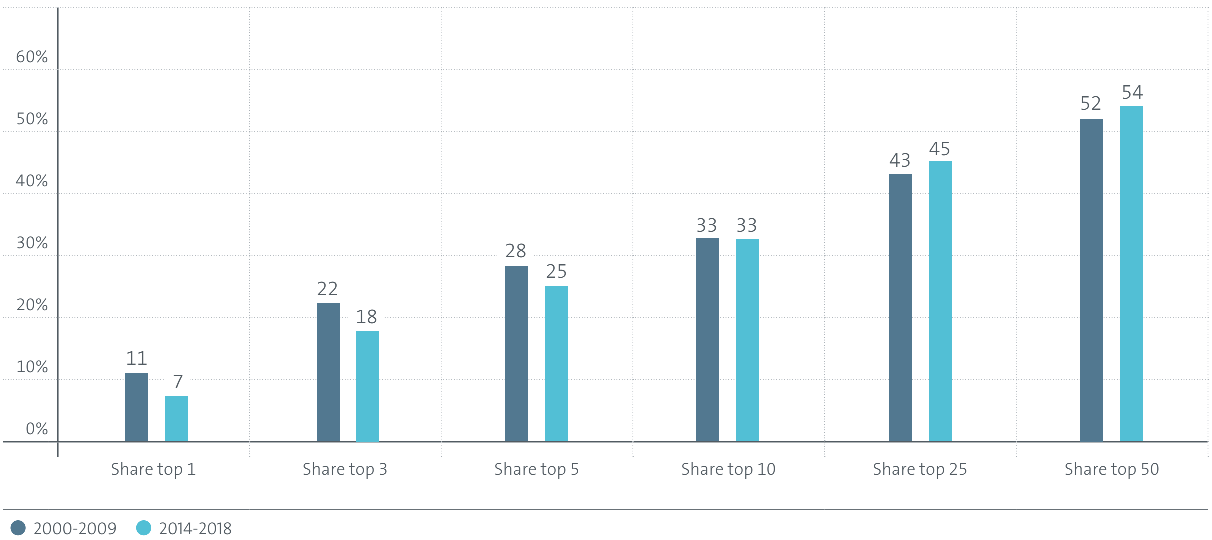
5.2 Applicant profiles

Together, the top 25 applicants have accounted for slightly less than half (47%) of all IPFs related to batteries since 2000. As indicated in Figure 5.3, this share has been rising slightly over the last five years, whereas the cumulative share of the top ten applicants has been falling to a similar extent. This trend towards a slight reduction in the concentration of innovation activities is a direct result of the interplay between established and new players: established innovators retain their importance but over the past decade have been joined by a rapid increase in innovation by new players (such as LG Electronics, Toyota and Bosch) looking to improve batteries for electric vehicles (Figure 3.2 above). It also suggests that the market for batteries is still growing and that the industry has not yet reached the trend towards concentration that can usually be observed at maturity.

Despite this slight trend toward diversification, innovation in battery technology is still mainly concentrated within a limited group of very large companies, which generated a stable share of about 80% of all IPFs related to batteries between 2000 and 2018 (Figure 5.4). The remaining share is split almost equally between SMEs and universities and public research organisations. With 358 IPFs, the CEA accounted for the majority of IPFs filed by universities and public research organisations in 2000-2018, followed by four Asian research organisations, namely Tsinghua University (141 IPFs), the Industrial Technology Research Institute (Chinese Tapei, 125 IPFs), the Korea Institute of Science and Technology (102 IPFs) and the Japanese National Institute of Technology (93 IPFs).

Figure 5.3

Trends in applicant concentration in battery technology

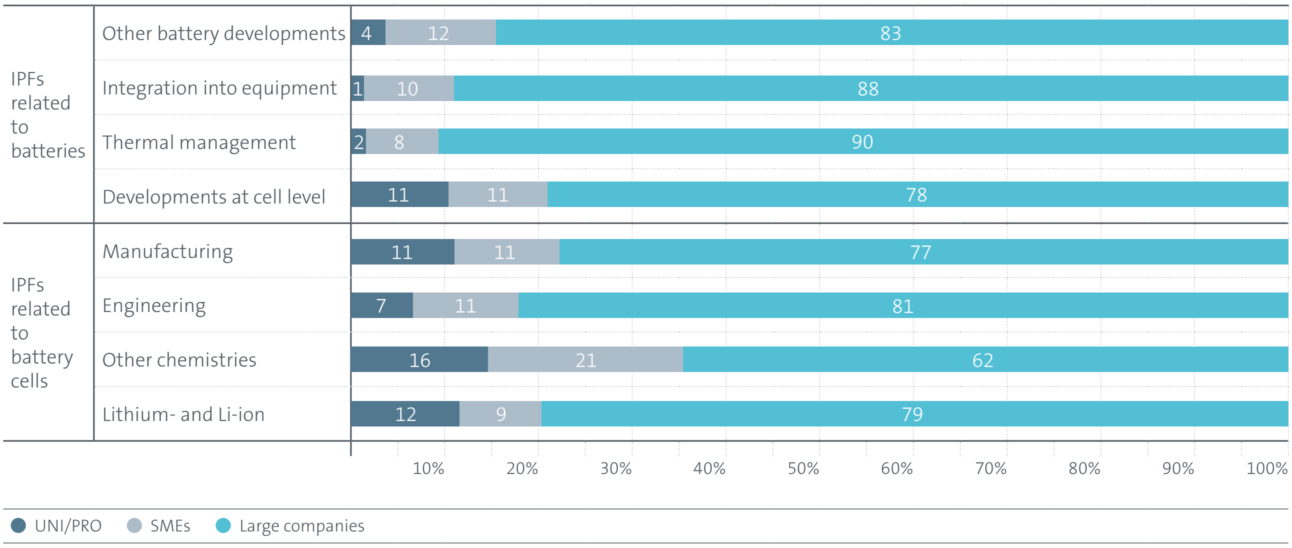


Source: European Patent Office

The profiles of the applicants also differ significantly between the sub-fields of battery technology (Figure 5.4). The proportion of SMEs and universities is much lower in fields more closely related to battery applications, such as integration into equipment and thermal management. By contrast, their contribution is higher in developments at the cell level, in particular for alternative chemistries to Li-ion. Universities account for 21% of IPFs in that field, and SMEs for another 16%.

Figure 5.4

Applicant profiles in battery technologies, 2000-2018



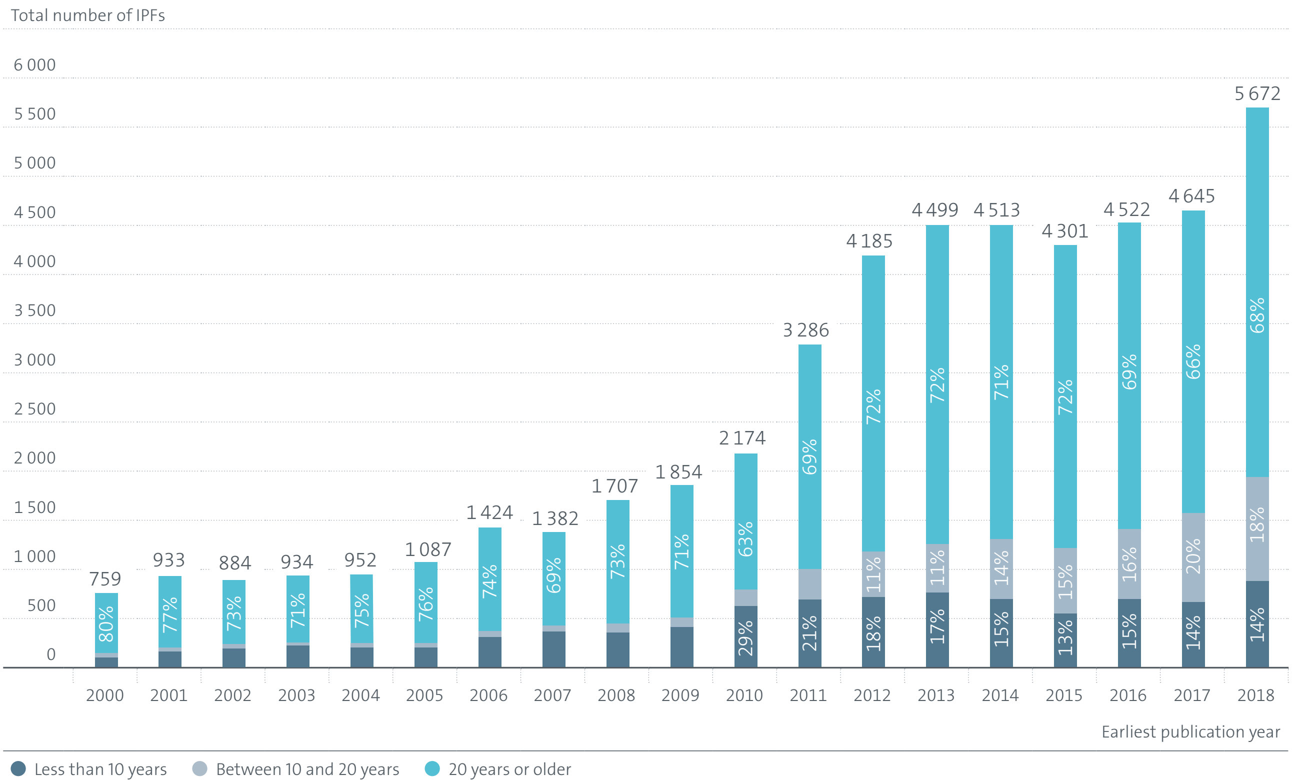
Source: European Patent Office

Among companies, 70% of IPFs in 2000-2018 were owned by entities that were more than 20 years old at the date of the IPF publication, meaning that up to 30% of IPFs were filed by companies less than 20 years old, most of which were actually less than ten years old at the date of publication. While the share of IPFs held by older companies has remained relatively stable over the last decade, the share of companies between ten and 20 years old almost doubled, rising to 18% in 2018, and the share of very young companies (less than ten years old) decreased (Figure 5.5).

Given the oft-presumed links between company dynamics (entry and exit) and the generation of breakthrough technologies, this is an area that warrants further attention. As such, further work could explore these links in greater detail, as well as the extent to which patents differ in their degree of "radicalness" based on organisational characteristics such as applicant age and type (e.g. company vs. university/public research organisation).

Figure 5.5

Age distribution of company applicants in battery technology, 2000-2018



Source: European Patent Office

6. Geographic origins of innovation in battery technology

6. Geographic origins of innovation in battery technology

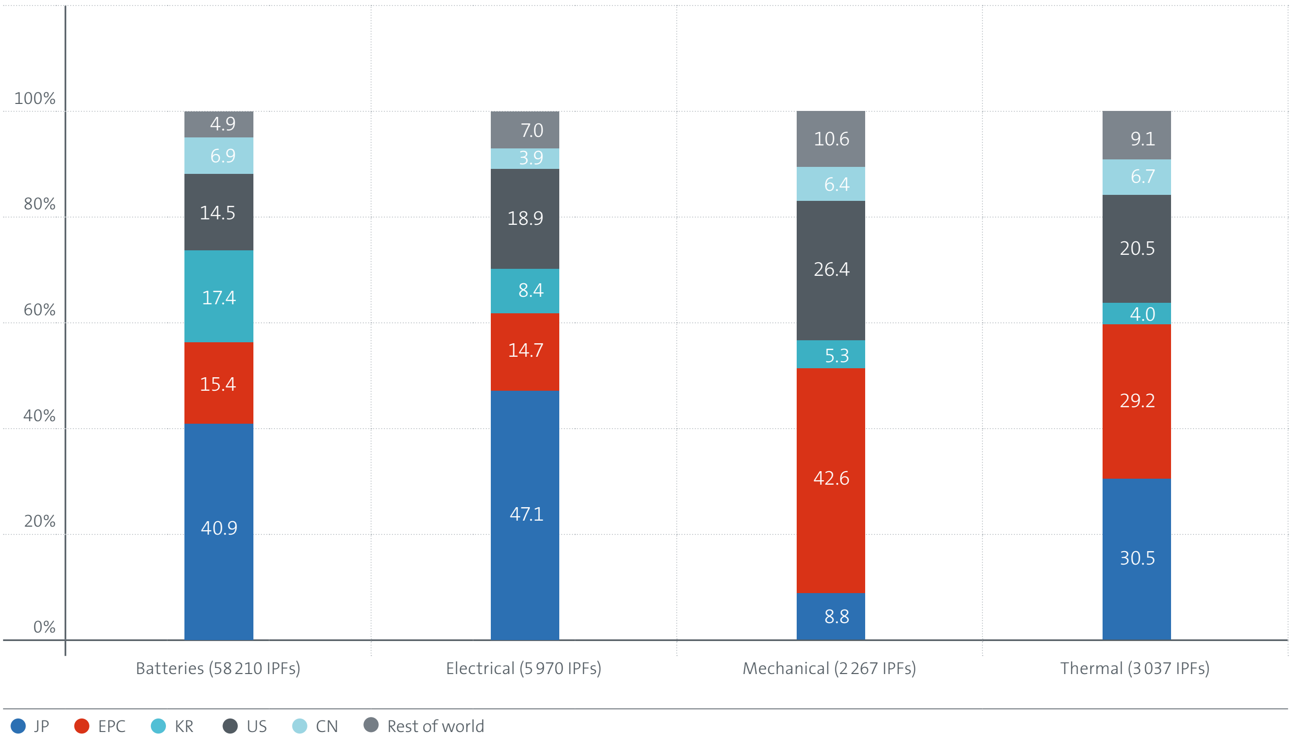
As documented above, most of the top applicants in battery technology are multinational corporations that have operations and R&D activities spanning many regions and countries. Therefore, applicant information does not always reveal where an innovation actually took place. This Section looks at the geographic origins of the inventors behind the IPFs related to battery technologies to identify the top innovation centres in the world and their technology specialisation profiles.

6.1 Global distribution of battery inventions

Figure 6.1 shows the geographic distribution of battery inventors in relation to the geographic distribution of inventors in other electricity storage technologies in 2000-2018. Japan is the clear leader in the two largest and most dynamic fields, its shares of IPFs related to batteries (40.9%) and electrical storage (47.1%) exceeding the combined shares of the second and third largest innovation centres in these fields. The Republic of Korea, Europe and the United States are next in the ranking in these two fields: they all hold roughly equal shares of IPFs in batteries, while the United States and Europe pull ahead of the Republic of Korea in the field of electrical storage. This trend is in stark contrast to the smaller and less dynamic fields of mechanical and thermal storage, where European inventors have a very strong position.

