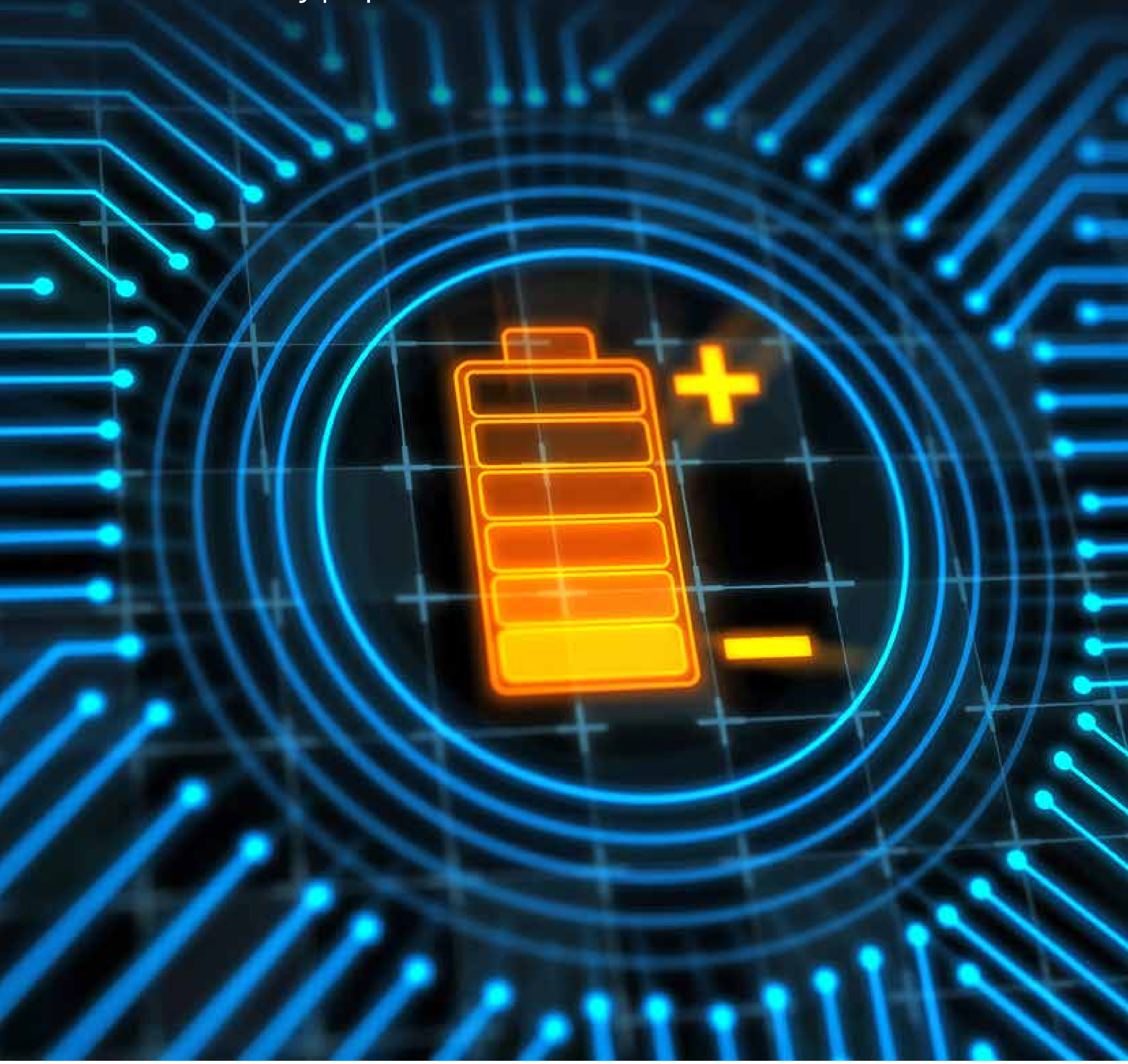
Innovation in batteries and electricity storage

A global analysis based on patent data

Executive summary | September 2020



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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.

