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LOW CARBON ENERGY OBSERVATORY

BATTERIES
Technology development report

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Contents

Foreword

The Low Carbon Energy Observatory (LCEO) is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database)

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

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Natalia LEBEDEVA has provided analysis of all-solid-state batteries with lithium metal anodes; Vanesa RUIZ RUIZ has collected and analysed data relevant for Li-S battery technology; Marek BIELEWSKI has performed analysis of Na-ion battery technology and related projects; Darina BLAGOEVA and Alberto PILENGA worked on RedOx flow battery technology; Analysis of cross-cutting projects relevant to several battery technologies has been performed by Natalia LEBEDEVA and Marek BIELEWSKI.

Fleur THISSANDIER and Nicolas BARON (KnowMade SARL) have prepared a patent landscape analysis, available in the Annex of this report.

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1 Introduction

With the announcement of the European Green Deal an intensified effort will be directed towards achieving a set of challenging targets to enable Europe to become the first climate-neutral continent by 2050.[1] Measures to facilitate this transition will need to be taken in many economic sectors, including energy, transport, industry and built environment.[1]

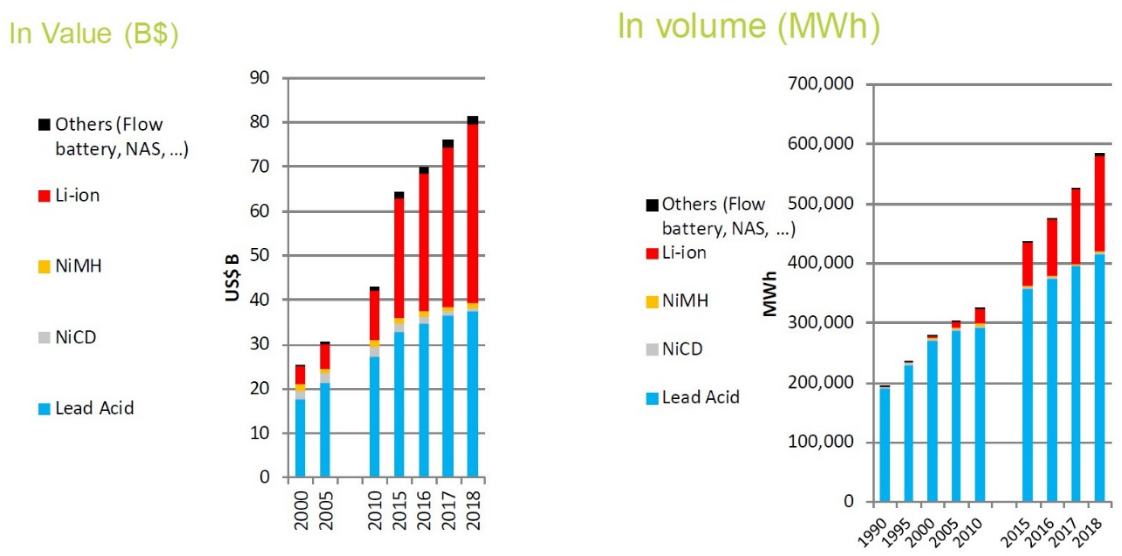
Battery energy storage is recognised as one of the key technologies for the transition to a decarbonised and clean energy system due to its broad application potential in the power sector and in transport.[2,3] Share of electricity from renewable energy sources, such as e.g. wind and solar, is expected to further increase and their inherently intermittent nature necessitates deployment of energy storage solutions.[4] While still in its infancy, battery energy storage at the grid level is set to play a key part in the future of the renewable energy industry and the **power sector**, by enabling the storage of surplus energy that currently goes to waste and by providing reliable grid services (e.g. peaking capacity, frequency and voltage control, peak shaving, congestion management, black start).[4,5] In behind-the-meter applications, batteries improve power quality and increase the reliance on self-generation.[5] In integrated systems supported by smart market designs, batteries may contribute to decentralisation and the shift of consumers to prosumers, thereby empowering the participation of the EU citizens in the energy market as envisaged in "Clean Energy for all Europeans" legislative package.[6]

Transport accounts for a quarter of the European Union’s greenhouse gas emissions and these continue to grow. The Green Deal seeks a 90% reduction in these emissions by 2050.[1] Together with low-carbon options such as hydrogen or advanced biofuels, the deployment of Electric Vehicles (EVs) at large scale is a prerequisite in the transition to zero-emission mobility.[3,4]

Batteries also stand at the interface of power and transport supporting their **sectoral integration**. In the longer term, coupling these sectors may introduce cost efficiencies in the system and help bring their emissions closer to zero.[5]

At present Li-ion battery technology is dominating the rechargeable battery market in value and, thanks to its explosive growing at compound annual growth rate (CAGR) of >15%, it is expected to break-even with such a well-established and mature battery technology as lead-acid also in volume in the near future (see Figure 1).[7]

Figure 1. The worldwide battery market. [Reproduced with permission from Ref. 7].



The success of Li-ion battery technology, covering a range of chemistries, is largely due to its superior energy density and power density compared to various well-established and mature battery technologies such as e.g. lead-acid, Ni-Cd, Ni-MH, etc. (see Figure 2 and Figure 3), and is further enabled by a rapid decrease of cost for Li-ion battery technology.[5]

Figure 2. Specific gravimetric and volumetric energy density of various battery technologies. [Reproduced with permission from Ref. 7].