Figure 6.1

Geographic origins of IPFs in electricity storage technologies, 2000-2018



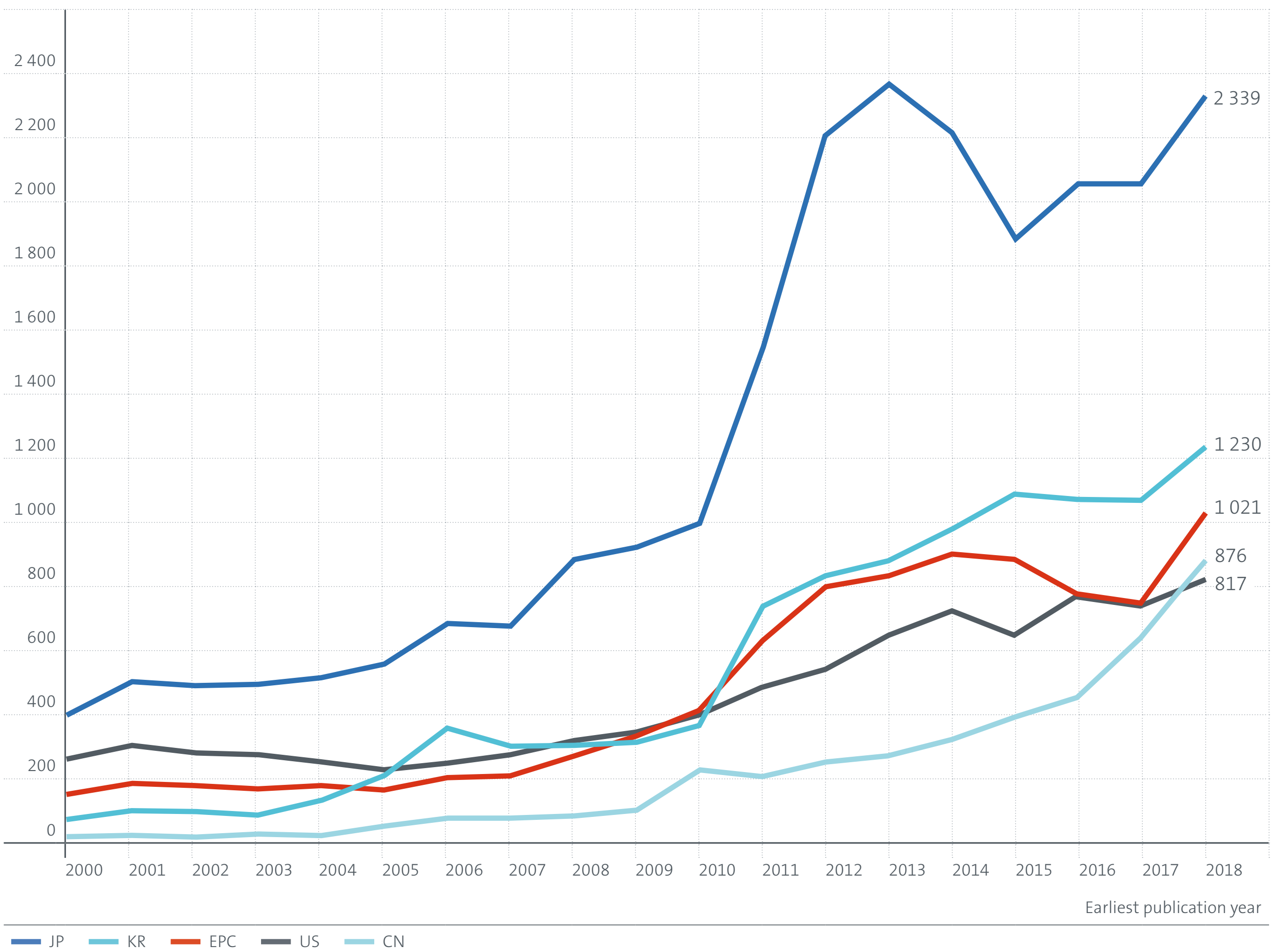
Source: European Patent Office

Japan has built on the global lead in battery technology it gained in the 2000s, gradually reinforcing its position between 2005 and 2015, during which time it saw a rapid rise in innovation in 2011-2012 in particular (Figure 6.2). It is noticeable, however, that Japan's leadership in battery technology has not yet translated into a large share of the global electric car market. The country represented just 2% of the global market in 2019, although Li-ion batteries are offered in some non-plug-in hybrids like the Toyota Prius. The Republic of Korea also experienced an acceleration of innovative activities around 2010, ranking second after Japan in 2018 after overtaking Europe and the United States in 2010-2011. The Republic of Korea has a similar share of the electric car market, but is a leader in stationary batteries for utility-scale power grid services and behind-the-meter applications in buildings.

Chinese inventors have been responsible for a notable national increase in electricity storage innovation over the last decade. As a result, the country had almost caught up with the United States in 2018 and now makes a similar contribution to global electricity storage innovation to Europe. This mirrors China's contribution to electric vehicle manufacturing in recent years. In 2011, 5 000 electric cars were sold in the country, representing 11% of the global electric car market. With 1.1 million cars, Chinese sales accounted for 50% of the global market in 2019. BYD, a battery and electric vehicle manufacturer, is the leading global producer of electric buses and sells a similar number of electric cars as Tesla.

Figure 6.2

Trends in IPFs in battery technology by geographic origin, 2000-2018

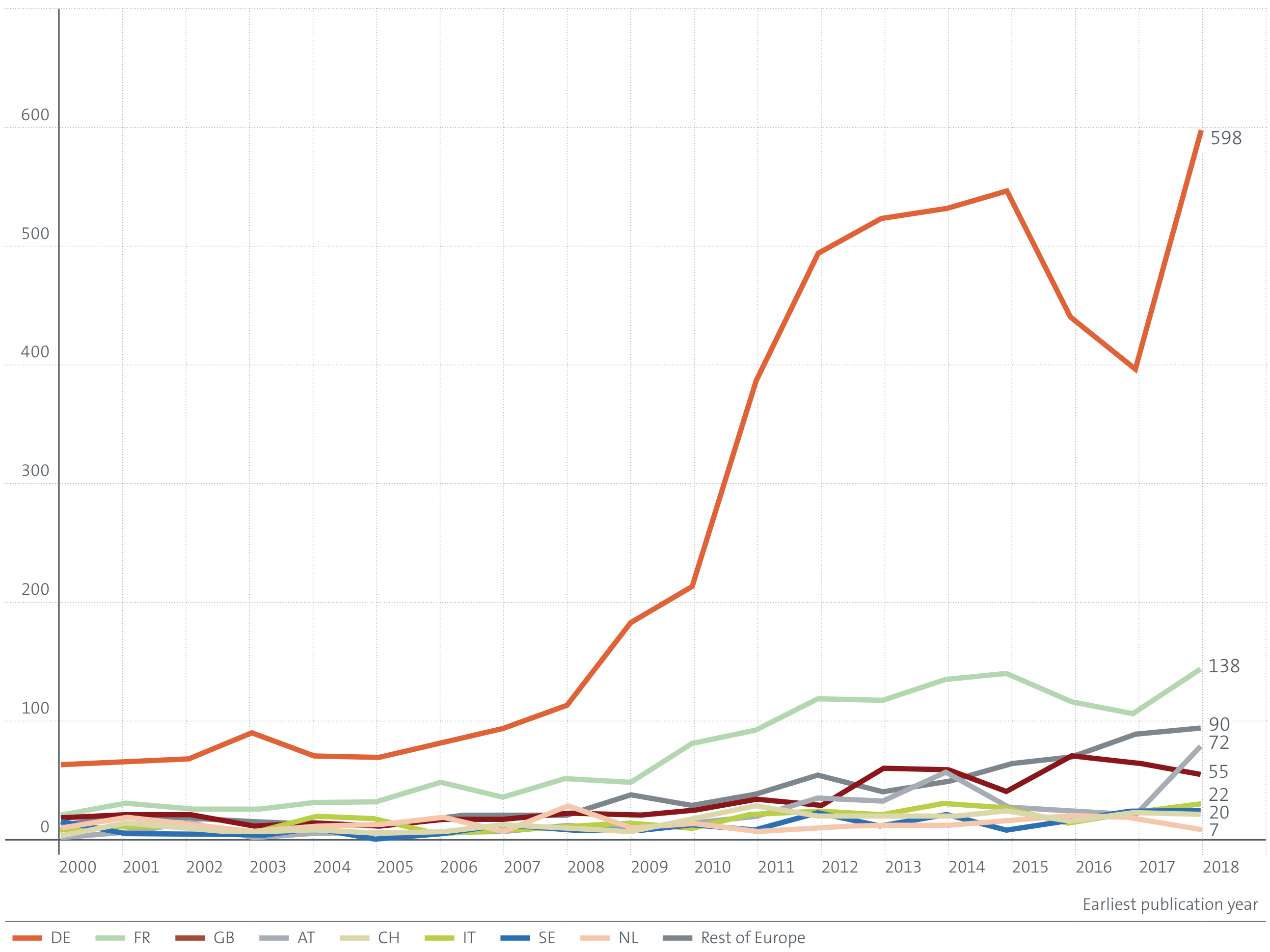


Source: European Patent Office

In Europe, innovation for battery technologies is largely dominated by Germany, which dramatically increased its lead over other European countries in 2008-2012 (Figure 6.3). Germany alone accounted for more than half of IPFs originating from Europe in 2000-2018, and is home to four of the five European entities in the top 25 battery applicants (Figure 5.1). France is the second most innovative country in Europe, responsible for less than 1% of IPFs related to batteries in 2000-2018 and home to one entity (the CEA) in the top 25.

Figure 6.3

Geographic origins of European IPFs in battery technology, 2000-2018



Source: European Patent Office

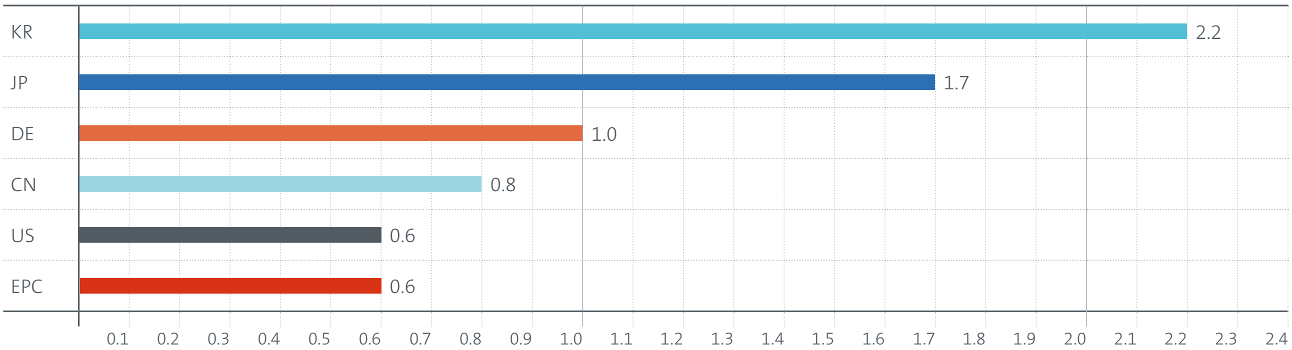
6.2 Country profiles

For governments seeking to understand their country's comparative advantage in battery technology, the revealed technological advantage (RTA) index indicates a country's relative specialisation in battery technology innovation in relation to other countries.[9] An RTA above one indicates that a country tends to produce more innovation in a given technology – batteries in this case – than it does in others. Conversely, in the absence of significant policy incentives, countries with a lower RTA in a given technology are likely to face a bigger challenge in developing the technological leadership needed to add significant value to their economy in future decades. Exploring the links between policy-setting and individual countries' RTAs in different fields is an important area for future research.

The RTA of the main innovation centres is reported for 2014-2018 in Figure 6.4. It underlines the stark contrasts between the world regions leading the race in battery innovation. The Republic of Korea and Japan stand ahead of the competition, with a very strong specialisation in this domain, while the United States, China and European countries show no specialisation. In Europe, Germany is the clear frontrunner with an RTA of close to one for 2014-2018, significantly up from its RTA of 0.7 in 2000-2013.

Figure 6.4

Revealed technological advantage in battery technology, 2014-2018



Source: European Patent Office

Note: EPC countries means the 38 contracting states to the European Patent Convention. Germany is also reported on separately owing to its outstanding contribution to innovation in battery technology.

9 RTA is defined here as a country's share of global battery-related IPFs divided by the country's share of IPFs in all fields of technology.

Table 6.1 presents further details of the specialisation profiles of the top five innovation centres for the different battery technologies and for technologies at the cell level. While Japan is the leader in all four general battery areas, it accounts for particularly high shares in developments at the cell level and other battery developments, with its shares in thermal management and integration into equipment somewhat lower. By contrast, Europe stands out as a major centre of innovation in these two fields, accounting for 29.1% of IPFs related to thermal management and 21.9% related to integration into equipment. The Republic of Korea's strengths lie in developments at the cell level (19.1%) and battery integration (18.4%). The United States' shares are almost equal in all four areas, whereas China's share is highest in other battery developments (10.1%), followed by battery integration (8.7%).

At the cell level, Japan tops the ranking in all fields, but its shares are particularly high when it comes to lithium and Li-ion batteries (45.9%) and the manufacturing of battery cells (43.1%). The Republic of Korea also performs well in all cell-level fields except for other chemistries, revealing its focus on lithium and Li-ion batteries. Europe and the United States, on the other hand, hold relatively high shares in batteries with other chemistries, at 19.5% and 25.0%, respectively.

Table 6.1

Profiles of leading innovation centres in battery technology, 2000-2018

		IPFs related to batteries				IPFs related to battery cells			
	Batteries	Develop-ments at cell level	Thermal management	Integration into equipment	Other battery develop-ments	Lithium and Li-ion	Other chemistries	Engineering	Manu-facturing
JP	40.9%	42.3%	28.9%	31.0%	41.6%	45.9%	35.2%	37.3%	43.1%
KR	17.4%	19.1%	16.0%	18.4%	10.7%	19.9%	8.3%	20.6%	20.8%
EPC	15.4%	13.8%	29.1%	21.9%	17.0%	11.9%	19.5%	15.7%	12.3%
DE	8.7%	7.7%	19.3%	14.0%	9.6%	6.9%	7.8%	9.1%	6.4%
US	14.5%	14.5%	16.3%	14.2%	14.2%	12.6%	25.0%	15.2%	14.2%
CN	6.9%	5.8%	5.8%	8.7%	10.1%	6.2%	4.2%	6.3%	5.6%

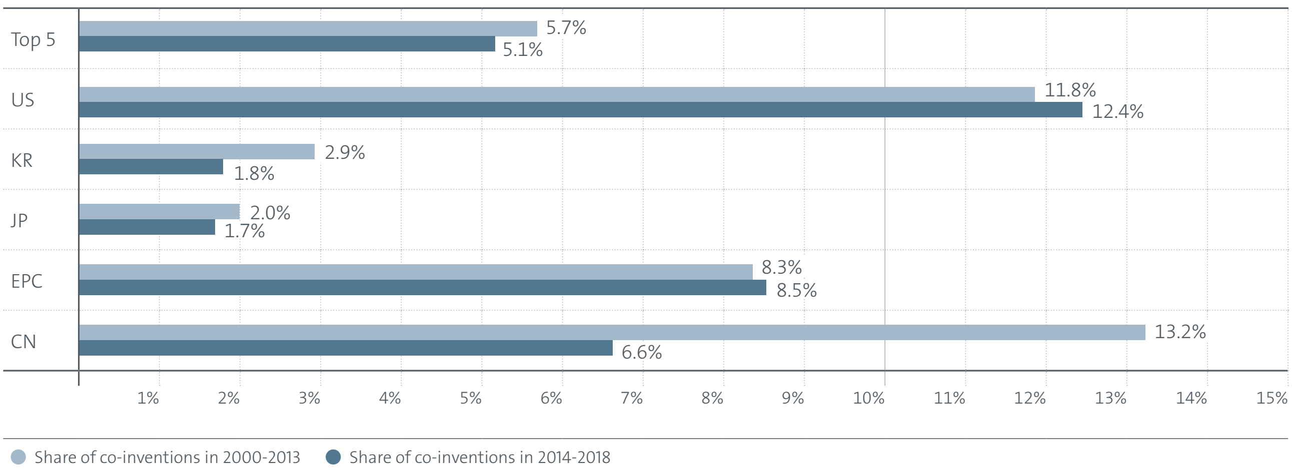
These differences between regions reveal the potential benefits associated with international research collaboration and exploiting complementary fields of specialisation. In this context, the evolution of international co-inventions from 2000-2018 shows the development paths of the main innovation centres from a new angle (Figure 6.5).

While Europe and the United States have seen their relative contributions to innovation in batteries decrease over the last five years, their involvement in international co-inventions has risen over the same period (from 8.3% to 8.5% in Europe and from 11.8% to 12.4% in the United States). Moreover, they carry out most of their international research collaboration with each other: 40% of European co-inventions and 55% of US co-inventions stem from transatlantic collaboration, leaving only a marginal role to research partners located in Asia. Since international research collaboration is an important vehicle through which firms can "access" the global frontier, delving deeper into the links between such collaboration and subsequent innovation activity would provide valuable insights.

By contrast, the rapid rise of China in battery innovation has been accompanied by a sharp decrease in the number of Chinese IPFs involving foreign co-inventors (from 13.2% to 6.6%). This may be due to Chinese innovation being less dependent on foreign support and the country's increasing expertise and reliance on home-grown inventions. Likewise, the Republic of Korea and Japan, which have traditionally had relatively low levels of co-inventions, saw further decreases, with the share of foreign co-inventors dropping from 2.9% to 1.8% in the case of the Republic of Korea and from 2.0% to 1.7% in the case of Japan. In total, the share of IPFs co-invented with inventors from other countries decreased from 5.7% for IPFs published between 2000 and 2013 to 5.1% for 2014-2018.