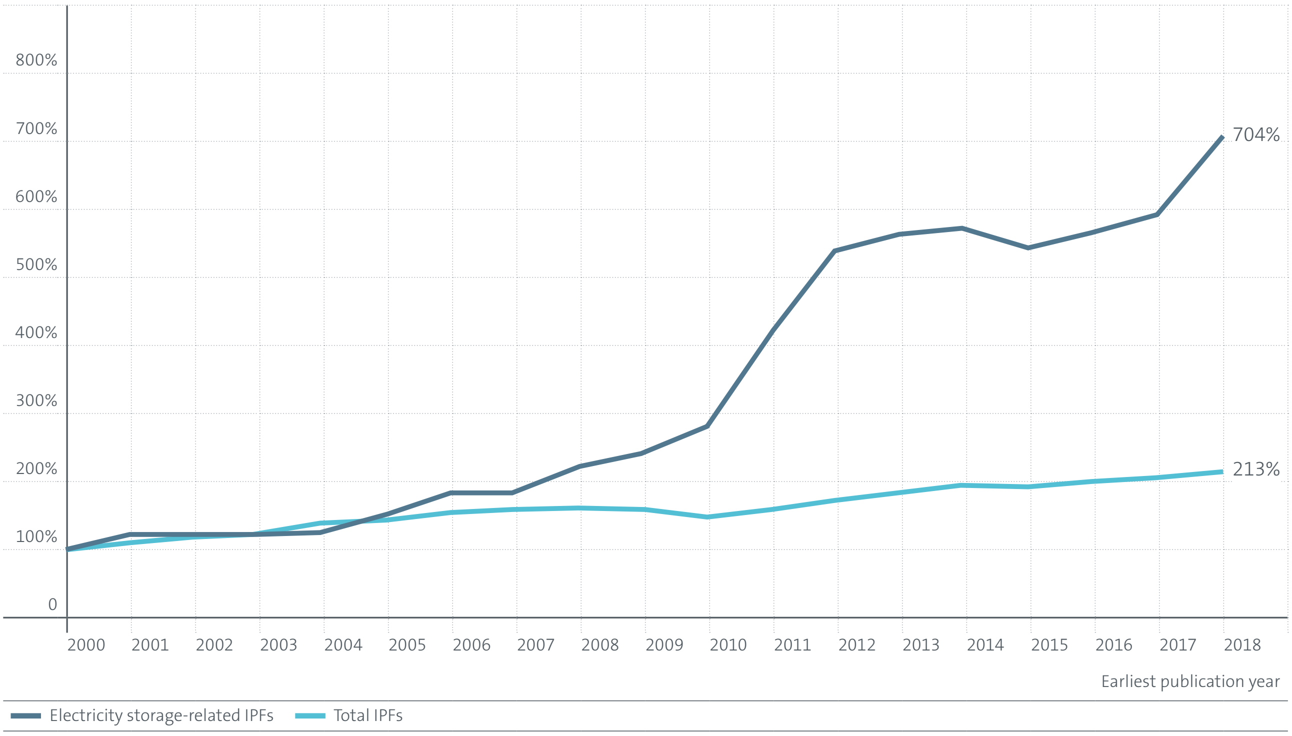
Highlight 1: *Patenting activity in electricity storage has grown much faster than patenting activity in general over the past decade, indicating a burst of innovation in this area, spearheaded by lithium-ion (Li-ion) batteries, in particular for electric vehicles.*

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.

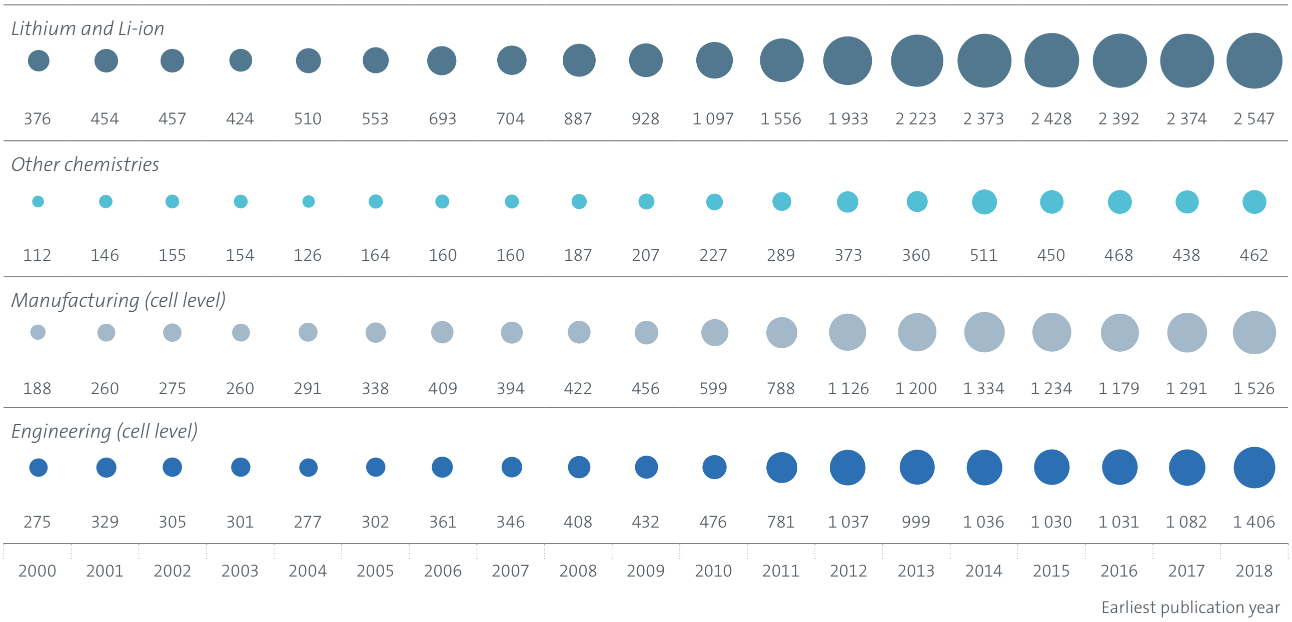
Within the area of battery technologies, patenting activity has been on the rise for most key technology variants, including lead acid, redox flow and nickel. It is Li-ion technology, however, which has been fuelling innovation in battery technologies since 2005 (Figure E2). Li-ion is currently the dominant 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