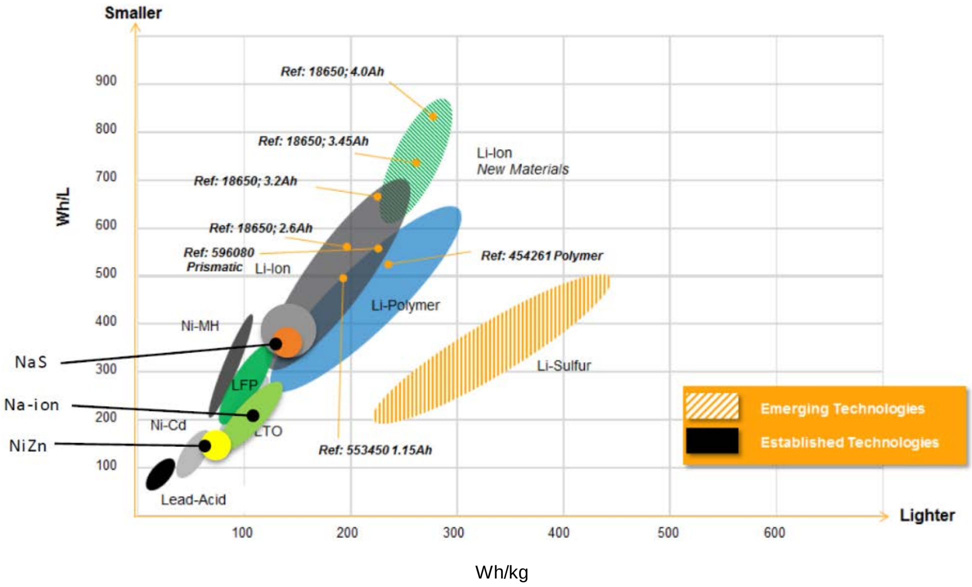
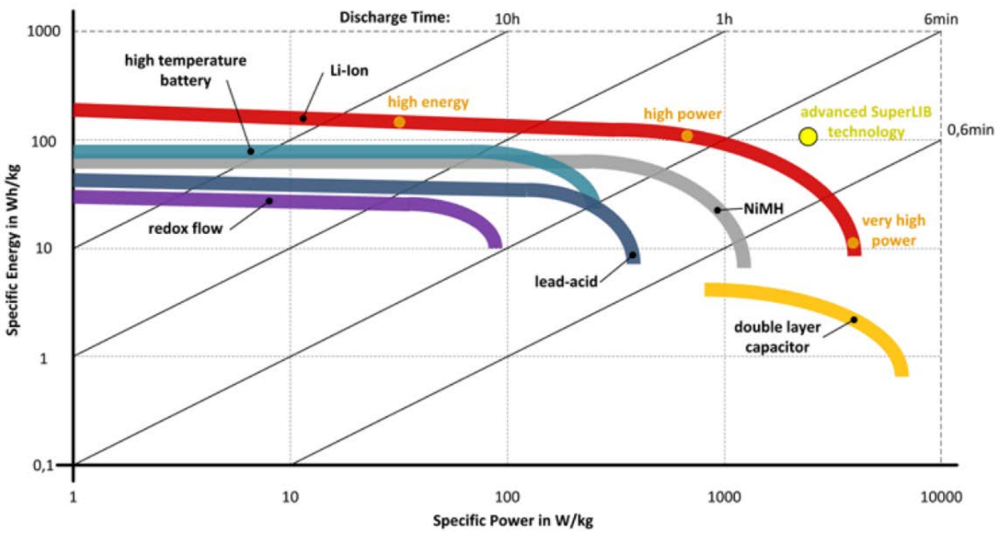


Figure 3. Specific energy and specific power characteristics of various battery technologies. [Reproduced with permission from Ref. 7].



Nevertheless, a broad range of applications requires a variety of fit-to-purpose batteries to satisfy the requirements for each application stimulating development of new types of batteries.[8,9] A large effort worldwide is directed towards research and development for various advanced Li-ion as well as post-Li and non-Li-ion battery technologies, such as:

a) All solid-state Li-ion batteries with Li metal anodes (ASSB LiM),

b) Lithium-sulfur batteries (Li-S),

c) Sodium-ion batteries (Na-ion),

d) RedOx flow batteries, including these with organic shuttles (organic RedOx),

e) Multivalent ion batteries, based on e.g. Mg^{2+}, Zn^{2+}, Ca^{2+} and Al^{3+},

f) Metal-air batteries, including Li-air, Na-air, Mg-air, Al-air, Si-air, Fe-air and Zn-air.

Current report focuses on the first three of the above-mentioned battery technologies and RedOx flow batteries with organic shuttles for their potential to deliver higher energy density (ASSB LiM, Li-S), improved safety and higher power density enabling fast charging (ASSB LiM, organic RedOx), reduced cost (Na-ion, Li-S), potential to avoid scarce raw materials including critical raw materials (CRMs) (Na-ion, Li-S, organic RedOx), extended lifetime and exceptional scalability and flexibility to improve the stability, efficiency, and sustainability of the power grid (organic RedOx).

Historically, manufacturing of Li-ion batteries and associated R&D&I support was concentrated in Asia, predominantly in Japan, South Korea and China. Maintaining the leading edge in this quickly growing and competitive sector requires constant technological improvements and, hence, significant R&D&I effort. It comes as no surprise that the above-mentioned Asian regions lead in battery research and innovation on both contemporary Li-ion as well as advanced Li-ion such as ASSB, post-Li-ion such as Li-S and non-Li-ion, i.e. Na-ion and RedOx flow batteries. European research helped gaining a deep insight into fundamental aspects of advanced battery technologies, a.o. underlying reaction mechanisms, materials properties, interfacial processes, battery components safety, etc. as well as associated limitations. Due to the absence of a well-developed ecosystem, these results were however not fully and systematically implemented by the European battery sector.

Recognising the need and urgency for the EU to become competitive in the global battery value chain, the Commission launched the European Battery Alliance (EBA) in 2017.[10] The technology and innovation platform of EBA - Batteries Europe[11] - drives the implementation of battery-related research and innovation actions of the Strategic Energy Technology (SET) Plan[12] and the Strategic Transport Research and Innovation Agenda[13] and is tasked with coordination of R&D&I efforts at regional, national and European levels and.

A range of actions have already been put in place, including a) strengthening of the Horizon 2020 programme in 2019-2020 with additional nearly €250 million for battery research funding,[14] b) preparing specific instruments for the next Research Framework Programme Horizon Europe, such as e.g. European Partnership for an Industrial Battery Value Chain[15] and c) stimulating investments, both national of the Member States and private, in creation of a modern and competitive EU battery value chain through Important Project of Common European Interest (IPCEI).[16] Significant support to R&D on batteries will continue also in the next frame work programme of the EU – Horizon Europe. The expected impact of these major efforts is that establishment of a battery value chain in Europe, being of strategic interest for our economy and society, will facilitate the transition to clean mobility and energy whilst creating jobs, sustainability and competitiveness as targeted by the European Green Deal.

Current report gives an overview of the technology state-of-art and technology development efforts for the above-mentioned four battery technologies as well as identifies barriers for their wider deployment and the needs for further research and innovation. Detailed patent landscape analysis for Li-S, Na-ion and organic RedOx batteries can be found in Annex 2 of this report. Data on Horizon 2020 projects, co-funded by the European Commission, was retrieved from the project dossiers via the COMPASS tool. Analysis of various national and international R&D programmes has been performed based on relevant scientific publications, presentations at international conferences, news items and other open information sources (such as, for example, websites of funding agencies). In order to identify the technology barriers and R&D needs, an analysis of the Horizon 2020 projects as well as of literature data was carried out.