Figure 6.5

Share of IPFs involving foreign co-inventors

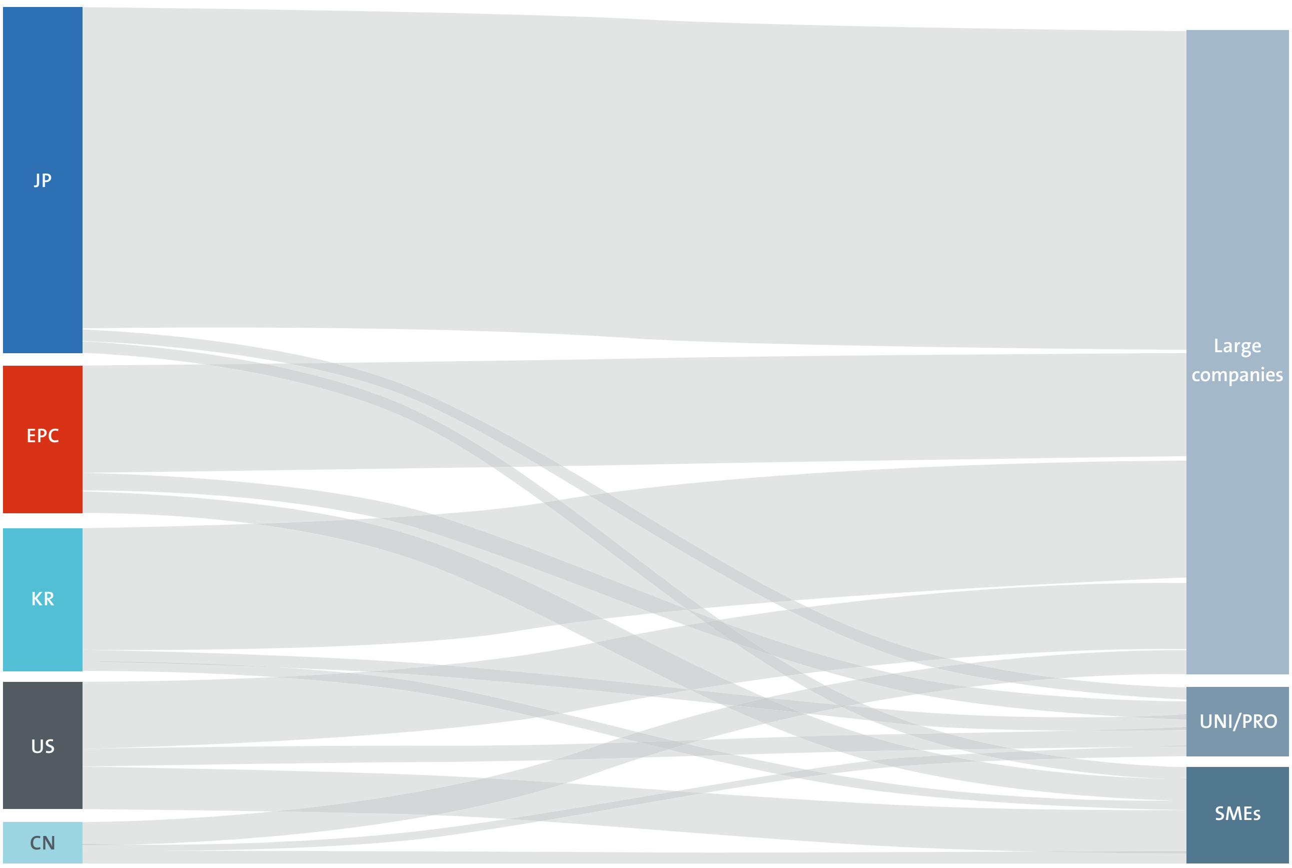


Source: European Patent Office

A further analysis of applicant characteristics also reveals some differences between different Asian countries on the one hand, and between the United States and Europe on the other (Figure 6.6). Innovative activity in Japan and the Republic of Korea is largely carried out by large or very large companies, with only a relatively small proportion of IPFs contributed by small companies (3.4% in Japan and 4.6% in the Republic of Korea) and universities or research organisations (3.5% in Japan and 9.0% in the Republic of Korea). By contrast, contribution from SMEs and universities is much larger in the United States (34.4% and 13.8%, respectively). The same is true – albeit to a lesser extent – for European countries, with SMEs accounting for a share of 15.9% and universities and public research organisations for a share of 12.7%. As a result, European countries are the second largest source of IPFs from SMEs and universities after the United States, despite only ranking fourth in terms of number of IPFs related to batteries.

Figure 6.6

Distribution of applicant types by applicant country, 2000-2018



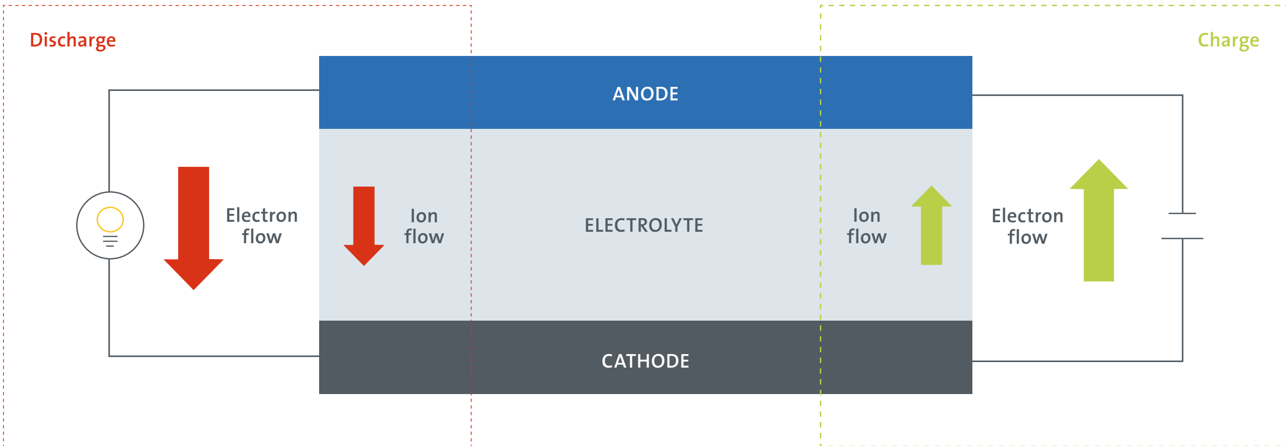
7. Recent developments in lithium-ion chemistries

7. Recent developments in lithium-ion chemistries

The high level of innovative activity in Li-ion technology, which alone was responsible for 40% of all IPFs in battery technologies between 2000 and 2018, is in part due to the different performance criteria of different battery applications on the one hand, and to the current lack of a dominant battery cell design for each application on the other. For example, smartphones, power tools, electric cars and utility-scale stationary batteries have different requirements and tolerances for energy and power density, durability, material costs, sensitivity and stability. While some of these features can be improved through innovation in manufacturing and engineering, their theoretical limits are defined by the core components – the battery electrodes and electrolyte – through which electricity is stored and conducted (Figure 7.1). This chapter therefore focuses on recent developments in these core elements.

Figure 7.1

Main components of rechargeable batteries



Source: Own research by EPO and IEA

7.1 Technology trends in lithium-ion chemistries

The number of IPFs related to electrode (cathodes and anodes) materials for Li-ion batteries has been increasing at a virtually steady rate since 2000. An extremely fast growth period was observed between 2010 and 2013, during which time the number of IPFs increased from 355 to almost 900. In 2018 around 40% of Li-ion IPFs were related to innovation in electrodes.[10] As illustrated in Table 7.1, a great variety of materials are being explored, with different properties and potential fields of application.

The cathode of Li-ion batteries has been the focus of the most intense inventive competition because it is the limiting factor in determining energy density (the amount of energy that can be stored per unit of battery volume), specific energy (the amount of energy that can be stored per unit of battery mass), and cost reductions. Energy density is very important for portable devices, for example for ensuring that smartphones still only need to be charged once a day despite the increasing energy demands of their applications. However, both energy density and specific energy are more important still for electric vehicles, which must match the performance and costs of internal combustion engine vehicles while keeping the weight of vehicles under control.

Table 7.1

Overview of lithium-ion electrode materials

Cathode materials	Main properties	Current main application areas
Lithium cobalt oxide (LCO)	– Excellent energy density and high cycling stability – High output voltage – High cost due to limited availability of cobalt	Portable electronics
Lithium nickel cobalt manganese oxide (NMC)	– High energy density and high capacity – High output voltage – Nickel improves capacity but is associated with low thermal and chemical stability – Cobalt improves charge/discharge kinetics but is expensive and in short supply – Manganese improves stability – Moving from NMC 811 to NMC 111, better thermal stability and capacity retention are achieved while discharge capacity decreases	Electric vehicles, portable electronics
Lithium nickel cobalt aluminium oxide (NCA)	– Highest energy density compared with NMC – Cathode materials with similar nickel content, high capacity – Lower safety than NMC	Electric vehicles, portable electronics
Lithium manganese oxide spinel (LMO)	– Moderate capacity and moderate energy density, good safety – Short lifetime	Power tools, medical devices
Lithium iron phosphate (LFP)	– Higher thermal and chemical stability than NMC, constant output voltage, longer cyclability, inexpensive and no toxic materials – Lower energy density and lower capacity than NMC	Stationary, electric vehicles, power tools

Anode materials	Main properties	Current main application areas
Lithium titanate oxide (LTO)	– High safety, long lifetime, high charging/discharging rate, longer cyclability, no toxic materials – Low energy density, lower capacity, lower output voltage	Stationary, small electric vehicles
Carbon/graphite/soft carbon/hard carbon	– High voltage output, high capacity, high energy density, good stability, low cost – Limited fast-charging performance at low temperatures	All high-energy Li-ion batteries
Lithium	– High energy density, high capacity, high output voltage – Safety issues due to thermal runaway and dendritic growth – Expensive to handle, need for inert atmosphere	No applications in secondary lithium batteries
Silicon	– High capacity – Poor cycling stability due to large volume expansion during cycling	Combined in small quantities with carbon-based anodes

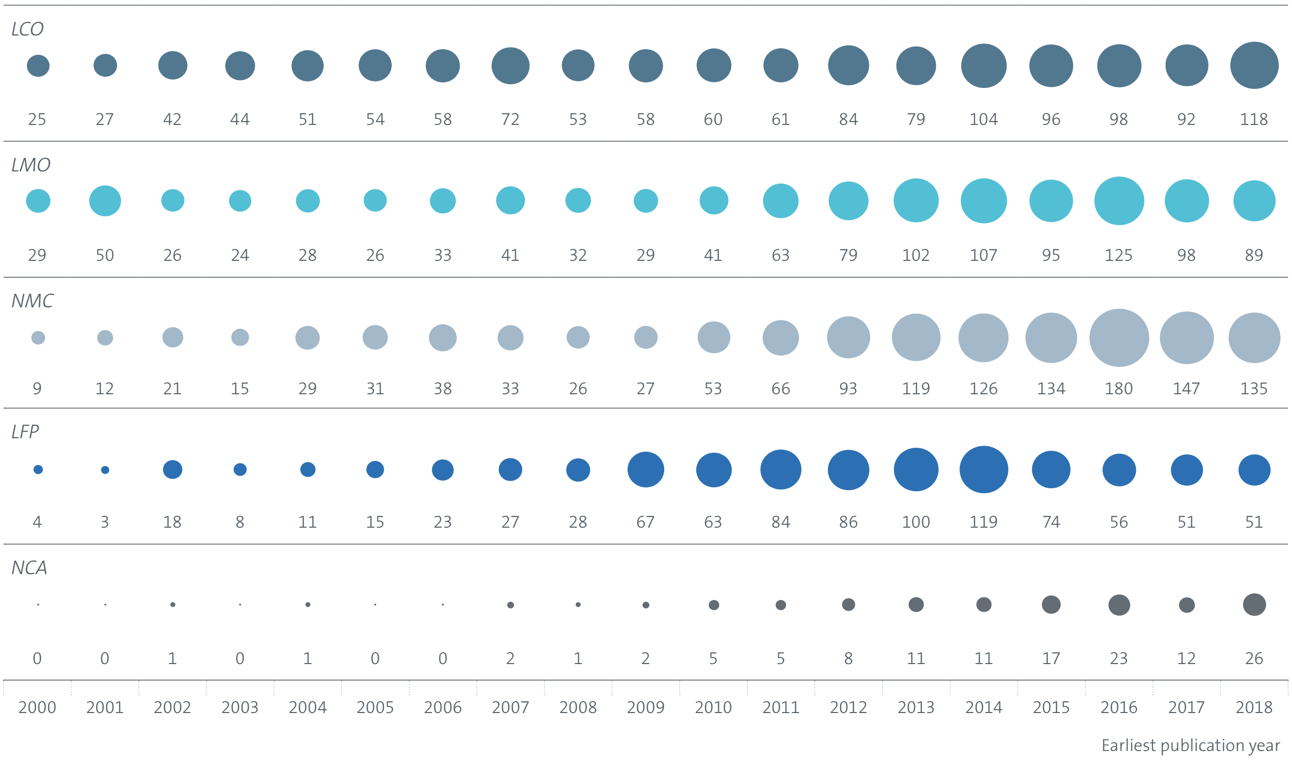
10 The other 60% are related to engineering – for example, focusing on thinner current collectors, thinner separators, higher voltages, and reduced electrolyte amounts – rather than substantial material developments. The share of inventions related to electrode materials has always fluctuated between 35% and 45%, suggesting that material developments have mostly developed in line with engineering and manufacturing techniques for Li-ion batteries.

The first serial production electric cars, launched just over a decade ago, used the same cathodes as those predominantly used in consumer electronics: lithium cobalt oxide (LCO) and lithium manganese oxide (LMO). Since then, the focus has moved onto other compositions, including NMC and LFP, owing to a shift in technical challenges away from maximising energy density and stability and towards improving specific energy (energy per unit mass), durability, power output, charge/discharge speed and recyclability. This trend can be seen in the patenting data: LCO patenting activity was double that of NMC in 2005, but overtaken by NMC in 2011, with NMC patenting activity rising by 400% between 2009 and 2018 (Figure 7.2). By way of comparison, over the same period LCO patents rose by just 200%. Today, NMC is generally regarded as having the best potential for electric vehicles in the near term, and researchers are continuing to work on ways to reduce the proportion of cobalt, which largely determines the overall cost and sustainability.

While the leading NMC designs have seen impressive modifications in recent years, tailoring battery performance to the application at hand and changing the proportion of metals used on the basis of their costs, NMC itself is expected to be displaced in due course. NCA in particular is increasingly in the spotlight as a promising alternative. NCA chemistry is based on the same chemistry behind NMC, and NCA batteries are already being used by Panasonic and Tesla for electric vehicles. Other leader companies such as Tesla and BYD are bringing to the market improved LFP-based batteries for their vehicles. The level of patenting activity in this area remains limited, but increased from almost zero before 2010 to levels closer to those of more established cathode chemistries by 2018.