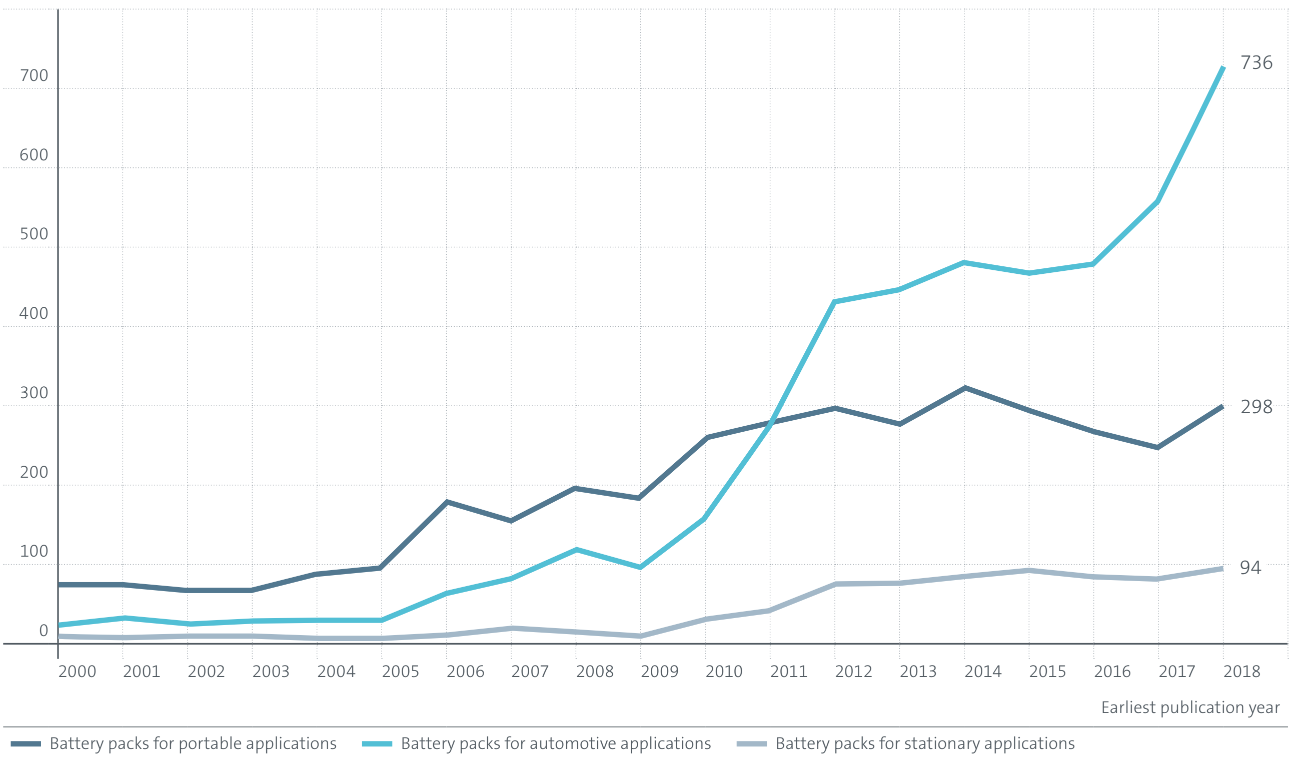


Source: European Patent Office

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

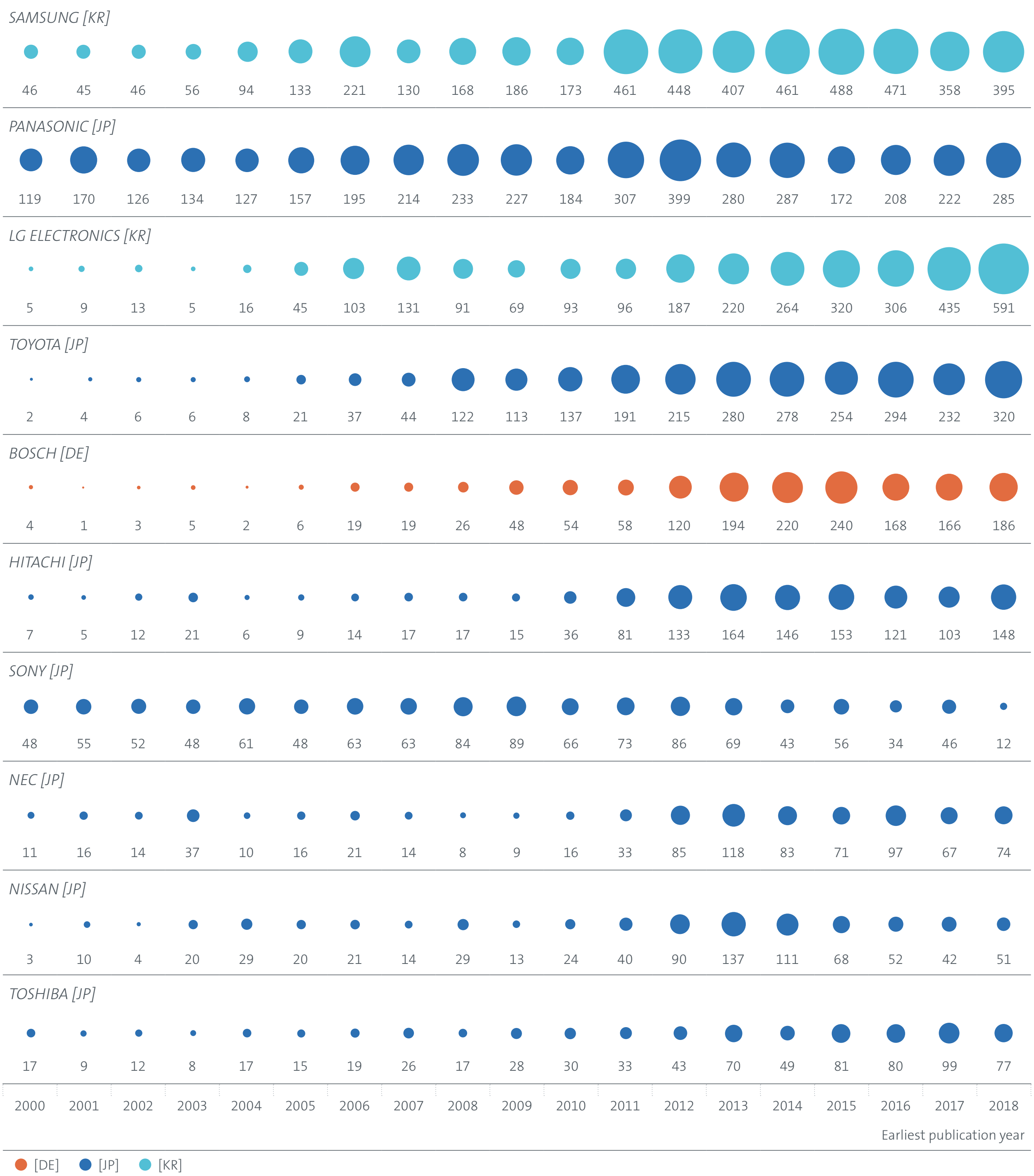
Highlight 2: *Japan and the Republic of Korea are leading the global battery technology race, pushing other countries to develop competitive advantages in specific parts of the battery value chain.*