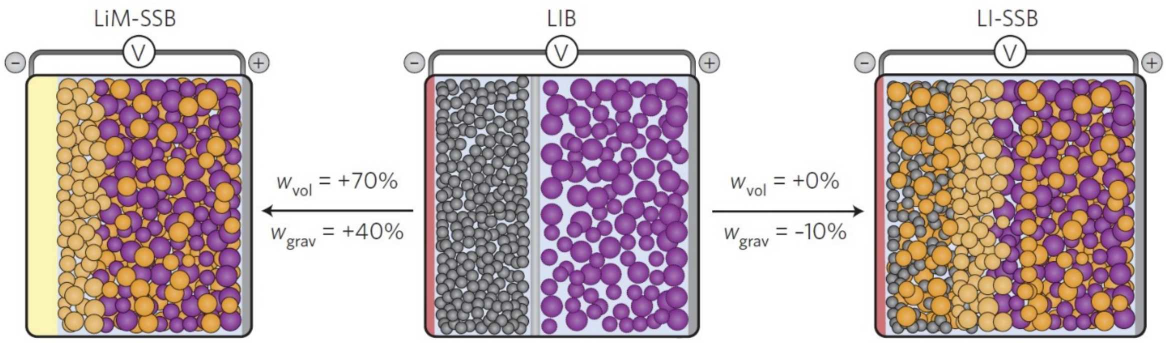
2 Technology state of the art and development trends

2.1 All Solid State Batteries with Li-metal anodes

What are ASSB LiM?

All solid-state Li-ion batteries differ from the contemporary Li-ion batteries by their lack of liquid electrolyte. Instead, a Li-ion conducting solid is used as both electrolyte and separator (see Figure 4). A significant increase in both gravimetric and volumetric energy densities of ASSB can be achieved when a thin layer of metal Li serves as an anode instead of an intercalation type material, e.g. graphite, currently used in the conventional Li-ion batteries.[17,18] This advantage continues to be one of the main drivers behind research on ASSB LiM. Conventional intercalation cathode materials can also be used in ASSB LiM and the trend is to go for high capacity and high voltage materials such as nickel manganese cobalt oxide (NMC) and nickel cobalt aluminium oxide (NCA).

Figure 4. Typical battery architectures for the conventional lithium-ion and solid-state batteries. [Reproduced with permission from Ref. 18] W_{vol} and W_{grav} stand for volumetric and gravimetric energy densities of an ASSB cell.



Why ASSB LiM?

ASSB LiM present a number of advantages compared to conventional Li-ion batteries with liquid electrolytes[19-23]:

- Higher gravimetric and volumetric energy densities, i.e. up to 700 Wh/kg and 1400 Wh/l (thanks to high specific capacity of Li metal anode, smaller amount of electrolyte required (both in mass and volume) and wider operating cell voltage window because many solid electrolytes are chemically more inert and more stable over a larger potential window, enabling also the use of high-voltage cathode materials),
- Improved safety (no flammable, toxic or corrosive electrolyte present),
- Higher power density (related to wider operating cell voltage window as well as to higher thermal conductivity) enabling fast charging,
- Broader operational temperature range, also due the ability to operate at elevated temperatures up to >100°C,
- Longer shelf life (low self-discharge rate),
- Custom cell and battery designs, including flexible and wearable architectures.

Commercially available ASSB LiM cells and packs

Although research on ASSB LiM has yielded some novel concepts already 50 years ago,[24] wide commercialisation of these batteries, especially for such applications as transport electrification and stationary energy storage, is yet to take place. It is commonly agreed that a noticeable market uptake of the ASSB LiM cannot be expected before 2030, especially in electrification of transport and stationary energy.[17]

Bolloré is the only company who introduced ASSB LiM to the mobility market and stationary energy storage (Table 1). The Li Metal Polymer (LMP) batteries (Bolloré Blue Pack Solutions) are used in EVs (Blue car & e-Mehari from Citroën), E-buses (Blue Bus) and stationary storage systems.[25] LMP battery has a relatively low energy density of 120 Wh/kg at the pack level and 240 Wh/kg at the cell level because it uses $LiFePO_4$ (LFP) cathode operating at a low voltage of 3.6 V. In addition, this LMP technology makes use of polymer-based solid electrolyte, which, due to its limited ionic conductivity at room temperature, requires operation at 60-80°C. This, in turn, means that the vehicles, equipped with LMP batteries, need to be plugged-in often to avoid cooling of the pack decreasing the overall system efficiency.

Other examples of commercially available ASSB LiM include small (micro)batteries for applications such as oil & gas production, wireless sensors, etc. (see Table 1).

Table 1. Commercially available ASSB LiM.[25-27]

Manufacturer	Application	Anode	Cathode	Solid electrolyte	Energy density	Comments
Bolloré (FR) "LMP"	Automotive traction, stationary energy storage	LiM	LFP	Polymer-based PEO-LiTFSI	120 Wh/kg (pack) 100 Wh/l (pack) 240 Wh/kg (cell)	Operating at 60-80°C Cycle life of up to 4000 cycles depending on the application
STMicro-electronics (CH) "EnFilm"	IoT, wireless sensors and networks, RFID tags, smart cards, wearable technology, non-implantable medical monitors, etc.	LiM	LCO	LIPON	480 Wh/l (cell)	4000 cycles (to 80% of initial capacity at 1C discharge rate between 75% and 0% of SOC)
Johnson Battery Technologies (USA)	Oil & gas, aerospace, defence and medical industries	LiM a.o.	LCO a.o.	LIPON		

Solid-state electrolytes

Solid state electrolytes are the key component of ASSB LiM and they need to satisfy a number of requirements to be suitable for this application,[19,20,28-30] namely:

a) to be chemically and electrochemically stable in contact with Li metal and cathode materials in a broad range of operating temperatures and cell voltages,

b) to exhibit sufficient conductivity for Li^+ (at least $>10^{-4}$ S/cm and better $>10^{-3}$ S/cm), while being non-conductive electronically $<10^{-12}$ S/cm (i.e. Li transference number as close as possible to 1),

c) to have adequate mechanical properties to withstand mechanical stress a.o. at interfaces caused by insertion/de-insertion of Li ions into the electrodes during battery cycling, and also to enable their incorporation into the ASSB LiM cells,

d) to show good charge transfer kinetics and low interfacial resistance between electrodes and ionic conductor phase,

e) to be ideally insensitive to water vapour and CO_2 in the air to facilitate their manufacturing and handling.

Four main types of solid-state electrolytes can be distinguished: polymer-based organic electrolytes, sulfides- and oxides-based inorganic electrolytes and various mixtures of the organic and inorganic materials forming hybrid electrolytes.