Figure 7.2

Number of IPFs in lithium-ion cathode materials, 2000-2018

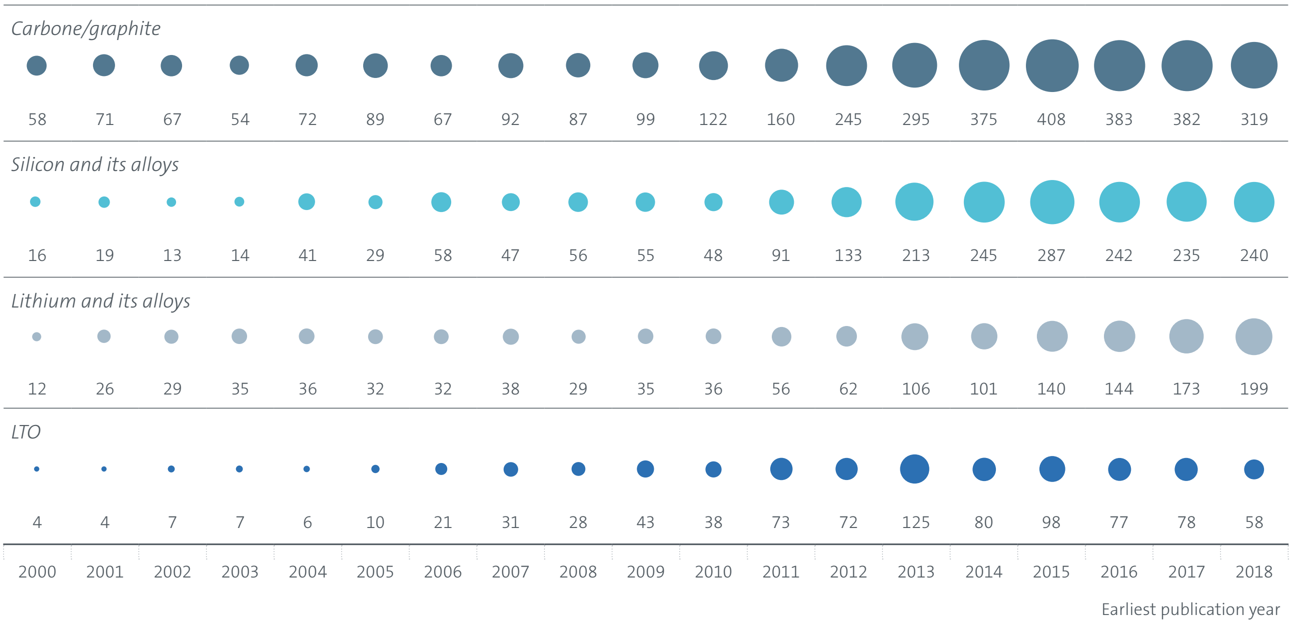


Source: European Patent Office

Innovation in Li-ion anodes is also on the rise. Carbon materials have generated the highest number of IPFs over the past decade, with a 200% rise in innovation between 2010 and 2015 (Figure 7.3). Such materials, in particular graphite, are generally used as the active material for anodes in commercial Li-ion cells (particularly in portable devices) owing to their low costs, accessibility and favourable electrochemical properties. However, graphite anodes come with limitations, such as poor lithium intercalation capacity, opening the door for alternative anode materials to take their place. Lithium alloy metals (such as lithium-aluminium and lithium-silicon) are currently the second most commonly used anode materials. In terms of innovation, they are currently the third largest group of IPFs for anode materials, but growing fast: after quadrupling between 2011 and 2018 to reach almost 200 IPFs in 2018, it is the only group of anode technologies currently experiencing strong growth.

Figure 7.3

Number of IPFs in lithium-ion anode materials, 2000-2018



Source: European Patent Office

Silicon and lithium titanate oxide (LTO) are other active materials currently being developed as alternatives to carbon anodes, but both technologies are struggling to meet the very high expectations established a decade ago. Silicon can store a considerably higher amount of charge than graphite and therefore facilitate longer durations of energy storage, but managing its tendency to swell when charged is an active area of research. Silicon-based anodes are associated with poor cycling stability, currently preventing them from being used in more than small amounts in combination with carbon-based anodes. According to the number of IPFs, silicon-based materials are the second largest anode material category. However, after the category peaked in 2015 with 287 IPFs, numbers quickly fell to around 240 in the following years. LTO is attracting significant interest for a different reason: it enables very fast charging. Innovation in LTO likewise reached a peak in 2013, but has seen a declining trend since then. Owing to the lower voltages of batteries featuring LTO, leading to lower energy density with respect to graphite anodes, LTO is currently limited to applications that do not require high energy density, such as stationary applications and small electric vehicles.

BOX 7.1

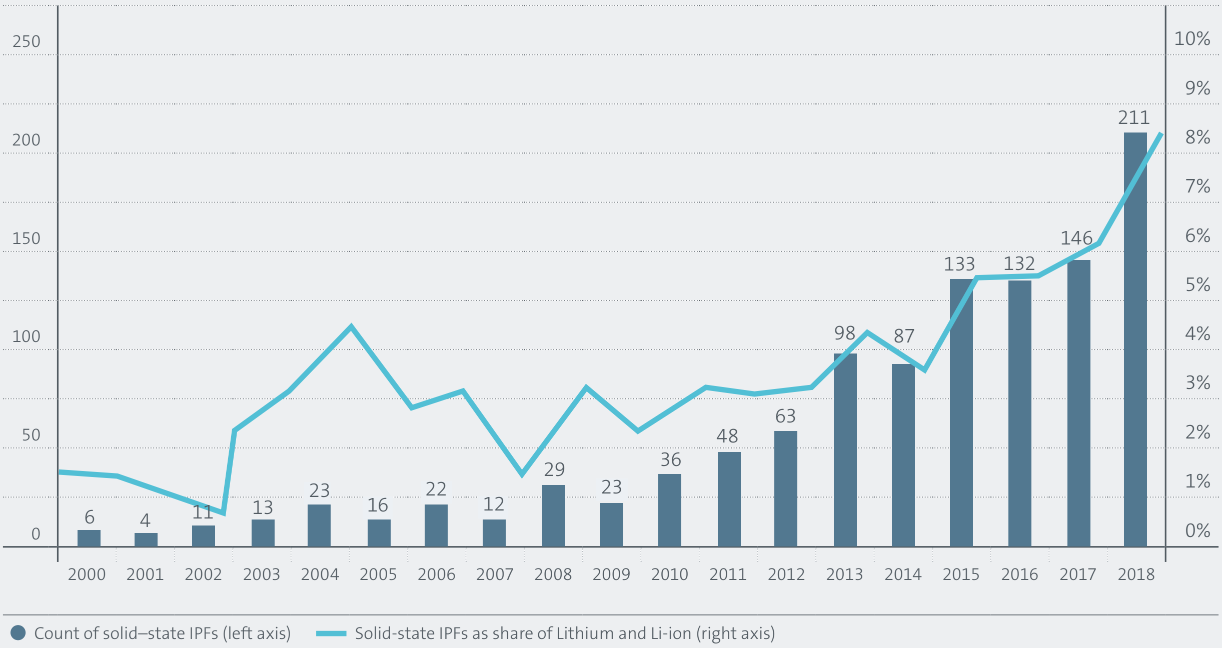
Solid-state batteries

Solid-state electrolytes are another major area of innovation today, with rising patenting activity revealing an emerging trend in the hunt for the next generation of Li-ion batteries. Electrolytes form the focus of inventive activity, with efforts underway to find alternatives to the liquid or polymer gel electrolytes used in current Li-ion batteries, which pose a flammability risk. Solid-state electrolytes feature a high level of specific energy and high degree of stability, but are currently expensive.

Patenting activity in this area has been growing by 25% per year on average since 2010. In 2018 it represented more than 8% of all patenting activity in Li-ion technology, compared with 3% in 2010. Innovators are targeting some of the shortcomings found in existing devices, including low lithium-ion conductivity, high contact resistance at the electrolyte/electrode interface and reliance on high-cost and scarce materials. Commercial applications of solid-state electrolytes in electric vehicles are anticipated in the next decade, and could generate spillovers that would help to make these batteries competitive for other applications, too.

Figure 7.4

IPFs related to solid-state lithium-ion technology, 2000-2018



Source: European Patent Office

7.2 Profiles of recent applicants in lithium-ion chemistries

Together, the top 15 applicants in Li-ion batteries in 2014-2018 accounted for a slightly lower share of IPFs related to electrode materials and solid-state batteries than those related to Li-ion technology in general (Table 7.2). The applicants' shares vary significantly between sub-fields, however, especially for cathode materials, with a high cumulative share of IPFs recorded in dominant chemistries such as NMC (50.6%) and LMO (44.5%), and a relatively small share of IPFs seen in emerging fields like NCA (27.9%) and LFP (29%). This kind of pattern is common, and shows that emerging fields are more likely to attract new entrants and new competition.

Although the top two applicants, LG Electronics and Samsung, have strong positions in a large numbers of fields, they are not active in all of them equally. Both LG Electronics and Samsung have a high share of IPFs related to LCO, a cathode chemistry long established in the area of electronics. In addition, Samsung has a strong foothold in the areas of NMC and NCA for cathodes, and silicon and its alloys for anodes. The trend towards selective specialisation can also be seen among some of the other top applicants, such as Toyota, a strong contributor to innovation in solid-state batteries, and Toshiba, which boasts a lead in LTO for anodes and, to a lesser extent, LMO for anodes.

Table 7.2

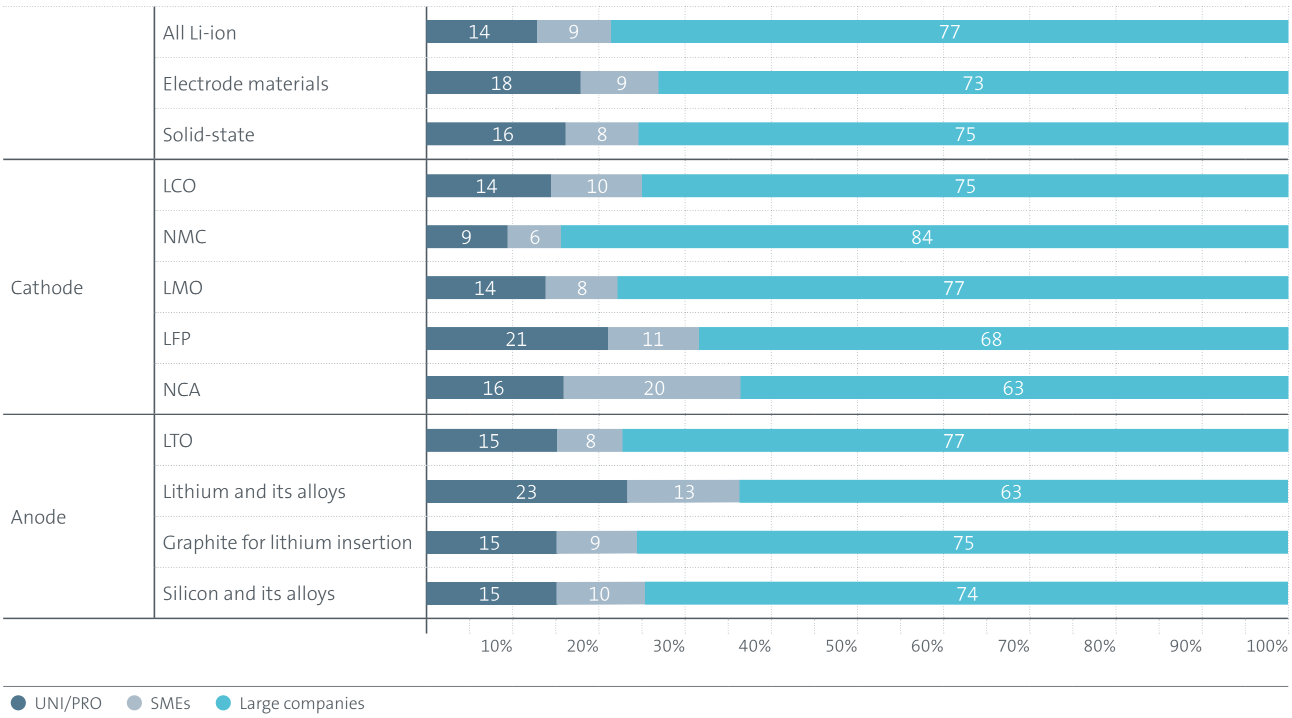
Technology profiles of top applicants in lithium-ion batteries, 2014-2018

				Cathode materials					Anode materials			
	All Li-ion	Electrode materials	Solid-state	LCO	NMC	LMO	LFP	NCA	LTO	Lithium & alloys	Graphite	Silicon & alloys
Top 15 Li-ion applicants	46.4%	41.1%	42.2%	39.3%	50.6%	44.5%	29.0%	27.9%	44.8%	34.8%	40.1%	44.3%
LG ELECTRONICS [KR]	9.3%	8.4%	1.6%	12.4%	6.9%	7.4%	8.8%	2.2%	7.2%	10.4%	8.0%	6.6%
SAMSUNG [KR]	8.0%	8.3%	4.9%	12.8%	10.7%	7.0%	5.7%	15.7%	4.6%	7.8%	7.0%	11.3%
TOYOTA [JP]	5.3%	3.7%	15.4%	1.4%	4.8%	5.8%	3.1%	0.0%	1.8%	3.2%	3.6%	4.0%
PANASONIC [JP]	4.2%	4.2%	4.2%	3.3%	6.4%	1.4%	0.3%	4.5%	3.3%	2.2%	4.8%	4.6%
BOSCH [DE]	3.7%	2.5%	4.5%	0.4%	1.5%	0.4%	0.0%	2.2%	0.8%	6.2%	1.2%	3.4%
HITACHI [JP]	2.4%	1.8%	3.0%	0.8%	3.2%	3.1%	0.3%	0.0%	2.3%	1.1%	2.5%	2.0%
NEC [JP]	2.2%	2.6%	0.1%	0.8%	3.5%	3.9%	0.0%	0.0%	0.5%	0.4%	3.9%	2.2%
TOSHIBA [JP]	1.9%	2.8%	0.8%	1.8%	3.5%	6.8%	2.0%	0.0%	21.0%	0.1%	1.3%	1.8%
NISSAN [JP]	1.8%	2.1%	0.1%	1.2%	5.4%	5.3%	0.0%	1.1%	0.0%	0.3%	2.2%	3.8%
SUMITOMO CHEMICAL [JP]	1.4%	0.4%	0.1%	0.0%	1.4%	0.6%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%
ZEON [JP]	1.4%	0.5%	0.7%	0.4%	0.3%	0.0%	0.0%	0.0%	0.0%	0.3%	0.8%	1.0%
MURATA MANUFACTURING [JP]	1.3%	0.9%	3.2%	1.6%	0.8%	0.8%	2.8%	0.0%	1.5%	0.3%	0.9%	1.0%
TDK [JP]	1.2%	0.8%	2.8%	1.6%	1.1%	1.2%	1.7%	1.1%	0.3%	0.9%	0.6%	0.9%
GS YUASA [JP]	1.2%	1.0%	0.0%	0.6%	1.0%	0.6%	2.3%	0.0%	0.0%	0.1%	1.9%	0.0%
CEA [FR]	1.1%	1.1%	0.8%	0.2%	0.1%	0.2%	2.0%	1.1%	1.5%	1.5%	1.0%	1.7%

While 78% of IPFs in Li-ion technology in general originate in large companies, SMEs, universities and public research organisations play a more important role in emerging fields of technology, such as novel cathode and anode materials for Li-ion batteries (Figure 7.5). Universities and public research organisations are especially important for lithium and its alloys for anodes (23%) and LFP (21%). Today, small companies are outpacing universities and public research organisations in the area of NCA, boasting an IPF share of 20%. These shares provide an insight into the relative maturity of competing options. By comparison, in the early days of LCO and LMO cathodes, it was universities that led the way, before large corporations, mostly in Japan, took over the development of the batteries once they started to be integrated into consumer products like camcorders in the early 1990s.

Figure 7.5

Applicant categories in lithium-ion batteries, 2014-2018



Source: European Patent Office

7.3 Geographic origins of innovation in lithium-ion chemistries

The geographic origins of IPFs in established electrode materials (Table 7.3) tend to confirm the global ranking for Li-ion innovation. Japan is dominant in the areas of NMC (47%), LMO (51%) and LTO (50%), and stands on a par with the Republic of Korea when it comes to LCO, accounting for 28% of IPFs. In line with its global position in Li-ion technology, the Republic of Korea ranks first in LCO (30%) and second in the other fields. It is followed by the United States, which performs better in these fields than in Li-ion innovation in general. By contrast, European countries hold modest positions in all categories, even in comparison with their share of all Li-ion IPFs.