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

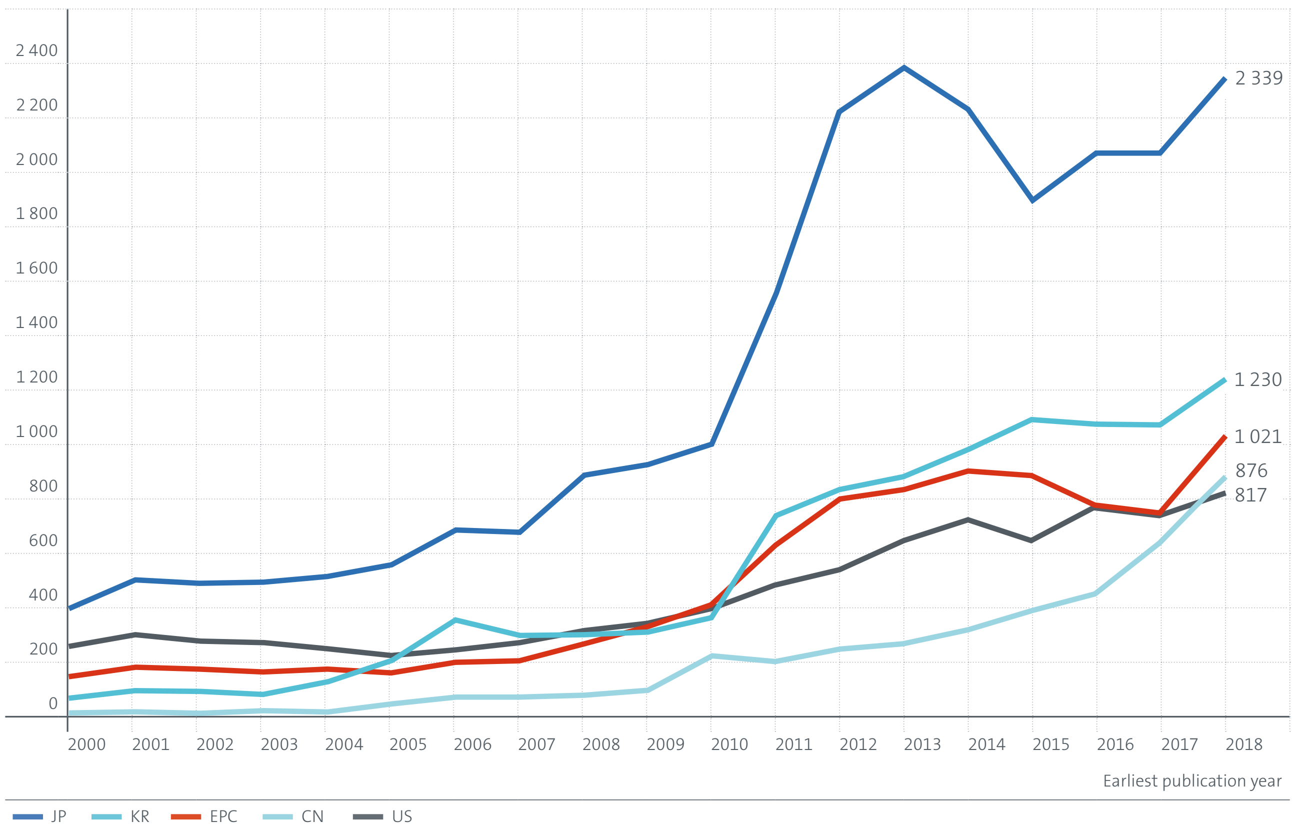
A broader analysis of the geographic origins of IPFs confirms Japan's strong leadership in battery technology (Figure E5). Japan was already paving the way worldwide in the 2000s, but further reinforced its lead at the turn of the last decade. Japanese-based companies and inventors generated more than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



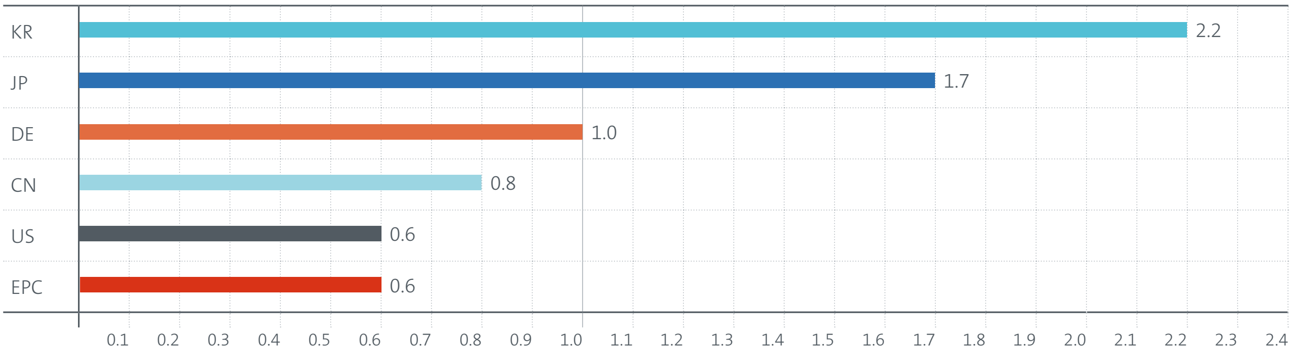
Source: European Patent Office

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.