Polymers: Poly(ethylene oxide) (PEO) is the most widely used polymer for all solid state battery R&D and at industrial level (Bolloré Blue Car, please see below).[31] However, this polymer has a low ionic conductivity at room temperature (10^{-5} S/cm range) and is unstable above 3.9 V vs. Li/Li^+.[31-33] Other examples of polymers are poly(propylene oxide) (PPO), poly(acrylonitrile) (PAN), poly(methyl methacrylate) (PMMA), and poly(vinyl chloride) (PVC). Recently, main-chain polyester-based polymer electrolytes (such as polycarbonate or poly(ε-caprolactone) based) have received considerable attention because of their high efficiency dissolving lithium salt by their polar groups, improved ionic conductivity and high electrochemical stability.[34,35] It has been shown that they can work at room temperature in an all-solid-state system.[36] Nevertheless, their ionic conductivity still requires improvement for real applications. In addition to their limited room-temperature ionic conductivity, solid polymer electrolytes are often contaminated by reactive residuals, which can negatively affect cell performance and durability. In general, polymer electrolytes are easy-to-process materials facilitating manufacturing of ASSB LiM. Dendrite-free operation of the ASSB LiM cells is only possible at low C rates, which hinders fast charging of the ASSB LiM with polymer solid electrolytes.

Oxidic solid electrolytes: Among the inorganic electrolytes, oxidic solid electrolytes such as LATP ($Li_{1+x}Al_xTi_{2-x}(PO_4)_3$) glass-ceramic and garnet-type LLZO ($Li_7La_3Zr_2O_{12}$) show high ionic conductivity (between 10^{-4} and 10^{-3} S/cm at 25°C[37]) and are under development for industrial use. LLZO is in addition stable against Li metal anode.[38] These materials have the advantage to be free of critical raw materials (such as e.g. germanium), do not decompose forming toxic gases (e.g. H_2S) and are thermally stable up to very high temperatures. However, most of oxidic solid electrolytes are very brittle, require high temperature treatment for the formation of a phase-pure compound and, in some cases, high pressure for the densification and above all are challenging to process both due to their unfavourable mechanical properties and also due to their sensitivity to atmospheric moisture and CO_2.

Sulfide- and thiophosphate-based solid electrolytes:
Room temperature conductivities higher than typical liquid electrolytes have been reported for a number of ternary and quaternary sulfides and thiophosphates, such as $Li_7P_3S_{11}$ (3 mS/cm) and $Li_{10}GeP_2S_{12}$ (12 mS/cm).[39,40] The absolute record in room temperature Li-ion conductivity (25 mS/cm) also belongs to sulfidic solid electrolyte $Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$.[41] In addition, sulfide-based electrolytes can be considered to be "easier-to-process", ductile solids, especially when compared to oxidic solid electrolytes. However, the major drawback of many sulfides and thiophosphates is their low thermodynamic stability. Most of these materials are easily reduced at low potentials and oxidised at intermediate potentials. Protecting interfaces are therefore required to stabilise the electrolyte/electrode contact. One of the main concerns with sulfide solid electrolytes is their poor chemical stability in air. Under ambient conditions, many sulfide materials undergo a hydrolysis reaction with atmospheric moisture and generate H_2S gas, degrading battery performance and creating safety issues.[42]

Hybrid ceramic-polymer electrolytes: embedding oxidic ceramic particles into polymer electrolyte matrices offers the opportunity for increasing mechanical flexibility, improving processing and controlling electrolyte thickness. However, the addition of ion conducting particles usually does not increase the ionic conductivity of a PEO polymer matrix above the level of 10^{-5} S/cm at room temperature.[43] This is due to the high interface resistance between the polymer and the oxidic particles. One of the major challenges when developing a hybrid solid electrolyte is the limitation in ionic conductivity at the material interfaces.

An interesting concept of solid nanocomposite electrolyte, consisting of mesoporous silica matrix wherein a Li-ion conductive ionic liquid electrolyte (ILE) is confined, has recently been proposed.[44] This nanocomposite electrolyte shows up to 200% higher conductivity than the ILE due to the formation of a 'mesophase' at the ILE/oxide interface providing enhanced Li^+ conductivity. The room temperature conductivity of this nanocomposite electrolyte (up to 18 mS/cm) is among the highest reported worldwide competing with the top performing sulfidic solid electrolyte (25 mS/cm) reported by Toyota.[41]

Li metal anode

Metallic Li is an ideal anode material for rechargeable batteries due to its high theoretical specific capacity (3,860 mAh/g), low density (0.5 g/cm^3) and the lowest negative electrochemical potential (-3.04 V vs. standard hydrogen electrode), all these characteristics contributing to high energy density of ASSB LiM battery cells. However, LiM is costly and to reduce cost the cell should be assembled with the smallest amount of Li necessary to maintain reliable cell performance.

Physical and chemical properties of Li metal: chemical reactivity, malleability, quick self-welding on contact and strong adhesion on most solid materials, including base metals, make processing of this metal very difficult and costly.

The utilisation and handling of thin lithium films are relatively easy when the thickness is ≥ 100 µm. The production of lithium thin films with thicknesses < 75 µm and lengths of several meters by fast and reliable processes is a significant technical challenge. Lithium metal can be cold rolled into sheets of even thickness by compressively rolling the lithium between smooth surfaces of a solid polymeric composition that have a suitable surface tension and are non-reactive with lithium.[45] Thinner films can be produced by extrusion followed by lamination, which are slow and expensive processes. In addition to being costly, very thin films (< 50 µm) are also difficult to handle because of the high deformability of lithium resulting from its malleability and its adhesiveness to most usual materials. Nevertheless, methods to manipulate lithium metal have been developed and very thin films with highly homogeneous surface can nowadays be manufactured.[46] In addition, coating methods based on outstanding wetting properties of molten lithium on a metal or plastic support have been developed.[47]

The purity of lithium foil depends on the ambient atmosphere and materials with which Li metal comes in contact during production. Operation in a dry atmosphere of an inert gas, such as helium or argon, avoids the formation of surface reaction products. The surfaces of the rollers/extrusion/lamination equipment should be smooth and non-reactive with Li to avoid contamination of Li metal foils.

High reactivity of metal lithium towards almost all materials, including the majority of the solid electrolytes, dictates the necessity to protect its surface with a thin protective layer to (1) enable mechanical handling and prevent reaction with environment during anode manufacturing and cell assembly, (2) act as artificial interphase layer for control of the solid-electrolyte/lithium anode interface. Ideally, one protective film should be able to serve both requirements.

One of the major issues with the switch from graphite-based anodes to Li metal anodes, is the significant increase in effective current density. While the effective area for the porous graphite anode can easily be over ten times that of the current collector footprint area, a planar Li metal foil has an effective area equal to the footprint area. This means that the Li plating during charging in a Li-metal battery will proceed at a higher effective current density than the Li-ion intercalation in Li-ion batteries. The trend to go to higher capacity cathodes and higher C-rates at the same time, then forms a major concern, knowing that Li dendrites start to form at current densities around 0.5 mA/cm^2 in liquid electrolytes, ca. 1 mA/cm^2 for thiophosphate solid electrolytes and a few mA/cm^2 for the best oxidic electrolytes such as LLZO.[17]

While this limiting current density can be extended for solid electrolytes as they typically have higher Li concentration and can mechanically block the dendrites, Li plating footprint current densities exceeding 10 mA/cm^2 may be required for high power ASSB LiM cells.[17] This requirement may be met using non-planar, e.g. micro-structured, anodes for area enhancement, and/or protective interface coatings. The role of thickness and stiffness of the electrolyte component and that of morphology and purity of anode layer/current collectors will need to be investigated.