Table 7.3

Geographic distribution of IPFs in lithium-ion batteries, 2014-2018

		CN	KR	JP	US	EPC	Rest of world
Cathode materials	All Li-ion	9.0%	21.9%	41.6%	11.8%	12.3%	3.4%
	Electrode materials	8.1%	22.7%	39.6%	14.9%	10.6%	4.1%
	Solid-state	1.6%	12.2%	54.3%	18.3%	12.3%	6.0%
	LCO	11.6%	30.4%	28.5%	20.5%	4.5%	4.5%
	NMC	6.0%	23.5%	47.3%	14.9%	4.8%	3.6%
	LMO	6.7%	16.8%	51.1%	16.2%	5.4%	3.8%
	LFP	16.2%	17.7%	30.9%	16.4%	11.2%	7.6%
	NCA	9.4%	23.6%	16.2%	35.6%	11.1%	4.1%
Anode materials	LTO	11.9%	13.6%	49.9%	14.1%	6.9%	3.7%
	Lithium and its alloys	5.1%	24.2%	18.4%	28.8%	18.1%	5.4%
	Graphite for lithium insertion	6.8%	20.7%	47.5%	11.8%	9.2%	4.1%
	Silicon and its alloys	6.5%	23.6%	36.9%	15.1%	13.6%	4.3%

Globally, competition is more of an open playing field when it comes to innovation in emerging cathode chemistries such as LFP and NCA. With 31% of IPFs related to LFP, Japan is slightly less dominant in this field, in which the Republic of Korea, the United States and the People's Republic of China are all important contributors (each with about 16% of IPFs). In the case of NCA, the United States is the clear frontrunner, accounting for 36% of the IPFs (of which up to 15% is contributed by SMEs and another 6% by universities). The Republic of Korea comes next with 24%, while Japan contributes just 16%. In the same vein, the United States is leading the way in lithium and its alloys for anodes (29%), again with a major contribution from SMEs and universities (8% in both cases). The share of European inventions is relatively modest in all fields, but doubles in newly emerging areas, with 11% of IPFs related to both LFP and NCA, up to 13% in silicon and its alloys and 18% in lithium and its alloys for anodes. Like the United States, European countries differ from Japan and the Republic of Korea owing to the comparatively higher proportion of IPFs originating from universities and SMEs in these fields. Universities in particular generated 41% of European IPFs in LFP, 24% in NCA and 22% in lithium and alloys.

Japan is the frontrunner in solid-state batteries, accounting for 54% of IPFs. The United States (18%) and European countries (12%) also performed better in this field, with equal or larger shares of IPFs in solid-state batteries than in all Li-ion overall. However, this was not the case for Korea and China, which hold relatively modest shares of IPFs in solid-state batteries (12% and 2%), despite accounting for 22% and 9%, respectively, of all IPFs related to Li-ion technology in 2014-2018.

8. Other emerging technologies

8. Other emerging technologies

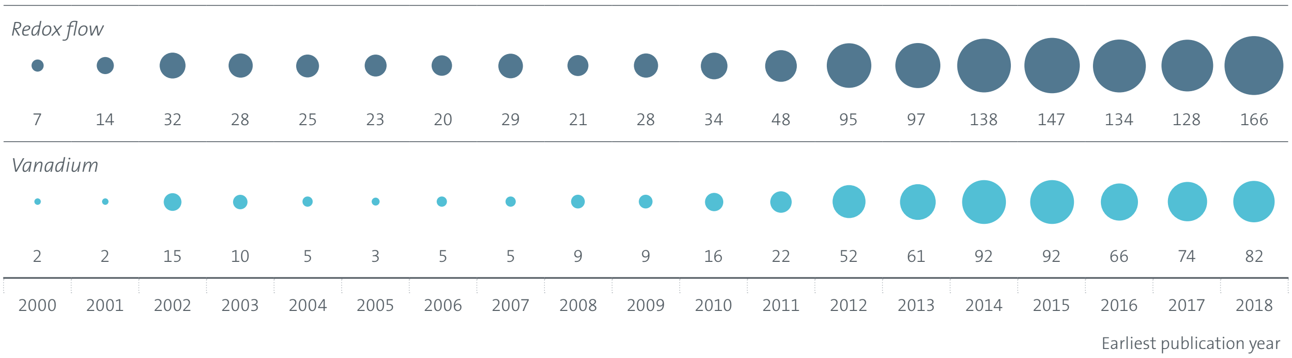
This chapter complements the analysis of Li-ion chemistries by highlighting two rapidly emerging electricity storage technologies, which, if successful, have the potential to address a number of weaknesses found in Li-ion batteries and other alternatives.[11] Firstly, redox flow batteries can provide a safer, more durable and more scalable alternative to Li-ion batteries for some applications. Secondly, supercapacitors can complement Li-ion batteries by addressing specific needs such as fast charging and discharging.

8.1 Redox flow batteries

Although redox flow batteries fall within the category of electrochemical storage technologies, they differ from ordinary batteries in several ways. Instead of relying on electrodes made in a solid or immobilised form, redox flow batteries use porous electrodes, wherein the active materials are flown in the form of positive and negative liquid solutions containing redox-active species. These solutions are stored in two tanks, with each being circulated to one of the electrodes. During discharge, ions migrate from the negative electrode to the positive electrode through an ion-exchange membrane, while electrons flow from the negative solution to the negative electrode, and then through an external circuit (for example an external device) to the positive electrode, and eventually to the positive solution.

Figure 8.1

Number of IPFs in redox flow batteries, 2000-2018



Source: European Patent Office

11 Other new storage technologies include batteries that rely on alternative mobile ions such as those of sodium, magnesium or even aluminium. Although these technologies have received substantial attention over the last few years, particularly in the academic sector, their relevance in industrial applications has still to be proven.

Since the liquid solutions are stored in tanks and can be pumped into the cell to generate energy, flow batteries can be used either like fuel cells (where the spent fuel is extracted and new fuel is added to the system) or like rechargeable batteries (where an electric power source is used to regenerate the fuel). Compared with Li-ion batteries, redox flow batteries can achieve lower degradation, improved safety and in particular can create almost unlimited longevity. The extent to which energy can be stored is determined by the volume of the tanks, which are easily scalable. This makes them particularly interesting for residential and large-scale stationary applications (e.g. storing energy from renewable sources and load balancing) as well as for electric vehicles. However, current models are comparatively less powerful than Li-ion solutions and require more sophisticated electronics.

Figure 8.1 presents developments in IPFs in redox flow batteries. Innovation in redox flow batteries has only recently become visible in patent applications. The number of IPFs in this area almost doubled in 2012, and had reached 166 by 2018. Redox flow batteries can have different chemistries, with vanadium the most commonly used redox-active cation. This can also be seen in the patent data. With an increase from less than 10 IPFs in 2009 to 82 in 2018, vanadium is now the focus of close to one in two IPFs related to redox flow batteries.

Table 8.1

Applicant profiles in redox flow batteries, 2000-2018

	Redox flow	Vanadium
Large companies	51.6%	51.8%
SMEs	25.0%	22.7%
UNI/PRO	21.8%	23.6%

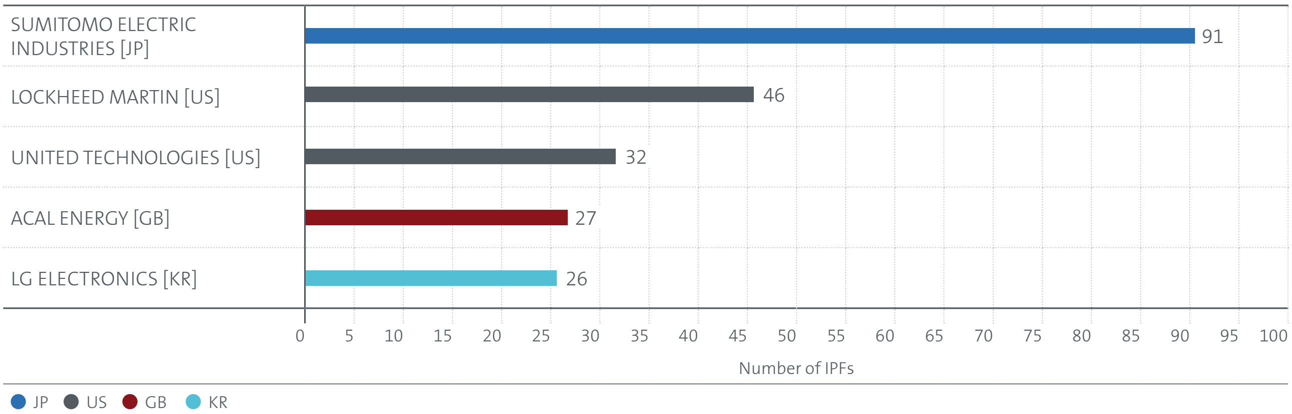
Note: The shares of unidentified applicant types in redox flow and vanadium IPFs were 1.4% and 1.9% respectively.

SMEs, universities and public research organisations still play an important role in the development of redox flow technology (Table 8.3). Together, they accounted for almost half of all IPFs in this area in 2000-2018, a typical trend for a dynamic and emerging technology field. Cumulatively, the top five applicants account for a significantly lower share of IPFs in this field (18%) than in the area of batteries in general (28%). The Japanese company Sumitomo Electric Industries has a clear lead (Figure 8.2), followed by the two US aerospace companies Lockheed Martin and United Technology, and Acal Energy, a smaller British company which operates only in this field. LG Electronics ranks fifth on the list, and is the only entity also represented in the top ten applicants for all battery technologies (Figure 5.1).

In this context, the geographic distribution of IPFs related to redox flow batteries differs significantly from that of IPFs related to Li-ion. The United States is the dominant innovation centre, accounting for almost one-third of all IPFs in the field in 2000-2018, followed by Europe with 23.7% of IPFs. Japan ranks third with 19.2% of IPFs (Table 8.2).

Figure 8.2

Top five applicants in redox flow batteries, 2000-2018



Source: European Patent Office

Table 8.2

Geographic distribution of IPFs in redox flow batteries, 2000-2018

	Redox flow	Vanadium
JP	19.2%	24.1%
KR	10.6%	12.4%
US	33.2%	28.4%
EPC	23.7%	19.5%
CN	4.6%	6.5%
Total IPFs	**1 214**	**622**

8.2 Supercapacitors

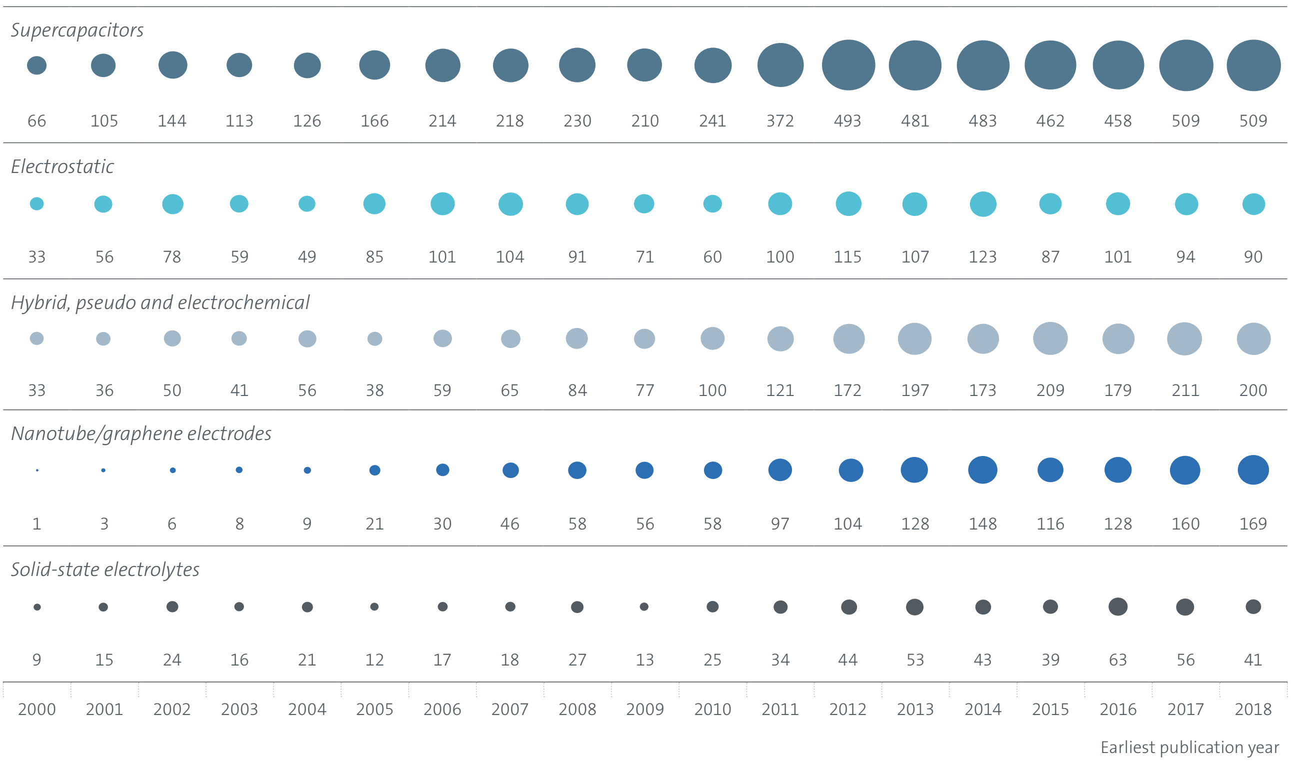
Supercapacitors, also known as ultracapacitors, fall within the category of electrical storage, as they do not typically involve chemical reactions. Recently, however, some hybrid solutions that combine electrical with electrochemical storage methods have been developed. Some of the key advantages of capacitors are that they can be charged and discharged within seconds and do not lose their storage capabilities over time. However, they cannot store electricity in quantities as large as batteries. This makes supercapacitors primarily suitable as a complement to batteries for applications that value bursts of power over the capacity of the storage medium.

Most supercapacitors are currently used in the automotive, industrial energy and electronics sectors, owing to their relatively high costs and low profile among potential users. The supercapacitor market is still growing, primarily driven by growth in regenerative braking system sales for elevator and hybrid electric vehicle markets, as well as their use in wind power, solar power, trains and aircrafts.

There were significant technical developments in supercapacitors in the 2000s, resulting in around 100 IPFs per year, a figure that had increased to more than 500 IPFs per year by 2017 (Figure 8.3). Early developments focused mostly on double-layer electrostatic supercapacitors alongside hybrid, pseudo and electrochemical supercapacitors. Views on the relative attractiveness of these types of supercapacitor appear to have diverged, however, with the number of IPFs in electrostatic supercapacitors remaining at a stagnated level since 2006 and technical improvements in hybrid, pseudo and electrochemical supercapacitors resulting in an increase in IPFs, reaching 200 per year in 2018. The use of nanotubes and graphene electrodes in supercapacitors has been another growing area of innovation in this field over the past 20 years, with the number of IPFs recorded rising from almost zero at the beginning of the 2000s to 169 by 2018. Unlike for batteries, developments in solid-state electrolytes for supercapacitors have not increased, with the number of IPFs hovering at around 50 since 2013.

Figure 8.3

Number of IPFs in supercapacitors, 2000-2018



Source: European Patent Office

With the exception of electrostatic supercapacitors, a category dominated by large companies with 81.2% of all IPFs (Table 8.3), a relatively large share of innovation in supercapacitors stems from SMEs and public research organisations. This confirms that supercapacitors are another dynamic emerging field in electricity storage. Almost 25% of IPFs in the area of hybrid, pseudo and electrochemical supercapacitors are generated by universities and public research organisations, rising to 34.8% for nanotube/graphene electrodes for supercapacitors.

Table 8.3

Applicant profiles in supercapacitors, 2000-2018

	Supercapacitors	Electrostatic	Hybrid, pseudo and electrochemical	Solid-state electrolytes	Nanotube/graphene electrodes
Large companies	68.0%	81.2%	57.8%	59.8%	47.8%
SMEs	13.2%	10.1%	16.6%	18.2%	16.6%
UNI/PRO	17.6%	7.5%	24.3%	20.5%	34.8%

The share of unidentified applicant types in supercapacitor IPFs was 1.2%.

The top five applicants account for just 13.5% of IPFs related to supercapacitors, underlining the low concentration of innovation in this fast-growing technology field. Of these applicants, four are based in Japan and one in the Republic of Korea, with Panasonic in the lead, followed by Samsung and Toyota. The profiles of the top five applicants in supercapacitors are presented in Table 8.4. The table clearly shows that Toyota focuses its innovative activities on electrostatic supercapacitors, a more mature area of technology, while Panasonic holds a strong position in hybrid, pseudo and electrochemical supercapacitors. Samsung is in the lead in the emerging field of supercapacitors with nanotube and graphene electrodes.