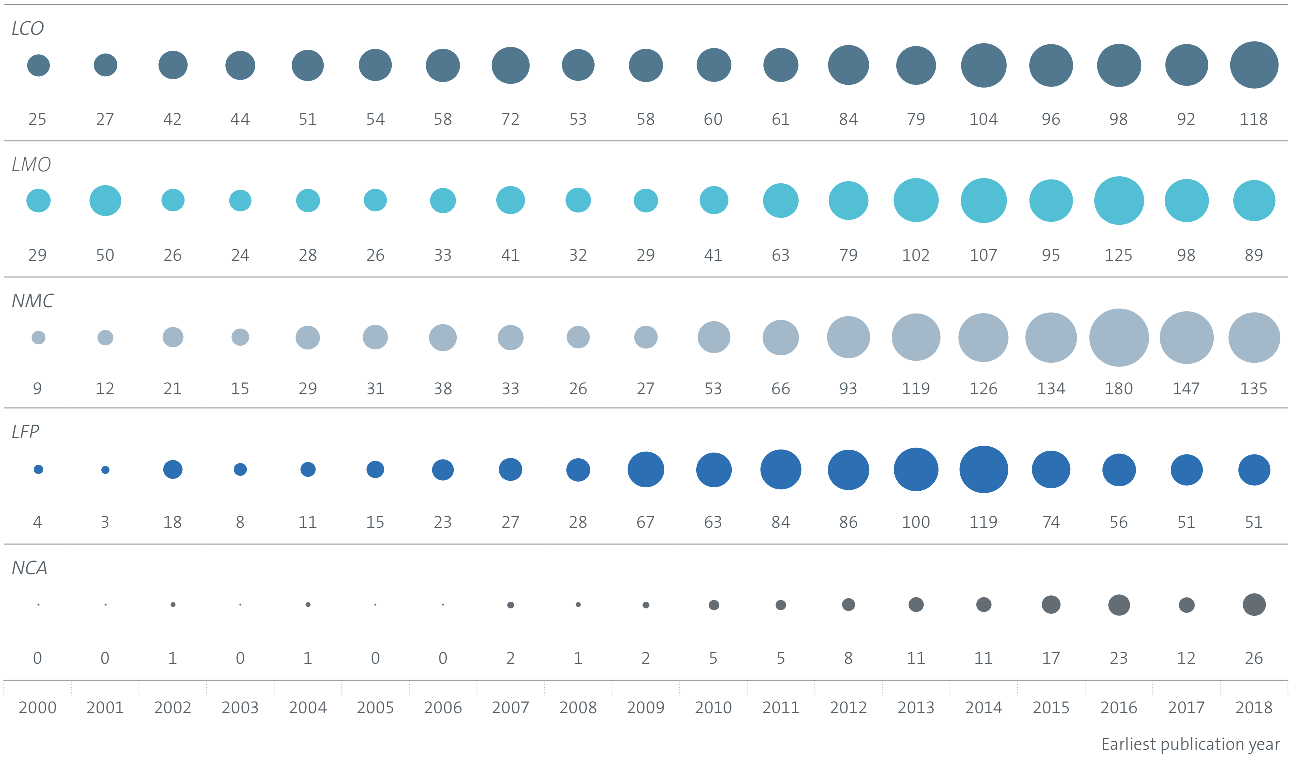
Highlight 3: *NMC cathode chemistry has seen the most innovative breakthroughs related to Li-ion batteries since the launch of mass-market electric vehicles, but potentially disruptive competitors are emerging outside the big companies and with more regional variation.*