Summarising, **three main challenges** can be defined for Li metal anodes:

1) Fabrication and handling of thin lithium metal layers (foils and/or Li deposits onto an anode current collector),
2) Integration of (protected) Li metal anodes into a ASSB LiM cell ensuring controlled anode/solid electrolyte interface,
3) High lithium plating rates (C-rate for charging) without formation of dendrites.

Anode-less ASSB LiM

In theory, a Li metal battery assembled in discharged state does not need any lithium metal at the anode side: during cell charging, Li ions from the cathode are plated out as metallic Li on a current collector (e.g. Cu) foil. However, it is generally believed that a thin lithium layer is needed as seed layer and to compensate for loss of lithium (e.g. solid electrolyte interface (SEI)).

Nevertheless, in October 2019 Samsung SDI has presented a concept of an anode-less ASSB LiM, in which Li metal is plated onto Ag metal-C nanocomposite layer on Cu current collector, demonstrating that an anode-free operation of ASSB LiM is possible with a suitable current collector.[17]

Interface contacts and stability

Due to mechanical properties of sulfidic and oxidic solid electrolytes, these solids are difficult to incorporate into the electrodes of a battery cell and interfaces between these electrolytes and active electrode materials often suffer from limited-area, point contacts. It is now well-understood that chemical reactions take place at both anode/electrolyte and cathode/electrolyte interfaces leading in many cases to the formation of SEI and CEI, respectively,[17,48-50] which often have higher impedance compared to the bulk phases. Also, volume changes occurring in the electrodes during charge/discharge processes degrade the mechanical integrity of the interface, negatively impacting the cell performance.[51]

The lack of knowledge on interfacial phenomena in solid-state battery systems and the complexity of “visualising” such phenomena using *in-situ* methods, limit the progress of this novel and promising solid-state battery technology. Efforts aimed at understanding and minimising interfacial impedances are necessary to enable solid-state Li-ion batteries for EV applications. This is far more important than optimising the bulk Li ion conductivity in the solid-state electrolytes. Chemical, electrochemical, and mechanical stability of the interfaces is absolutely essential to minimise interfacial impedances and for obtaining practical power densities.[52] Therefore, development of new approaches and manufacturing processes to form intimate and low-impedance contact between solid electrolytes and active electrode materials, which remains (electro)chemically and mechanically stable throughout the lifetime of a ASSB cell are of crucial importance.

Full battery cell design and manufacturing

ASSB LiM cells require a new cell design and processing methodology to achieve low interfacial resistance and optimal electrochemical performance.[52] This optimisation of key cell design parameters for solid-state technology is still at an early research stage.[53] Until recently most of the reported R&D was focused on materials development and deeper understanding of materials properties and their interaction (e.g. at interfaces). The next step would be to test materials, cell components and associated manufacturing approaches in a full cell configuration.[17] Harmonised protocols for testing of cell performance, durability and safety are needed to enable technology benchmarking and inter-laboratory comparisons.

Depending on the choice of materials and design approaches for electrodes with stable, low-impedance interfaces, cell manufacturing techniques for ASSB LiM may be very different from the currently exploited concepts for Li-ion batteries with liquid electrolytes. Challenges such as damage-free handling of electrode and separator layers (especially with adhesive materials such as metallic lithium), methods for cathode composite manufacturing, cell manufacturing approaches (e.g. consecutive components deposition versus manufacturing of the individual cell components followed by their stacking and cell assembly steps), tab welding (especially when bonded to raw thin LiM foil), cell packaging and the application of variable or fixed pressure during cell operation will need to be addressed.

Recycling of ASSB LiM will also need to be addressed to ensure these batteries are sustainable. Since many of the ASSB LiM concepts plan to utilise conventional cathodes currently used in contemporary Li-ion batteries, a challenge would be to handle and recycle lithium metal anodes and solid-state electrolytes in a safe and economically-viable way.

2.2 Lithium-Sulfur Batteries

Lithium-Sulfur (Li-S) batteries are considered one of the so-called post lithium-ion battery technologies and have attracted great attention in the battery community in the past decade. This is reflected by the exponential growth in scientific publications in recent years. Before 2010 only several tens of publications could be found on the topic, after 2010 they are counted by the thousands.

The main characteristics of Li-S batteries are that the anode is made of lithium metal and the cathode contains sulfur as main constituent (typically in a mixed form with a carbon material).

How they work

Their working principle, although complex and somehow still under debate, can be summarised as follows. During the battery discharge step, the most stable form of sulfur (S_8) from the cathode is reduced and produces multiple polysulfide species (Li_2S_x), which are highly soluble in the electrolyte. Li^+ ions moving to the cathode (due to the oxidation of the Li metal in the anode) react with these polysulfides and form the reduced species: Li_2S (or Li_2S_2) which precipitates onto the surface of the carbon material.[54]

$$16\ Li + S_8 \leftrightarrow 8Li_2S \qquad \text{(Eq. 1)}$$

Upon charging, the species created do not fully convert back to S_8 but they form high-order polysulfides highly soluble in the electrolyte, which tend to shuttle through the separator to the anode where they get reduced (and precipitate) into low-order species (Li_2S/Li_2S_2), therefore some of the active sulphur is lost with each cycle, also the oxidation potential of elemental sulfur is not obtained on charging and therefore the full capacity of the cell cannot be achieved.

Advantages

It is generally highlighted that one of the main advantages of Li-S batteries is their low cost (<<1€/kg), attributed to the price of sulfur and world wide availability particularly when comparing to other cathode materials. Regarding electrochemical performance, Li-S batteries have a high gravimetric capacity (theoretical capacity of the sulfur cathode is 1,675 mAh/g, due to the 16 electron reduction for each S_8 molecule). It has been presented that a 25–33% of the theoretical values could be achieved in reality.[55] Also, Li-S batteries have a high gravimetric energy density (with future expectations reaching as high as 500 Wh/kg; theoretically 2,500 Wh/kg), and a low operating voltage.[56]

Current state of the art is able to easily reach 300-400 Wh/kg comparing to 100-250 Wh/kg typically delivered by Li-ion cells.

As lithium is used both as anode and current collector the use of cupper foils and necessary coating techniques of traditional batteries is avoided.