Table 8.4

Profiles of the top five applicants in supercapacitors, 2000-2018

	IPFs related to supercapacitors		Electrostatic	Hybrid, pseudo and electrochemical	Solid-state electrolyte	Nanotube/ graphene electrodes
	Number of IPFs	Share of IPFs	Share of IPFs	Share of IPFs	Share of IPFs	Share of IPFs
PANASONIC [JP]	250	4.5%	6.4%	4.3%	6.7%	2.0%
SAMSUNG [KR]	176	3.1%	1.9%	1.4%	3.5%	4.2%
TOYOTA [JP]	140	2.5%	6.7%	0.7%	0.5%	0.6%
SEMICONDUCTOR ENERGY LABORATORY [JP]	97	1.7%	0.2%	1.4%	1.9%	1.9%
TDK [JP]	96	1.7%	1.9%	1.2%	1.0%	0.1%

The distribution by geographic origin is very similar to that seen in batteries. Japan is the clear frontrunner, accounting for almost 50% of all IPFs published between 2000 and 2018 (Table 8.5). Its dominance is due to its position in electrostatic supercapacitors, where it generates almost two-thirds of all IPFs. The United States ranks second with a share of 18.2%, which is thanks to its strong position in hybrid, pseudo and electrochemical supercapacitors, as well as in supercapacitors with solid-state electrolytes and nanotube/graphene electrodes. Europe's total share in supercapacitors is 13.6% and its highest share is in hybrid, pseudo and electrochemical supercapacitors.

Table 8.5

Geographic distribution of IPFs in supercapacitors, 2000-2018

	Supercapacitors	Electrostatic	Hybrid, pseudo and electrochemical	Solid-state electrolytes	Nanotube/graphene electrodes
JP	48.8%	66.2%	30.3%	40.7%	30.3%
KR	8.6%	6.7%	7.2%	6.8%	11.0%
US	17.6%	7.5%	24.3%	20.5%	34.8%
EPC	13.6%	10.6%	19.9%	14.6%	14.2%
CN	3.9%	1.2%	7.3%	2.5%	7.1%
Total	**5 600**	**1 604**	**2 101**	**570**	**1 346**

Annex

Annex A. Applicant name and entity type

Information retrieved from the Bureau van Dijk ORBIS (2019 version) database was used to harmonise and consolidate applicant names and identify their type and industrial sector (statistical classification of economic activities in the European Community, Rev. 2). In the case of multiple applicants, one was selected, with priority given to those available in ORBIS.

Applicant name

The following rules were applied after matching the applicant names to ORBIS:

1. Take the global ultimate owner (GUO) of the applicant.
2. If the GUO is not available, take the applicant name matched to ORBIS.
3. For the remaining applications, take the first applicant and manually clean the names in accordance with available ORBIS (GUO) company names.

Entity type

Using information in ORBIS and PATSTAT (TLS206_PERSON), the following rules were applied to assign patent applications to the following categories: (a) small and medium-sized enterprises (SMEs) and individual entrepreneurs; (b) large and very large companies; and (c) universities, hospitals and public research organisations. Additional manual checks were carried out at all stages.

1. Categorise all patent applications as *Universities, hospitals and public research organisations* if there is at least one applicant of type GOV NON-PROFIT, UNIVERSITY or HOSPITAL according to PATSTAT or as identified manually using a keyword list with manual checks (UNIV, ECOLE, HOCHSCHUL, SCUOLA, COLLEGE, INST, POLITEC, HOSPITAL, etc.). In addition, search manually for variations in the top 100 GOV NON-PROFIT, UNIVERSITY or HOSPITAL applicants.

2. For the remaining patent applications, if matched to ORBIS, take the company size category, as provided in the dataset – i.e. small company, medium-sized company, large company, very large company – which is based on thresholds relating to the number of employees, total assets and operating revenue (see ORBIS – user guide https://help.bvdinfo.com/mergedProjects/68_EN/Home.htm).

3. For the remaining patent applications, assign to *individual entrepreneurs* if PSN_SECTOR in PATSTAT of all applicants is INDIVIDUAL.

4. The remaining applicants were dealt with manually via online searches.

Annex B. Identification of patent applications related to electricity storage

The cartography was assembled on the basis of the intellectual input of patent examiners at the EPO and developed and populated using the following three steps.

Step 1:
Mapping the cartography to the patent classification scheme

Technology experts were asked to identify the technologies relevant to electricity storage from their areas of expertise and, together with patent classification experts, to provide information about the field ranges of the Cooperative Patent Classification (CPC) scheme in which inventions related to different technologies can be found. The results were used to create a concordance table of electricity storage technologies and CPC ranges (Table B.1).

The table contains around 100 different technologies with assigned CPC field ranges in all technical fields and sectors of the electricity storage cartography scheme. The cartography and the assignment of CPC ranges were verified by applying ad hoc queries to the EPO's full-text patent database and analysing the results. Anomalies were reassessed by classification experts and corrected/amended where necessary.

Example

Technology	Description	CPC ranges	General query	Type of electricity storage
Liquid metal and zebra batteries	Liquid metal batteries and Zebra battery (Na-NiCl2)	H01M10/399	Specific class	Batteries

Step 2:
Identifying patent applications related to electricity storage

Upon identification of the relevant technology fields, a distinction was made between specific and non-specific classes. Specific classes were included in their entirety, while non-specific classes were combined with a set of semantic keywords referring to the technology. With regard to patent documents in these non-specific classes, full-text search queries were applied to all published documents in the respective CPC ranges in order to identify documents relating to the concepts of electricity storage. Any occurrence of any of the terms in one of the family members, including translations, was considered valid. Nevertheless, emphasis was placed on retrieving true positives with the highest degree of certainty.

Step 3:
Assigning patent applications to the cartography fields

All CPC codes assigned to all patent applications related to electricity storage within the international patent family (IPF) during the patenting process were extracted and combined. The unique CPC classes for each application were then mapped to the respective technology fields and sectors of the cartography using the concordance table from step 1.

For the purposes of this study, the statistics on patent applications related to electricity storage were based on a simple count method, reflecting the number of inventions assigned to a particular field or sector of the cartography, independently of whether some of these inventions were also classified under other fields or sectors.

Table B.1

Concordance table of electricity storage technologies and Cooperative Patent Classification ranges

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Electrical storage	**Supercapacitors**	**Electrostatic**			H01G11/00/low, H01G4/00/low, H01G9/00/low, H01G2/00/low	electrostatic supercapacitors (double layer)	(4og double?, layer?, (or capacitor?, condenser?)) not (or (hybrid 2d (or capacitor?, condenser?)), (lithium 3d (or capacitor?, condenser?)), (electrochemical 3d (or capacitor?, condenser?)), pseudo_capacitor?, pseudo_condenser?, (redox 2d (or capacitor?, condenser?)))	doppelschicht_kondensator?? not (or ultra_kondensator??, super_kondensator, pseudo_kondensator?? redox_kondensator??, hybrid_kondensator??, lithium_kondensator??, (3ug(or elektrochemisch??, lithium), kondensator??))	(4ug condensateur?, double, couche?) not (or super_condensateur?, ultra_condensateur?, pseudo_condensateur?, (4ug condensateur?, (or hybrid??, [e,é]lectrochimique?, lithium), redox))
Electrical storage	**Supercapacitors**	**General**			H01G11/00/low, H01G4/00/low, H01G9/00/low, H01G2/00/low	supercapacitors in general	or ultra_capacitor?, ultra_condenser?, super_capacitor?, super_condenser?, super_cap?, pseudo_capacitor?, pseudo_condenser?, (4og double, layer?, (or capacitor?, condenser?)), (redox 2d (or capacitor?, condenser?)), (hybrid 2d (or capacitor?, condenser?)), (lithium 3d (or capacitor?, condenser?)), (electrochemical 3d (or capacitor?, condenser?))	or ultra_kondensator??, super_kondensator??, doppelschicht_kondensator??, pseudo_ kondensator??, redox_kondensator??, hybrid_kondensator??, lithium_kondensator??, (3ug(or elektrochemisch??, lithium), kondensator??)	or super_condensateur?, ultra_condensateur?, pseudo_condensateur?, (4ug condensateur?, double, couche?), (4ug condensateur?, (or hybrid??, [e,é]lectrochimique?, lithium), redox)
Electrical storage	**Supercapacitors**	**Hybrid, pseudo and electrochemical**			H01G11/00/low, H01G4/00/low, H01G9/00/low, H01G2/00/low	hybrid, pseudo and electrochemical capacitors	(or (hybrid 2d (or capacitor?, condenser?)), (lithium 3d (or capacitor?, condenser?)), (electrochemical 3d (or capacitor?, condenser?)), pseudo_capacitor?, pseudo_condenser?, (redox 2d (or capacitor?, condenser?))	(or ultra_kondensator??, super_kondensator, pseudo_kondensator??, redox_kondensator??, hybrid_kondensator??, lithium_kondensator??, (3ug(or elektrochemisch??, lithium), kondensator??)) not doppelschicht_kondensator??	(or super_condensateur?, ultra_condensateur?, pseudo_condensateur?, (4ug condensateur?, (or hybrid??, [e,é]lectrochimique?, lithium), redox)) not (4ug condensateur?, double couche?)
Electrical storage	**Supercapacitors**	**Nanotube/ graphene electrode**			H01G9/04/low, H01G11/32/low, H01G4/005/low	supercapacitors with electrodes comprising nanotube/graphene	or nanotube?, fullerene?, graphene?, cnt?	or nanotube?, nano_rörchen, nanor??rchen, graphen??, fulleren??, cnt?	or nanotube?, fuller[è,e]ne?, graph[è,e]ne?, cnt?
Electrical storage	**Supercapacitors**	**Solid-state electrolyte**			H01G09/025/low, H01G11/56, H01G4/06/low	supercapacitors with solid-state electrolyte	or ultra_capacitor?, ultra_condenser?, super_capacitor?, super_condenser?, super_cap?, (4og double, layer?, (or capacitor?, condenser?)), (redox 2d (or capacitor?, condenser?)), (hybrid 2d (or capacitor?, condenser?)), (lithium 3d (or capacitor?, condenser?)), (electrochemical 3d (or capacitor?, condenser?)), pseudo_capacitor?, pseudo_condenser?	or ultra_kondensator??, super_kondensator??, doppelschicht_kondensator??, pseudo_kondensator??, redox_kondensator??, hybrid_kondensator??, lithium_kondensator??, (3ug(or elektrochemisch??, lithium), kondensator??)	or super_condensateur?, ultra_ condensateur?, pseudo_condensateur?, (4ug condensateur?, double, couche?), (4ug condensateur?, (or hybrid??, [e,é]lectrochimique?, lithium), redox)
Electrical storage	**Superconducting magnetic**				–	superconducting magnetic energy storage	6ug (or super_conductor?, super_conducting, super_conductivity), (or magnet?, magnetic), energy, (or storage?, store?, storing)	or (6ug (or supraleiter?, supraleitend??), magnetisch??, (or energie_speicher?, speichern))	10ug(or stockage?, stocker, stocké??), [e,é]nergie, magn[e,é]tique??, (or supraconducteur?, supraconduction?, supraconductrice?)
Electrochemical storage	**All developments**				(or H01M2/LOW, H01M4/02/LOW, H01M10/LOW, H01M12/LOW) not (or H01M6/LOW, H01M4/06/low)	rechargeable batteries: all developments	–	–	–
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Graphite (anode)**		H01M4/587	graphite for lithium insertion in anode	–	–	–
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Silicon (anode)**		H01M4/386	silicon and its alloys for anode	–	–	–
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium (anode)**		H01M4/382, H01M4/405	lithium and its alloys for anode	–	–	–
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Solid-state**		H01M10/0562 and H01M10/052	solid-state lithium batteries	–	–	–

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Other except solid-state**		H01M10/052/low NOT H01M10/0562	all lithium secondary batteries except solid-state	–	–	–
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium cobalt oxide (cathode)**		H01M4/525, H01M4/131/low	lithium-ion lithium cobalt oxide (LCO)	15ug (or embodiment?, invention?, aspect?, claim?), (or lithium_cobalt?te?, lithium_cobalt_oxide, Li_Co_O_2)	15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or lithium_[k,c]obalt+, lithium_[k,c]obalt+_oxid??, Li_Co_O_2)	15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), (or (lithium 2d cobalt?te?), (4ug lithium, cobalt, oxyde?), LiCoO2)
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium nickel cobalt manganese oxide (cathode)**		H01M4/525, H01M4/131/low	lithium-ion lithium nickel cobalt manganese oxide (NCM)	or (15ug (or embodiment?, invention?, aspect?, claim?), lithium, nickel, cobalt, manganese), (15ug (or embodiment?, invention?, aspect?, claim?), lithium, nickel, (or active_material?, oxide?)), (15ug (or embodiment?, invention?, aspect?, claim?), (or NMC, NCM, NCM111, NCM811, NCM721, NCM622, NCM523, NCM442, NMC111, NMC811, NMC712, NMC622, NMC532, NMC424))	or (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), lithium, nickel, [k,c]obalt, mangan), (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), lithium, nickel, (or aktiv_material??, aktivenmaterial??, oxid??)), (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or NMC, NCM, NCM111, NCM811, NCM721, NCM622, NCM523, NCM442, NMC111, NMC811, NMC712, NMC622, NMC532, NMC424))	or (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), lithium, nickel,cobalt, manganèse), (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), lithium, nickel, (or matériau actif, composé actif, oxyde?)), (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), (or NMC, NCM, NCM111, NCM811, NCM721, NCM622, NCM523, NCM442, NMC111, NMC811, NMC712, NMC622, NMC532, NMC424))
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium manganese oxide (cathode)**		H01M4/505, H01M4/131/low	lithium-ion lithium manganese (spinel or OLOs) oxide (LMO)	15ug (or embodiment?, invention?, aspect?, claim?), (or (7og li, mn, o), (7og lithium, manganese, (or oxide?, spinel?)))	15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch+, aspekt??), (or (7og li, mn, o), (7og lithium, mangan, (or oxid??, spinell??)))	15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), (or (7og li, mn, o), (7og lithium, manganèse, (or oxyde?, spinel???)))
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium iron phosphate (cathode)**		H01M4/5825, H01M4/136	lithium-ion lithium iron phosphate (LFP)	or (15ug (or embodiment?, invention?, aspect?, claim?), lithium, iron, phosphate?), (15ug (or embodiment?, invention?, aspect?, claim?), (or LiFePO4, (6og li, fe, o)))	or (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), lithium, eisen, phosphat??), (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or LiFePO4, (6og li, fe, o)))	or (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), lithium, fer, phosphate?), (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), (or LiFePO4, (6og li, fe, o)))
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium nickel cobalt aluminum oxide (cathode)**		H01M4/525, H01M4/131/low	lithium-ion lithium nickel cobalt aluminum oxide (NCA)	or (15ug (or embodiment?, invention?, aspect?, claim?), lithium, nickel, cobalt, alumin[,i]um), (10ug (or embodiment?, invention?, aspect?, claim?), NCA)	or (15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), lithium, nickel, [k,c]obalt, aluminium), (10ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), NCA)	or (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), lithium, nickel, cobalt, aluminium), (15ug (or (mode 2d réalisation?), invention?, aspect?, revendication?), NCA)
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium titanate (anode)**		H01M4/485, H01M4/131/low	lithium-ion lithium titanate (LTO)	or (15ug (or embodiment?, invention?, aspect?, claim?), lithium, titanium, oxide?), (15ug (or embodiment?, invention?, aspect?, claim?), lithium, titanate?), (5ug (or embodiment?, invention?, aspect?, claim?), (or Li4Ti5O12, (6og li, ti, o)))	15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or lithiumtitanoxid??, tetralithiumpentatitandodecaoxid??, lithiumtitanat_spinell??, (or Li4Ti5O12, (6og li, ti, o)))	15ug (or invention?, revendication?, (mode 2d realisation), aspect?), (or (lithium 2d titanate?), (or Li4Ti5O12, (6og li, ti, o)))
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium-sulfur/ sulfide**		H01M4/5815, H01M4/38	lithium-sulfur/sulfide	15ug (or embodiment?, invention?, aspect?, claim?), lithium, (or sulfur, sulphur)	15ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), lithium, schwefel??	10ug (or invention?, revendication?, (mode 2d realisation), aspect?), lithium, soufre
Electrochemical storage	**Development at cell level**	**Lithium and Lithium-ion**	**Lithium-air**		H01M12/08	lithium-air	(10ug (or embodiment?, invention?, aspect?, claim?), (or Li, lithium), (or oxygen, O_2, air), (or battery, batteries, cell?, accumulator?, storage_device?)) and (5ug (or recharge, recharging, recharged, charge, charging, charge, secondary, cycled, cycling, cycle?), (or batteries, battery, cell?, accumulator?, storage_device?))	(10ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or Li, lithium??), (or sauerstoff??, O_2, luft), (or akkumulator??, batterie?, (elektrochemisch?? 2D (or speicher??, speicherung??)), energiespeicher??)) and (5ug (or laden, geladen, zykl+), (or akkumulator??, +batterie?, (elektrochemisch?? 2D (or speicher??, speicherung??)), energiespeicher??, energiespeicherung??))	(10ug (or invention?, revendication?, (mode 2d realisation), aspect?), (or Li, lithium), (or oxyg?ne, air, O_2), (or accumulateur?, batterie?, pile?_electrique?)) and (5ug (or recharg???, charg???, secondaire?, cycl???), (or accumulateur?, batterie?, pile?_electrique?))
Electrochemical storage	**Development at cell level**	**Manufacturing (cell level)**	**Filling cells with elelctrolyte**		H01M2/36/low	filling cells with elelctrolyte	–	–	–
Electrochemical storage	**Development at cell level**	**Manufacturing (cell level)**	**Processes of manufacturing electrodes**		or H01M4/04low, H01M4/139/low, H01M4/16/low, H01M4/26/low	processes of manufacturing electrodes	–	–	–
Electrochemical storage	**Development at cell level**	**Manufacturing (cell level)**	**Machines for cell assembly**		H01M10/0404/low	machines for cell assembly	–	–	–