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

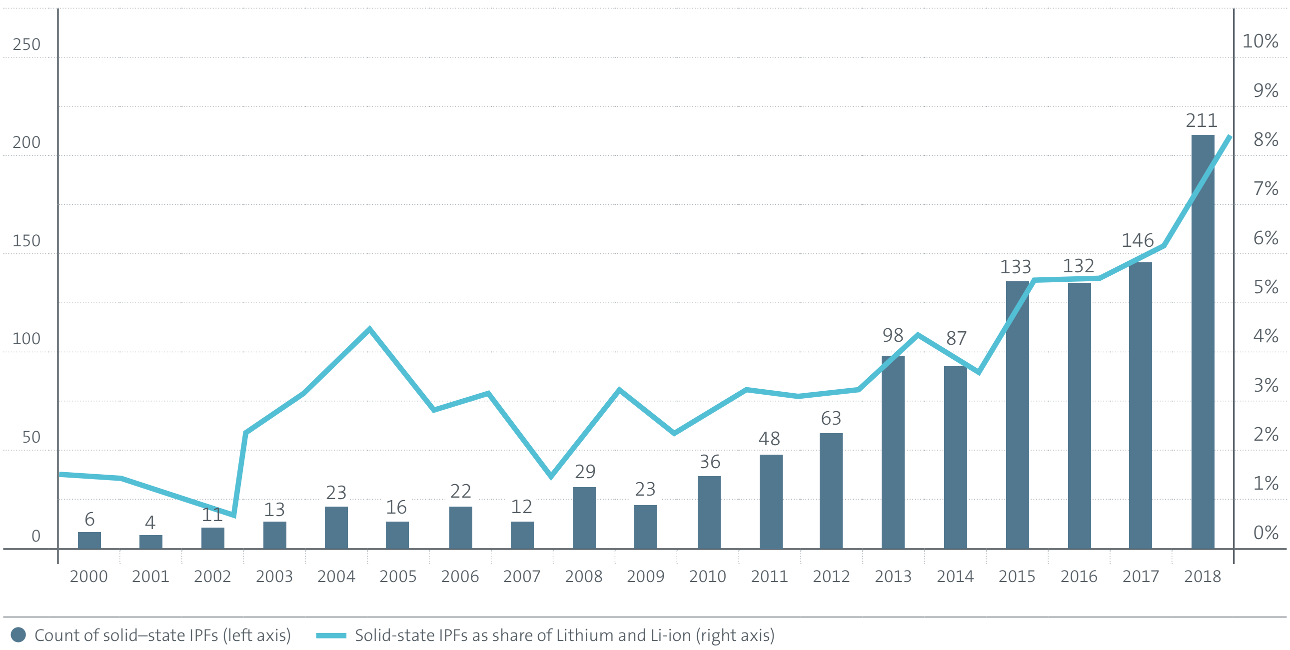
The first serial production electric cars, launched just over a decade ago, used the same cathodes as those dominating the field of consumer electronics: lithium cobalt oxide (LCO) and lithium manganese oxide (LMO). Since then, the focus has moved onto other chemistries, including NMC, lithium iron phosphate (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