Also Li-S batteries can be considered less toxic than traditional lithium-ion batteries offering a smaller environmental footprint as do not use heavy metals such as cobalt and are free of critical raw materials.

Regarding shelf discharge, Li-S batteries can be stored during long periods of time with negligible degradation, even when stored at 0% State of Charge (SOC), which results very beneficial from a safety perspective.

Challenges and difficulties

Li-S batteries are not yet commercialised as there are still big gaps in research and development to be addressed by academic researchers before advancing to industrial scale production. Some limitations of Li-S batteries which are preventing their mass commercialisation are summarised below.

From the point of view of manufacturing, it is clear that handling metallic lithium poses great concerns. Manufacturing Li-S batteries requires some processing steps to be carried out in a dry room, where the moisture content should remain very low (e.g. < 100ppm).

Sulfur as cathode material is non-electrically conductive, so it requires significant amounts of additives (typically carbon materials) up to 20-30wt.%, which reduces the amount of active material in the electrode.

Since both S and Li_2S have poor electronic - and ionic – conductivity, polysulfides although considered indispensable, have associated unavoidable drawbacks due to their high solubility in the electrolyte: 1) creation of voids in the cathode, 2) increased viscosity of the electrolyte leading to a reduced conductivity, 3) precipitation of insoluble and insulating low order Li_2S_x (x=between 0-2) due to the polysulfides' shuttle effect back and forth to the anode, 4) decrease in anode surface. This is reflected in loss of active material and battery capacity fade, self-discharge, poor cycle life, low specific capacity, and low efficiency.

An additional challenge of Li-S batteries relates to the electrolyte itself. This, which can be solid or liquid, needs to fulfil the following requirements in order to have a well-performing battery cell: high polysulfide solubility, low viscosity, and, most importantly, ability to hinder the polysulfide shuttle effect.[56] This unwanted process represents one of the major challenges facing the commercialisation of Li-S cells. $LiNO_3$-free electrolytes have proven to be the solution towards decreased polysulfide solubility and therefore improved cyclability.[57]

Li-S electrode cells expand significantly (approximately by 80% upon reduction to Li_2S according to references[58,59]). The mechanical damage associated favours fast degradation.

Another challenge that needs mentioning is the intrinsic problematic of the anode which is also analogous to all solid state batteries; Lithium metal anode tends to react with, and deplete, the electrolyte forming a thick and unstable SEI layer that pulverises upon cycling, generating active sites for dendrites nucleation which can lead to internal short circuits. When polysulfides precipitate in the anode the phenomena is aggravated. The properties of the SEI layer are critical to the anode performance.

Regarding their electrochemical performance, Li-S batteries offer a limited cyclability and low volumetric density (Wh/L). Prolonged cycling can be achieved by having excess electrolyte, but this translates to extra weight (e.g. up to 40 - 50% of weight in an optimised Li-S cell belongs to the electrolyte).

Li-S batteries have been traditionally associated to reduced safety (due to the use of metallic lithium and dendrite formation). However, this is overcome by the use of smart electrode passivation layers and electrolytes having high flash points, which eliminate the risk of thermal runaway.

Finally, at the end of their working live, the heavily cycled lithium metal anodes are rather reactive, not to forget that the organic solvent is highly flammable. This makes the perfect mixture that facilitates fire when spent Li-S batteries are either opened and disposed of or recycled in the presence of air. Although the recycling of Li-S is not urgent at present, as this technology is not commercialised, recycling of the lithium source from spent Li-S batteries seems paramount if Li-S is to be commercialised in higher volumes.[60]

Applications

As high gravimetric energy density systems their field of application is potentially broad. However, one must distinguish between current and potential future applications. Currently their field of application is rather limited as they can compete with difficulty with other well-performing systems, such as Li-ion batteries. Therefore, applications where high cycle life and high power are mandatory are out of reach for current Li-S batteries. However, Li-S batteries have low density which has advantages for submarine and aeronautical applications. Is here were we can report the use of Li-S in high altitude long endurance unmanned aerial vehicles (HALE UAVs),[61-63] where they are powered by solar panels during the day and slowly discharged overnight.

Future applications depend very much on whether Li-S batteries can keep up to the expectations, but it is rather clear in any case that their spread in the market will be limited in a first wave to single cell /few cells applications.

Regarding the automotive market, Li-S batteries have the potential to power electric buses and trucks (not so much passenger vehicles) as they are generally in operation during the day and slowly charging overnight and high power is not expected.

High cost applications could include electric aircrafts and space applications (e.g. satellites, next-generation launchers) where powerful loads are required, with high safety requirements at lower mass.

Comparison with existing Li-ion technologies

Li-S batteries have potentially higher gravimetric energy density in comparison with existing Li-ion batteries (in the range from 2-3 times higher). Applications where weight is a critical parameter can benefit from this aspect. However, existing products are far from achieving the theoretical energy density values (around 2,500 Wh/kg). On the other hand, the power capabilities of Li-ion batteries are better and cycling of Li-S batteries rarely goes beyond 1C-rate.

As mentioned previously Li-S batteries can be stored in a fully discharged state, whereas Li-ion batteries need to be stored at an intermediate level (e.g. 40%) to avoid irreversible capacity loss.[55]

Li-S cells tend to have a density of around 1 gcm^{-3}, much lower than Li-ion cells.[55] Therefore, Li-S cells are lighter than Li-ion batteries for the same volume.

As sulfur is electrically insulating it requires a significantly larger amount of conductive carbon additive compared to Li-ion batteries (30-40 wt.% compared to 2-4 wt.%[55]).

However, the main difference is their functioning mechanism. Whereas in Li-ion batteries there is a shuttling effect of Li^+ between electrodes, Li-S follows a rather complex mechanism. One consequence is the poor cycleability of Li-S batteries (in the range of only a few hundred cycles) compared to Li-ion batteries which can reach thousands of cycles.

The possible <u>strategies to solve the issues</u> associated to Li-S batteries are summarised below[56]:

Modifications of the electrolyte

Electrolytes are the central problem of Li-S batteries. As conventional electrolytes cannot be used, as they are unable to fulfil the requirements for Li-S batteries, multiple alternatives have been explored to limit polysulfide dissolution and migration: liquid electrolytes, ionic liquids, gel-polymers, solid-state electrolytes and hybrid solutions. The concept of hybrid electrolyte was created.[64] This is a dual-phase non-aqueous electrolyte. Two types of electrolyte are used and separated by a protective lithium super ionic conductor glass film that is permeable to Li ions while impermeable to polysulfide anions.

An excellent review of electrolytes for Li-S batteries can be found in reference.[65]

A plausible solution to the challenge is to opt for solid state electrolytes or quasi-solid electrolytes.[66] Finding the right balance of conductivity and mechanical strength is paramount.