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Electrochemical storage	Development at cell level	Manufacturing (cell level)	Processes of manufacturing cells		H01M10/38, H01M10/28/low, H01M10/12/low, H01M10/058/low, H01M10/04/low	processes of manufacturing cells	10ug (or battery, batteries, accumulator?), (or method, process, processes, methods), (or manufacture, manufacturing, assembly, assemblying, construction, constructing, fabricate, fabrication, fabricating, produce, producing)	or (10ug (or zelle?, akku?, akkumulator??, batterie?, (elektrochemisch?? 2D speicher??), energie_speicher??, speicher_batterie?, batterie_speicher??, strom_speicher??), (OR METHODE?, PROZEDUR??, PROZESS??, VERFAHREN?), (or ANFERTIGUNG??, FABRIKATION??, FERTIGUNG??, HERSTELLUNG??, MONTAG??, PRODUKTION??)), (5ug (or zelle?, akku+, +batterie?, (elektrochem+ 2D speicher+), energiespeicher+, speicherbatterie?), (OR herstellung?METHODE?, herstellung?PROZEDUR??, herstellung?PROZESS??, herstellung?VERFAHREN?, ??fertigung?METHODE?, ??fertigung?PROZEDUR??, ??fertigung?PROZESS??, ??fertigung?VERFAHREN?, fabrikation?METHODE?, fabrikation?PROZEDUR??, fabrikation?PROZESS??, fabrikation?VERFAHREN?, produktion?METHODE?, produktion?PROZEDUR??, produktion?PROZESS??, produktion?VERFAHREN?))	10ug (or batterie?, pile?, cellule?, accumulateur?), (or méthode?, procédé??, procédure?), (or assemblage?, construction?, fabrication?, manufacture?, montage?, préparation?, production?, usinage?)
Electrochemical storage	Development at cell level	Other chemistries	Aluminum-ion/ aluminum		H01M10/054	aluminum-ion/ aluminum batteries	or (5ug (or alumin[,i]um_ion, Al_ion, alumin[,i]um), (or batter+, cell?, accumulator?)), (5ug (or alumin[,i]um_ion, Al_ion, alumin[,i]um), (or energy, power, electric, electrics, electricity), (or storage?, storing, stored))	or (5ug (or aluminium_ion??, Al_ion??, aluminium), (or batterie, batterien, zelle?, akkumulator??)), (5ug (or aluminium_ion??, Al_ion??, aluminium), (or energie?, strom, ströme?, stroem??), (or speichern, gespeichert, gespeicherte, gespeicherten))	or (5ug (or aluminium_ion?, Al_ion, aluminium), (or batterie?, pile?, cellule, accumulateur?)), (5ug (or aluminium_ion?, Al_ion?, aluminium), (or énergie, électricité?), (or stocké??, stockage, stocker))
Electrochemical storage	Development at cell level	Other chemistries	Sodium-ion/ sodium		H01M10/054	sodium-ion/sodium batteries	or (5ug (or sodium_ion, Na_ion, sodium), (or batter+, cell?, accumulator?)), (5ug (or sodium_ion, Na_ion, sodium), (or energy, power, electric, electrics, electricity), (or storage?, storing, stored))	or (5ug (or natrium_ion??, Na_ion??, natrium), (or batterie, batterien, zelle?, akkumulator??)), (5ug (or natrium_ion??, Na_ion??, natrium), (or energie?, strom, ströme?, stroem??), (or speichern, gespeichert, gespeicherte, gespeicherten))	or (5ug (or sodium_ion?, Na_ion?, sodium), (or batterie?, pile?, cellule, accumulateur?)), (5ug (or sodium_ion?, Na_ion?, sodium), (or énergie, électricité?), (or stocké??, stockage, stocker))
Electrochemical storage	Development at cell level	Other chemistries	Nickel	Nickel-cadmium	H01M10/30	nickel-cadmium	or (2og nickel, cadmium), Ni_Cd	or (2og nickel, cadmium), Ni_Cd	or (2og nickel, cadmium), Ni_Cd
Electrochemical storage	Development at cell level	Other chemistries	Nickel	Nickel-metal hydride	H01M10/30, H01M10/345/low	nickel-metal hydride (NiMH)	or (4og nickel, hydride?), Ni_M_H	or (4og nickel, hydrid??), Ni_M_H	or (4og nickel, hydrure?), Ni_M_H
Electrochemical storage	Development at cell level	Other chemistries	Other metal-air batteries		H01M12/08	other metal-air batteries	(10ug (or embodiment?, invention?, aspect?, claim?), (or metal, zinc, aluminum, aluminium), (or oxygen, O_2, air), (or battery, batteries, cell?, accumulator?, storage_device?)) and (5ug (or recharging, recharge, recharged, charged, chaging, charge, secondary, cycled, cycling, cycles), (or battery, batteries, cell?, accumulator?, storage_device?))	(10ug (or ausf??hrungsform??, ausf??hrungsart??, erfindung??, aspr??ch??, aspekt??), (or metall+, zink, aluminium), (or sauerstoff+, O_2, luft), (or akku+, +batterie?, (elektrochemisch?? 2D (or speicher??, speicherung??, gespeichert??)), energiespeicher+, energiepseicherung??)) and (5ug (or laden, geladen, zykl+), (or akku+, +batterie?, (elektrochem+ 2D speicher+), energiespeicher+))	(10ug (or invention?, revendication?, (mode 2d realisation), aspect?), (or zinc, aluminium, m?tal), (or oxyg?ne, air, O_2), (or accumulateur?, batterie?, pile?_electrique?)) and (5ug (or recharg???, charg???, secondaire?, cycl???), (or accumulateur?, batterie?, pile?_electrique?))
Electrochemical storage	Development at cell level	Other chemistries	Lead-acid	General	H01M10/06/low, H01M4/14/low, H01M4/56/low, H01M4/627, H01M4/68/low, H01M4/73	lead-acid batteries in general	4og lead, acid	or (5ug (or blei, blei_s?ure?, blei_saure?), (or zelle?, akkumulator??, +batterie?, (elektrochemisch?? 2D (or speicher??, gespeichert??, energiespeicherung??)), energiespeicher??, energiespeicherung??)), blei_akkumulator??	5ug (or plomb_acide, plomb), (or accumulateur?, batterie?, pile?_electrique??)
Electrochemical storage	Development at cell level	Other chemistries	Lead-acid	Advanced/ carbon-enhanced	H01M10/06/low, H01M4/14/low, H01M4/56/low, H01M4/627, H01M4/68/low, H01M4/73	advanced lead-acid/ carbon-enhanced lead-acid	20ug (or graphite, carbon+, capacitive, graphene, nanotube?, (ketjen 2d black), (ketchen 2d black), (carbon 2d black)), (or negative, anode)	20ug (or graphit??, grafit??, russ, kapazitiv??, kapazitanz, graphen??, nanorohr??, nanor??rchen??, (ketjen 2d black), (ketchen 2d black), (carbon 2d black)), (or negativ??, anod??)	20ug (or graphite?, graphitique, carbon??, capacitive, graph[e,è]n??, graph[e,è]nique??, (noir 2d (or fumée, lampe, thermique, tunnel, fourneau, acetylene)), nanotube?, (ketjen 2d black), (ketchen 2d black), (carbon 2d black)), (or negativ??, anod??)
Electrochemical storage	Development at cell level	Other chemistries	Redox flow	Vanadium	H01M8/188	vanadium redox flow batteries	or vanadium, (20UG ((4UG v_2,v_3) OR (4UG v_4,v_5)),redox)	or vanadin?, vanadium?, (20UG ((4UG v_2,v_3) OR (4UG v_4,v_5)), redox, reduktion??_oxidation??)	or vanadium, (20UG ((4UG v_2,v_3) OR (4UG v_4,v_5)), oxydoreduction?, redox)
Electrochemical storage	Development at cell level	Other chemistries	Redox flow	Other	H01M8/184/low	other flow batteries	–	–	–

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Zinc-halogen**		H01M10/365, H01M12/085	zinc-halogen	–	–	–
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Sodium-sulfur**		H01M10/3909/low	sodium-sulfur	–	–	–
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Liquid metal and zebra**		H01M10/399	liquid metal batteries and zebra battery (Na-NiCl2)	–	–	–
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Photoelectro-chemical storage cells**		H01M14/005	photoelectrochemical cells	–	–	–
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Printable batteries**	**General**	H01M/low	printable batteries in general	(or printable_battery, printed_battery, printing_battery, printable_cell?, printed_cell?, printing_cell?, printable_batteries, printed_batteries, printing_batteries) and (5ug (or recharging, recharge, recharged, charged, chaging, charge, secondary, cycled, cycling, cycles), (or battery, batteries, cell?, accumulator?, storage_device?))	(or druckbar??_batterie?, gedruckt??_batterie?, druckbar??_akkumulator??, gedruckt??_ akkumulator??, druckbar??_zelle?, gedruckt??_zelle?) and (5ug (or laden, geladen, zyklen, zyklisieren, zyklisierung, gezykelt??), (or akkumulator??, batterie?, (elektrochemisch?? 2D (or speicher??, speicherung??)), energiespeicher??, energiespeicherung??))	(or batterie?_imprim?????, accumulateur?_imprim?????, pile?_imprim?????) and (5ug (or recharg???, charg???, secondaire?, cycl???), (or accumulateur?, batterie?, pile?_electrique?))
Electrochemical storage	**Development at cell level**	**Other chemistries**	**Printable batteries**	**Zinc polymer**	H01M/low	printable zinc polymer	(or printable_battery, printed_battery, printing_battery, printable_cell?, printed_cell?, printing_cell?, printable_batteries, printed_batteries, printing_batteries) and (5ug (or recharging, recharge, recharged, charged, chaging, charge, secondary, cycled, cycling, cycles), (or battery, batteries, cell?, accumulator?, storage_device?)) and (or zinc_polymer, (5ug zinc, polymer?, electrolyte?))	(or druckbar??_batterie?, gedruckt??_batterie?, druckbar??_akkumulator??, gedruckt??_akkumulator??, druckbar??_zelle?, gedruckt??_zelle?) and (5ug (or laden, geladen, zyklen, zyklisieren, zyklisierung, gezykelt??), (or akkumulator??, batterie?, (elektrochemisch?? 2D (or speicher??, speicherung??)), energiespeicher??, energiespeicherung??)) and (or zink_polymer??, zink_polymerelektrolyt??, (5ug zink, polymer?, electrolyt??))	(or batterie?_imprim?????, accumulateur?_imprim?????, pile? imprim?????) and (5ug (or recharg???, charg???, secondaire?, cycl???), (or accumulateur?, batterie?, pile?_electrique?)) and (or zinc_polym?r?????, (5ug zinc, polym?r?????, electrolyte?))
Electrochemical storage	**Development at cell level**	**All developments**			(or H01M10/02, H01M10/04/LOW, H01M10/05/LOW, H01M10/06/LOW, H01M10/20/LOW, H01M10/24/LOW, H01M10/34/ LOW, H01M10/36/ LOW, H01M12/LOW, H01M8/188, H01M4/13/LOW, H01M4/14/LOW, H01M4/24/LOW, H01M4/36/LOW, H01M4/62/LOW, H01M4/64/ LOW, H01M2/02/ LOW, H01M2/12/ LOW, H01M2/14/ LOW, H01M2/22/ LOW, H01M2/30/ LOW, H01M2/32/LOW, H01M2/34/LOW)	rechargeable batteries: developments at cell-level	–	–	–
Electrochemical storage	**Integration in equipment (battery packs)**	**Automotive applications**			H01M2/1072/low not (or H01M6/LOW, H01M4/06/low)	battery packs for auto-motive applications	5ug (or battery, batteries, accumulator?, electricity, electrical, electric), (or AUTOMOBILE?, AUTOMOTIVE, autobus??, CAR, LORRY, MOTORCAR?, TRUCK?, VEHICLE?, bicycle?, lorry, pedelec?, airplane?, aircraft?, motorbike?, scooter?, train?, helicopter?, drone?, submarine?, ship?)	or fahrzeug?batterie?, fahrzeug?akkumulator??, autobatterie?, (5ug (or akku?, akkumulator??, batterie?, (elektrochemisch?? 2D speicher??), energie_speicher??, speicher_batterie?, batterie_speicher??, strom_speicher??), (or schiff??, auto?, fahrzeug??, LKW?, PKW?, hybrid_fahrzeug??, fahrr?d???, pedelec?, flieger?, flugzeug??, helikopter?, hubschrauber?, drone?, unterseeboot??, U_boot??, autobus???, lastkraftwagen??, lastwagen?, krad??, motorr?d???))	5ug (or batterie?, pile?, cellule?, accumulateur?), (or AUTOMOBILE?, MOBILETTE?, MOTO?, MOTOCYCLETTE?, TRACTEUR?, VEHICULE?, VOITURE?, camion?, autobus, AERONEF?, AEROPLANE?, AVIATION, AVION?, HELICOPTERE?, drone?, pedelec?, scooter?, train?, BATEAU?, NAVAL??, NAVIRE?, VAISSEAU?, YACHT?)