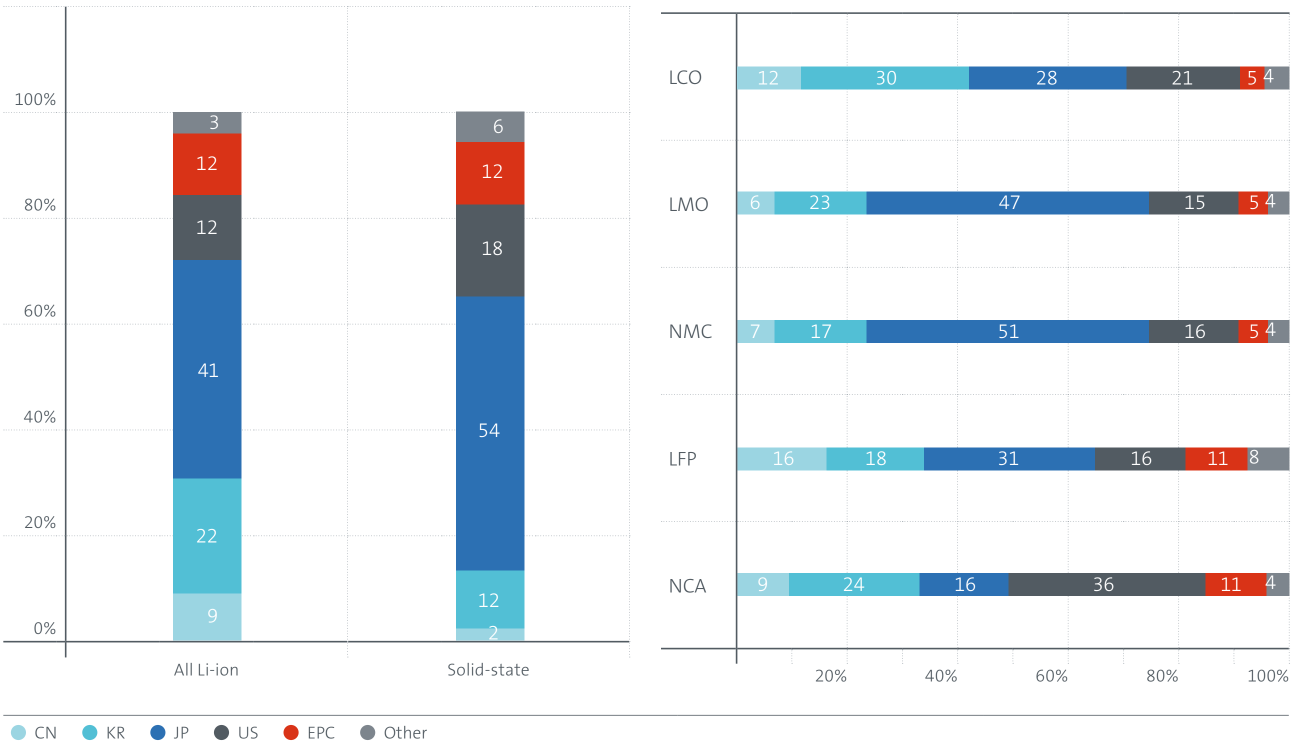
Source: European Patent Office

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

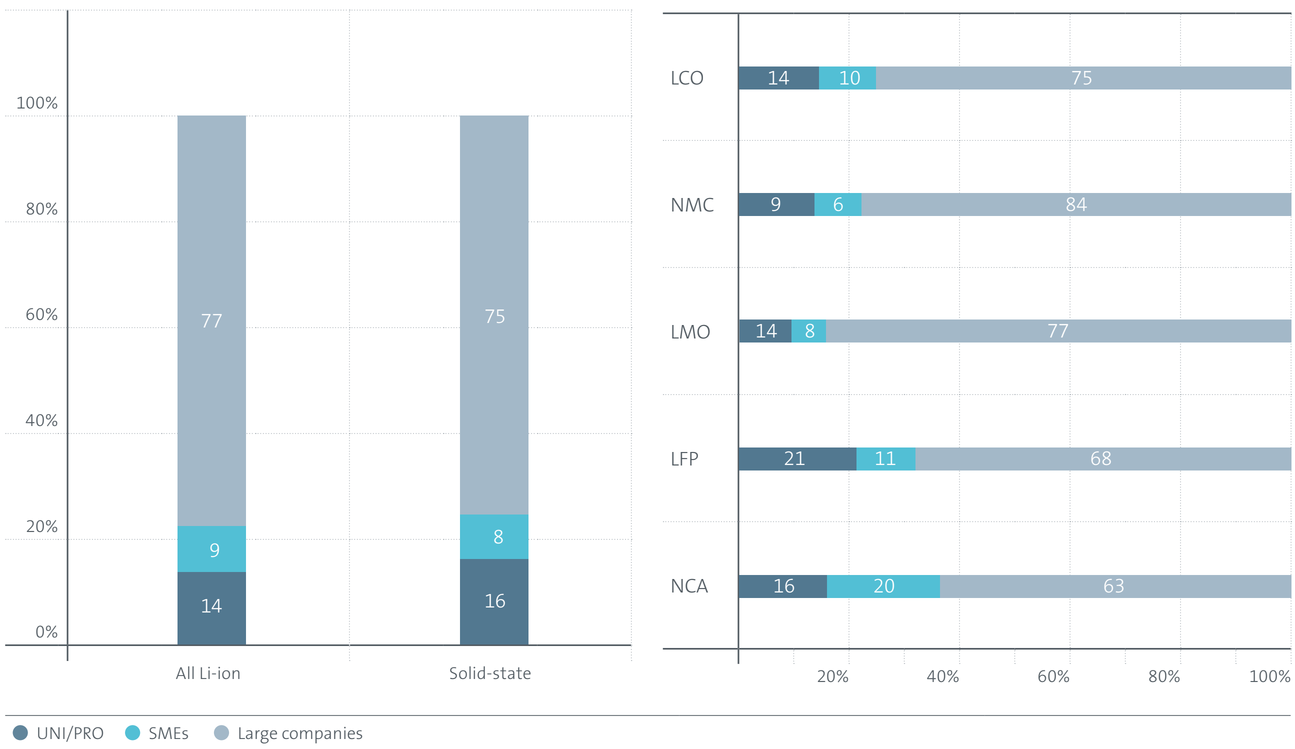


Source: European Patent Office

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



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