The additives used in Li-S's electrolytes are only a few (in numbers), but greatly needed. The most prominent example is $LiNO_3$, used to stabilise the Li-metal surface in 1,3-dioxolane (DIOX) containing electrolytes.

Modification in the cathode

2.1) with carbon materials

The use of carbon to modify the cathode is one of the strategies most generally explored.[67-69] This strategy can improve the conductivity of the electrode, capacity of the material and the long-term cycleability.

These types of carbon materials have been presented in the literature: graphene/graphene oxide, carbon nanotubes, carbon nano fibres and mesoporous or microporous carbons and combinations of those (e.g. graphene/mesoporous carbon, graphene/carbon nanotubes).

Among all carbon coating materials, graphene (or graphene oxides) show the best performance in terms of discharge capacity and overall cell performance, due to their high electrical conductivity and their ability to confine polysulfides dissolution. Also it maintains the cathode integrity. Some mesoporous materials also render promising results.

Based on the deep analysis carried out in references 56 and 69 it can be concluded that the best performing material consisted of a Li_2S – carbon nanocomposite with a discharge capacity of 1,300 mAh/g at 0.2 C after 200 cycles.[70]

2.2) with electrocatalysts

The idea of this concept is to convert the generated polysulfides into other materials that do not impair the performance of the battery by using noble metals (platinum as the most promising one) and earth abundant electrocatalysts – transition metals (nickel). As demonstrated in the literature, this strategy can be easily scalable (probably not at a negligible cost).

Modifications in the separator

In this strategy a functional coating and/or an interlayer separator is used to confine the generated polysulfides. For example, polyolefin separators coated with Nafion-thin films, or ceramic coatings for effective separation of anode and cathode.[71]

Modifications in the lithium metallic anode

The strategy consists of the passivation and protection of the metallic lithium anode material which allows the diffusion of lithium ions. This passivation layer must be: thin, insoluble in the electrolyte, inert to the polysulfides, and highly conductive. Both *in situ* passivation and *ex situ* are possible.

4.1) in Situ passivation

The most chemical additives found in the literature are: lithium nitrate, lithium fluoride, and ammonium salts and phosphorus pentasulfides;[72-74] they can generate a sacrificial layer that passivates the anode and suppresses the formation of dendrites

4.2) ex Situ passivation

Another reliable strategy is the passivation of the metallic lithium with a coating. Examples of this are; Al_2O_3, carbon, polymers, etc.

4.3.) replacement of lithium metal

Alternatives to lithium metal anode can be: Na, Mg, Ca, Al, etc. These alternative battery cell materials have an improved safety. Other alternatives include graphite, silicon-based anodes, etc., but these reduce even more the already low cell potential.

Modifications in the current collector

Lithiophilic surface treatments enables melting deposition of lithium onto the current collector foil.

Overall, fundamental scientific understanding is lacking and therefore significant effort is still needed in the area of materials development.

Technology readiness level (TRL)

The technology readiness level of Li-S batteries goes hand in hand with the availability of a suitable battery management system (BMS) and this is still in the learning curve. A prototype Li-S battery pack including 16 cells connected in series developed by OXIS Energy[75] can be found with promising results, aiming at extending current TRL 2 to TRL 4 in the next coming years.

2.3 Sodium-ion Batteries

Na-ion batteries – the working principle of sodium-ion batteries is analogous to that of Li-ion, with a difference that the charge transfer relies on sodium ions (Na^+) instead of lithium ions (Li^+) and electrode RedOx reactions involve Na instead of Li. The cell design of Na-ion batteries is also similar to that of Li-ion – in short, the cell is composed of a cathode containing a sodium compound and an anode able to accept the sodium atom. Both electrodes are deposited on metallic current collectors, immersed in a liquid electrolyte allowing for mobility of ions between electrodes, and separated by electrically non-conductive, porous (to allow ions mobility) layer preventing internal short-circuit.

While charging, Na^+ ions are removed from the cathode material, transported to the anode and deposited into the anode active material; during discharge (work part of the cycle) the reactions spontaneously occur in opposite direction.

The early development of the sodium-ion chemistry took place in parallel with the development of lithium-ion batteries in the 1970s and early 1980s. At a later stage, its development was superseded by "loosing competition" against the higher energy density lithium-ion chemistry in 1990s and 2000s. Recently increase of the research interest in sodium-ion batteries has been observed due to availability and price issues of Li-ion basic raw materials, related to the fast increase of demand from mobility, mobile electronics and stationary applications confronted with limited availability of the supply side.[76,77]

Anode: Despite many chemical similarities of Li^+ and Na^+ ions, the latter one has a larger ion radius, causing that graphite, the dominant active anode material in Li-ion batteries cannot be used in Na-ion chemistry due to a very low Na^+ ion storage capacity. Instead, a disordered, amorphous carbon material, so called “hard carbon” is the current Na-ion anode of choice. Its capability to store Na^+ ions was discovered by Stevens and Dahn in 2000, and was measured at 300 mAh/g.[78] This material exhibits also a good cycling stability and is providing with a sloping potential profile above 0.15 V vs. Na/Na^+ reference electrode, accounting for approximately half of the capacity, and a potential plateau below 0.15 V vs. Na/Na^+. Such characteristic is similar to that observed for lithium storage in graphite in case of Li-ion batteries. The first Na-ion cell with hard carbon anode was demonstrated in 2003 and showed a 3.7 V average voltage during discharge.[79] There are several companies offering hard carbon commercially for Na-ion battery applications.

Possible alternatives to hard carbon, the current Na-ion cell anode of choice were investigated. In 2014 it was reported that graphite could store sodium through solvent co-intercalation in ether-based electrolytes.[80] Capacities of ~100 mAh/g were observed together with working potentials of 0 - 1.2 V vs. Na/Na^+. Some sodium titanate phases like $Na_2Ti_3O_7$[81-83] or $NaTiO_2$[84] exhibit capacities of 90 - 180 mAh/g at working potentials <1.0 V vs. Na/Na^+ and cycling stability of few hundred cycles. Anode materials storing sodium via an alloy reaction mechanism and/or conversion reaction mechanism have been also reported,[76] however, they suffer from severe stress-strain during work cycles, especially in large-format cells, leading to fast cell degradation.