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Electrochemical storage	**Integration in equipment (battery packs)**	**Portable applications**			H01M2/1022/low not (or H01M6/LOW, H01M4/06/low)	battery packs for portable applications	–	–	–
Electrochemical storage	**Integration in equipment (battery packs)**	**Stationary applications**			H01M2/1072/low not (or H01M6/LOW, H01M4/06/low)	battery packs for stationary applications	5ug (or battery, batteries, accumulator?, storage?, electricity, electrical, electric), (or stationary, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, building?, residential, (behind 2d meter?), UPS, uninterruptible)	5ug (or akku?, akkumulator??, batterie?, (elektrochemisch?? 2D speicher??), energie_speicher??, speicher_batterie?, batterie_speicher??, strom_speicher??), (or station?r??, UPS, geb?ude?, USV, unterbrechungsfreie?_stromversorgung??)	5ug (or batterie?, pile?, cellule?, accumulateur?), (or sans_interruption?, stationnaire?, UPS, ASI, ASSC, alimentation_statique?, batiment?, immeuble?, édifice?)
Electrochemical storage	**Thermal management**				H01M10/60/low not (or H01M6/LOW, H01M4/06/low)	thermal management of batteries	–	–	–
Mechanical storage	**Flywheels**				F05B2260/42/LOW, H02K7/025, H02J3/30, H02J/007	flywheels	(10ug (or energy, energies, electricity, current, power), (or storage, storing, stored, accumulation, accumulated, accumulating)) and fly_wheel?	(or energiespeicher??, (10ug (or energie?, elektrizit?t, elektrizitaet, strom, ströme?, stroem??), (or speichern, gespeichert, gespeicherte, gespeicherten))) and (or schwungsgrad??, schwungsscheibe?)	(10ug (or énergie, électricité), (or stockage?, stock???, accumulateur?)) and volant?
Mechanical storage	**Pneumatic (CAES)**				H02J15/006, H02J3/28, F02C6/16, F03D9/17	CAES for energy storage	–	–	–
Mechanical storage	**Pumped hydro**	**For sea water**			E02B7/02/low, E02B9/00/low, H02J15/003, F03B13/06	pumped hydro for sea water	(or ((or hydro_electric?, hydro, hydroelectricity, hydroelectrics) 3d (or power+, energy, plant?)), hydro_power, ((or electric, electrics, electricity, energy) 4d (or generation?, generating, generated, produced, producing, production?, power?))) and ((or sea_water, water, (sea 2d water), (salt? 2d water)) 4d (or pump+, re_pump+, re_charged, re_charging, lifted, lifting, re_used, re_using, re_planishing, re_planished, re_filled, re_filling)) and (or (sea 2d water?), (salt? 2d water), brine?, sea_water)	(or (or wasserkraftanlage?, wasserkraftwerk??, speicherkraftwerk??, speicherkraftanlage?, pumpspeicherkraftwerk?), ((or energie?, strom, ströme, strömen) 4d (or erzeug+, hergestellt, herstell+)), energieerzeugung??, stromerzeugung??) and ((or meerwasseer, seewasser, salzwasser, wasser) 4d (or +pump+, auffüllen, aufgefüllt+)) and (or seewasser, salzwasser, meerwasser)	(or (hydro_électrique? 3d (or énergie, centrale?)), hydro_électricit[e,é]?, ((or électric+, énergie) 4d (or g[e,é]n[e,é] ration, g[e,é]n[e,é]r??, production?, produir, produit??))) and ((or eau, (eau 2d mer), (eau 2d salée)) 4d (or pomp+, remont+, riemp+, recharg+, r?utili+)) and (or (eau 2d mer), (eau 2d salée))
Mechanical storage	**Pumped hydro**	**General**			E02B7/02/low, E02B9/00/low, H02J15/003, F03B13/06	pumped hydro	(or ((or hydro_electric?, hydro, hydroelectricity, hydroelectrics) 3d (or power+, energy, plant?)), hydro_power, ((or electric, electrics, electricity, energy) 4d (or generation?, generating, generated, produced, producing, production?, power?))) and (water 4d (or pump+, re_pump+, re_charged, re_charging, lifted, lifting, re_used, re_using, re_planishing, re_planished, re_filled, re_filling))	(or (or wasserkraftanlage?, wasserkraftwerk??, speicherkraftwerk??, speicherkraftanlage?, pumpspeicherkraftwerk?), ((or energie?, strom, ströme, strömen) 4d (or erzeugung??, erzeugt??, erzeugen, hergestellt??, herstellung??, herstellen)), energieerzeugung??, stromerzeugung??) and (wasser 4d (or pumpen, gepumpt??, aufpumpen, aufgepumpt??, auffüllen, aufgefüllt??))	(or (hydro_électrique? 3d (or énergie, centrale?)), hydro_électricit[e,é]?, ((or électric+, énergie) 4d (or g[e,é]n[e,é] ration, g[e,é]n[e,é]r??, production?, produir, produit??))) and (eau 4d (or pomp???, remont???, riemp???, recharg???, r?utili???))
Recycling	**General**				H01M10/54, H01M6/52, Y02W30/84	recycling of batteries in general	–	–	–
Recycling	**Lead-acid batteries**				H01M10/54, H01M6/52, Y02W30/84	recycling of lead-acid batteries	10ug (or reclaim, reclaimed, reclaiming, recycling, recycled), lead, (or accumulator?, battery, batteries, cell?)	10ug (or wiederverwerten, wiederverwertet??, wiedergewinnung??, wiedergewinnen??, wiedergewonn??, recy[c,k]ling, recy[c,k]led, recy[c,k] len??), (or (5ug (or blei_s?ure?, blei_saure?), (or zelle?, akku+, +batterie?, (elektrochem+ 2D speicher+), energiespeicher+)), bleiakku+)	10ug (or recup, recuperation?, recycl???, recyclage?), (or plomb_acide, plomb), (or accumulateur?, batterie?, pile?_[é,e]lectrique?)
Recycling	**Lithium and lithium-ion batteries**				H01M10/54, H01M6/52, Y02W30/84	recycling of Lithium and Lithium-ion batteries	10ug (or reclaim, reclaimed, reclaiming, recycling, recycled), (or lithium_ion, Li_ion, lithium), (or accumulator?, battery, batteries,cell?)	10ug (or wiederverwerten, wiederverwertet??, wiedergewinnung??, wiedergewinnen??, wiedergewonn??, recy[c,k]ling, recy[c,k]led, recy[c,k] len??), (or lithium_ion, lithium_ionen, lithium, Li_ionen, Li_ion), (or zelle?, akkumulator??, +batterie?, (elektrochemisch?? 2D (or speicher??, gespeichert??, energiespeicherung??)), energiespeicher??, energiespeicherung??)	10ug (or recup, recuperation?, recycl???, recyclage?), (or lithium, lithium_ion), (or accumulateur?, batterie?, pile?_[e,é]lectrique?)

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Recycling	**Ni-Cd batteries**				H01M10/54, H01M6/52, Y02W30/84	recycling of Ni-Cd batteries	10ug (or reclaim, reclaimed, reclaiming, recycling, recycled), (or Ni_Cd, nickel_cadmium, nickle_cadmium), (or battery, batteries, cell?, accumulator?)	10ug (or wiederverwerten, wiederverwertet??, wiedergewinnung??, wiedergewinnen??, wiedergewonn??, recy[c,k]ling, recy[c,k]led, recy[c,k]len??), (or Ni_Cd, nickel_cadmium), (or zelle?, akkumulator??, +batterie?, (elektrochemisch?? 2D (or speicher??, gespeichert??, energiespeicherung??)), energiespeicher??, energiespeicherung??)	10ug (or recup, recuperation?, recycl???, recyclage?), (or Ni_Cd, nickel_cadmium), (or accumulateur?, batterie?, pile?_[e,é]lectrique?)
Recycling	**Ni-MH batteries**				H01M10/54, H01M6/52, Y02W30/84	recycling of Ni-MH batteries	10ug (or reclaim, reclaimed, reclaiming, recycling, recycled), (or Ni_M_H, nickel_metal_hydride?, nickel_hydride?, nickel_hydrogen, nickle_metal_hydride?, nickle_hydride?, nickle_hydrogen), (or accumulator?, battery, batteries,cell?)	10ug (or wiederverwerten, wiederverwertet??, wiedergewinnung??, wiedergewinnen??, wiedergewonn??, recy[c,k]ling, recy[c,k]led, recy[c,k]len??), (or Ni_MH, nickel_wasserstoff, nickel-metall-hydrid), (or zelle?, akkumulator??, +batterie?, (elektrochemisch?? 2D (or speicher??, gespeichert??, energiespeicherung??)), energiespeicher??, energiespeicherung??)	10ug (or recup, recuperation?, recycl???, recyclage?), (or Ni_MH, nickel_hydrure_m?tallique, nickel_hydrure, nickel_hydrogene), (or accumulateur?, batterie?, pile?_[e,é]lectrique?)
Recycling	**Primary batteries**				H01M10/54, H01M6/52, Y02W30/84	recycling of primary (disposable) batteries	10ug (or reclaim, reclaimed, reclaiming, recycling, recycled), (or alkaline, dry), (or battery, batteries, cell?)	5ug (or wiederverwerten, wiederverwertet??, wiedergewinnung??, wiedergewinnen??, wiedergewonn??, recy[c,k]ling, recy[c,k]led, recy[c,k]len??), (or alkali_mangan_batterie?, alkali_mangan_zelle?, trockenbatterie?, trockenzelle?, zink_kohle_zelle?, zink_kohle_batterie?, zink_braunstein_zelle?, zink_braunstein_batterie?)	10ug (or recup, recuperation?, recycl???, recyclage?), (or alkaline?, seche?, saline?, zinc_carbone), (or batterie?, pile?)
Thermal storage	**Cryogenic**				–	cryogenic storage	(or (5ug cryogenic, energy, storage?), (10ug storage, energy, (or liquefied, liquid, liquified, liquify+, liquefy+), (or gas, gases, air, methane, nitrogen, carbon_dioxide, CO_2))) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (5ug (or kryogen??????, tiefkalt??, tieftemperatur??), (or speicher?, energiespeicher?, speicherung??, energiespeicherung??)), (10ug (or speicher?, energiespeicher?, speicherung??, energiespeicherung??), (or verfl?ssig???, fl?ssig??), (or gas??, luft?, methan??, stickstoff??, Kohlendioxid??, Kohlendioxyd??, kohlens?ure?, CO_2))) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, aus-gleicht, ausgeglichen??)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischenspeicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(or (5ug cryogénique?, (or énergie, électricité?), (or stocké??, stockage, stocker, réservoir)), (10ug (or énergie, électricité?), (or stocké??, stockage, stocker, réservoir), (or liquid??, condens???, liquéfi????), (or gaz, air, methane, azote, (gaz 2d carbonique), (dioxyde 2d carbone), CO_2))) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Thermal storage	General				–	thermal electricity storage in general	((or storing, stored, accumulated, store?, accumulation, accumulate?, storage) 2d (or thermal, heat)) and (electric?? 2d (or heating, heater?, boiler?, stove?, furnace?, oven?)) ((or storing, stored, accumulated, store?, accumulation, accumulate?, storage) 2d (or thermal, heat)) and (electric?? 2d (or heating, heater?, boiler?, stove?, furnace?, oven?)) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	((or w?rmespeicher?, ((or speicher?, energiespeicher?, gespeicher???, energiespeicherung??, speicherung??) 2d (or thermisch???, w?rme))) and (elektrisch?? 2d (or heizung??, erhitzer?, heitzer?, heizelement??, heizk?rper?, heizaggregat??, heizplatte?, heizapparat?, boiler?, dampfkessel?, heisswasserspeicher?, heizungskessel?, ofen?, heizkessel?))) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen?)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischenspeicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	((or stocké??, stockage, stocker, réservoir, accumul??????) 2d (or thermique?, chaleur?)) and (électriqu?? 2d (or résistance, chauffage?, chaudiére?, chauffe_eau)) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))
Thermal storage	Gravel/rocks/ pebble bed				–	gravel/rocks/ pebble bed	(10ug (or storing, stored, accumulated, store?, accumulation, accumulate?, storage), (or thermal, heat, energy), (or high_temperature?, elevated_temperature?, hot), (or rock?, pebble?, gravel?, bead?, grain?, pellet?, sand?, stone?)) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (10ug (or w?rmespeicher?, w?rmespeicherung??), (or hochtemperatur??, heiss??), (or kieselstein??, kiesel??, flintstein??, ger?ll?, rollstein??, stein??, sand?)), (10ug (or energiespeicherung??, speicherung??, speicher?, energiespeicher?, gespeicher???), (or thermisch???, w?rme), (or hochtemperatur?, heiss??, gl?hen???), (or kieselstein??, kiesel??, flintstein??, ger?ll?, rollstein??, stein??, sand?))) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen?)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischens- peicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(10ug (or stocké??, stockage, stocker, réservoir, accumul??????), (or thermique?, chaleur?), (or haute_temperature??, chaude?, chauff????), (or pierre?, gravier?, caillou???, sable?, sablon?)) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Thermal storage	**Molten salt**				–	molten salt	(10ug (or storing, stored, accumulated, store?, accumulation, accumulate?, storage), (or energy, thermal, heat), (or fused, melted, molten), salt?) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (10ug (or w?rmespeicherung??, w?rmespeicher?), (or schmelz????, geschmolz????, aufschmelz????, aufgeschmolz????), salz??), (10ug (or speicher?, energiespeicher?, gespeicher???, energiespeicherung??, speicherung??), (or thermisch???, w?rme), (or schmelz????, geschmolz????, aufschmelz????, aufgeschmolz????), salz??)) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen??)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischenspeicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(10ug (or stocké??, stockage, stocker, réservoir, accumul??????), (or thermique?, chaleur?), (or fondre, fondu?, fusion, liquef????), sel?) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))
Thermal storage	**Silicon-based**				–	silicon-based	(10ug (or storing, stored, accumulated, store?, accumulation, accumulate?, storage), (or thermal, heat, energy), (or high_temperature?, elevated_temperature?, molten, melted, hot), silicon) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shav-ing, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (10ug (or w?rmespeicher?, w?rmespeicherung??), (or hochtemperatur??, heiss??, schmelz????, geschmolz????, aufschmelz????, aufgeschmolz????, gl?hen???), silizium), (10ug (or energiespeicherung??, speicherung??, speicher?, energiespeicher?, gespeicher???), (or thermisch???, w?rme), (or hochtemperatur??, heiss??, schmelz????, geschmolz????, aufschmelz????, aufgeschmolz????, gl?hen???), silizium)) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen??)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischens-peicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(10ug (or stocké??, stockage, stocker, réservoir, accumul??????), (or thermique?, chaleur?), (or haute_temperature??, chaude?, chauff????, fondre, fondu?, fusion, liquef????), silicium?) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))

L1	L2	L3	L4	L5	Ranges of CPC classes (combine with GQ)	Specific design	Queries in English	Queries in German	Queries in French
Thermal storage	**Sorption**				–	sorption	(10ug (or storing, stored, accumulated, store?, accumulation, accumulate?, storage), (or thermal, heat, energy), sorption) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (5ug (or w?rmespeicherung??, w?rmespeicher?), sorption???), (10ug (or speicher?, energiespeicher?, gespeicher???, speicherung??, energiespeicherung??), (or thermisch???, w?rme), sorption???)) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen??)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischenspeicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(10ug (or stocké??, stockage, stocker, réservoir, accumul??????), (or thermique?, chaleur?), sorption) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))
Thermal storage	**Thermochemical**				–	thermochemical	(10ug (or storing, stored, accumulated, store?, accumulation, accumulate?, storage), (or thermal, heat, energy), (or thermochemistry, thermochemical)) and (or (5ug(or electricity, electrical, electric), (or storage, storing, store?, accumulation, accumulate?, accumulating, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration)), (8ug(or electric, electrical), (or power, energy), (or storage, storing, store?, accumulation, accumulate?, accumulating, buffer?, buffering, buffered, manage?, managing, deferral, deferred, deferring, defers), (or renewable, solar, wind, photovoltaic?)), (8ug grid?, (or load?, peak?), (or level?ing, level?, level?ed, shaving, shave?, balance, balancing, balanced, arbitrage, compensation, compensating, compensate?, arbitration, buffer?, buffering, buffered, firming, firmed, manage?, managing, deferral?, deferred, deferring, defers)))	(or (5ug (or speicher?, speicherung??, w?rmespeicher?,energiespeicher?, gespeicher???), thermochemisch???), (10ug (or speicher?, energiespeicher?, gespeicher???, speicherung??, energiespeicherung??), (or thermisch???, w?rme), thermochemisch???)) and (or (10ug(or elektrizität, elektrisch??, elektrizit??t, stromnetz, energienetz, elektrizitätsnetz, stromversorgungsnetz, energieversorgungsnetz), (or (or speicher?, gespeichert??, speicherung??, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage?, arbitration?, Spitzenausgleich??, Spitzenlastausgleich??, belastungsausgleich??, lastausgleich??, spitzenlast??, lastmanagement?, spitzendeckung??, spitzenabdeckung??), (4ug(or Last??, Spitze?, Spitzenlast??, Belastung??), (or ausgleichen, ausgleicht, ausgeglichen??)))), (or (8ug elektrisch??, (or strom, energie), (or speicher?, gespeichert??, speicherung??, speichersystem??, buffer?, buffering, puffer?system??, pufferspeicher?, pufferanlage?, pufferspeicherung??, puffereinheit??, zwischenspeicher?, zwischenspeicheranlage?, zwischenspeicher?system??, zwischenspeicherung??)), (or (erneubar?? 2d energie), renewable?, solarenergie, solarstrom windenergie, windkraft, windrad, windräder?, windstrom, photovoltaik)))	(or (5ug (or stocké??, stockage, stocker, réservoir, accumul??????), thermochimi????), (10ug (or stocké??, stockage, stocker, réservoir, accumul??????), (or thermique?, chaleur?), thermochimi????)) and (or (5ug (or électricité, électrique?), (or stocké??, stockage, stocker, réservoir, accumul??????, off_peak, peak_level?ing, peak_shaving, load_level?ing, load_shifting, arbitrage, arbitration, effacement, lissage, délestage?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or stocké??, stockage?, stocker, réservoir, accumul??????, équilibrage?, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage?, délestage?), (or renouvelable?, photovolta?que?, solaire?, éolien?, éolienne?)), (8ug (or électricité, électrique?, réseau?_électrique?), (or offre_demande, offre, demande, consommation, désequilibre, pointe?), (or équilibrage, équilibrer, management?, manager?, effacement?, lissage?, piloter, pilotage, délestage?)))

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