Cathode: Significant progress has been recently achieved in developing cathodes for high energy density Na-ion cells. Similar to Li-ion, Na-ion cathodes also store sodium via intercalation reaction. Those based on sodium transition metal oxides were studied most, due to their high working potentials and high capacities. Targeting cost reductions, one stream of research has been oriented on eliminating costly and scarce elements like Co, Cr, Ni and V from the oxides. A P2 $Na_{2/3}Fe_{1/2}Mn_{1/2}O_2$ oxide composed of earth-abundant elements was demonstrated in 2012 to reversibly store 190 mAh/g at average discharge voltage of 2.75 V vs. Na/Na^+ employing Fe^{3+}/Fe^{4+} redox couple – reaching energy density parity to commercial Li-ion cathodes such as $LiFePO_4$ or $LiMn_2O_4$.[85] However, sodium deficiency of P2 oxides meant lower energy density in practical use. This issue was overpassed, and in 2015 a mixed P3/P2/O3-type $Na_{0.76}Mn_{0.5}Ni_{0.3}Fe_{0.1}Mg_{0.1}O_2$ was demonstrated to deliver 140 mAh/g at average discharge voltage of 3.2 V vs. Na/Na^+.[86] Faradion has patented the highest energy density ever, oxide-based cathode material for Na-ion applications.[87] The O3-type $NaNi_{1/4}Na_{1/6}Mn_{2/12}Ti_{4/12}Sn_{1/12}O_2$ oxide can store 160 mAh/g at average voltage of 3.22 V vs. Na/Na^+. Another series of doped Ni-based oxides of stoichiometry $Na_aNi_{(1-x-y-z)}Mn_xMg_yTi_zO_2$ was reported to be capable to deliver 157 mAh/g in a Na-ion “full cell” with hard carbon anode at average discharge cell voltage of 3.2 V and utilising the Ni^{2+}/Ni^{4+} redox couple.[88] Such performance at cell level is comparable to current commercial Li-ion cells. Recently, it was reported that partial substitution of Mn by Ti atoms in P2-$Na_{0.66}Li_{0.22}Mn_{0.78}O_2$ that is leading to P2-type $Na_{0.66}Li_{0.22}Ti_{0.15}Mn_{0.63}O_2$ compound significantly reduces O_2 evolution reaction leading to better cycling stability.[89] Moreover, it exhibits superior stability in ambient air atmosphere, or even against water treatment, presenting a potential for practical industrial application. Another approach was recently presented by Shenzhen Institute of Advanced Technology (SIAT) of the Chinese Academy of Sciences, in collaboration with the National Institute of Synchrotron Radiation Sources of Thailand.[90] This group has developed a new, mixed polyanionic compound $Na_2Fe(C_2O_4)SO_4{\cdot}H_2O$ as a cathode active material. This compound is characterised by high electrochemical stability and reversibility, due to the large size of Na^+ migration channels and rigid three-dimensional framework. Its electrochemical activity originates from Fe^{2+}/Fe^{3+} RedOx reaction. It is capable of 300 cycles at 1.7-4.2 V window (vs. Na/Na^+) with limited degradation.

Today Na-ion cathode of choice is P2 or O3 type oxide, developed by Faradion. Other R&D efforts were focused on developing cathodes based on polyanions. They are characterised by lower density than oxide-based cathodes and usually the strong, covalent bonds making them durable with positive impact on cathode cycle life and safety. Sodium vanadium phosphate and fluorophosphate have demonstrated excellent cycling stability, the last one also a significant capacity of 120 mAh/g at average discharge voltage of 3.6 V vs. Na/Na^+.[91-93] There was also reported use of some Prussian blue analogues (PBAs) as Na-ion cathodes e.g. the rhombohedral $Na_2Mn[Fe(CN)_6]$ exhibiting capacity of 150-160 mAh/g and a 3.4 V average discharge voltage.[94-96] This chemistry was developed by Novasis Energies Inc. and together with hard carbon anode is a basis for their commercial Na-ion solution. This chemistry formulation should however be carefully evaluated for its toxicity related issues, as it contains cyanide compounds, relative to Prussian blue which itself is not classified as imposing a toxicological risk[97] for its stability, but which can generate toxic[98] hydrogen cyanide (e.g. following a path leading to the discovery of hydrogen cyanide[99]).

Electrolyte: Na-ion cells can use both aqueous and non-aqueous electrolytes. The first ones, due to the electrochemical stability window of water, are characterised by lower voltages and thus also energy densities. To better utilise the voltage range of active materials, the same carbonate ester polar aprotic solvents used in Li-ion electrolytes - such as ethylene carbonate, dimethyl carbonate, diethyl carbonate, propylene carbonate etc. - can be used. The most widely used salt additive to non-aqueous electrolytes formulation is sodium hexafluorophosphate. A comprehensive study reporting on the optimisation of Na-ion electrolyte formulation and compatibility with positive and negative electrode materials was published.[100] Mixtures of ethylene carbonate, propylene carbonate and dimethyl carbonate (EC:PC:DMC) and alternative one, ethylene carbonate, propylene carbonate and dimethoxyethane (EC:PC:DME) were found to exhibit optimum ionic conductivities and low viscosities, resulting in good C-rate capability and high capacity upon sustained cycling for hard carbon electrodes. An overview of research efforts aiming at development of electrolyte formulation for Na-ion cells has been published in 2015.[101] Another approach in development of Na-ion electrolytes is utilising gel-polymer electrolyte, less prone to leakage issues.[102] A new concept, called water-in-salt (WiS) electrolyte has recently been reported.[103] It is based on a super-high concentrated salt containing Na^+ (or other ion, like Li^+, K^+, Mg^{2+}, Zn^{2+}) in aqueous solution. For example a new class of the inert-cation-assisted WiS (IC-WiS) electrolytes containing the Na^+ ion and tetraethylammonium (TEA^+) inert cation in super-high concentrations of 31 mol/kg exhibits a wide electrochemical window of 3.3 V, prohibits dissolution of transition metal from the cathode, and provides single step intercalation process of sodium into both cathode and anode electrodes during cycling.

Current collectors: in contrast to Li-ion batteries, where for the negative electrode (anode) current collector in form of copper foil is used, Na-ion cells may employ aluminium as current collector at both electrodes. This is due to the different voltage window characterising both chemistries. Because of this feature Na-ion cells may profit from cheaper material usage and increased cell energy density.

Technology readiness level (TRL)

The technology readiness level of Na-ion batteries depends on the development of active materials, cell designs and validation of manufacturing processes. It is still in the learning phase. A demonstration Na-ion based energy storage systems (ESS) of hundreds of kW are already in realisation phase, multiple prototypes of smaller batteries are developed, delivering promising results. The spin-off companies are already looking at commercialisation. The TRL can be defined at 6-8 depending on exact chemistry and design.

Recycling of Na-ion batteries

The current batteries recycling processes do not include a step of identifying Na-ion cells for separate recycling due to marginal share of this chemistry in EOL battery streams. Na-ion batteries is a new technology with few chemistries involved in active materials. Due to structural, and partly chemical similarities to currently dominating Li-ion chemistry one may expect some similarities in the recycling processes, leading to synergy effects, economic benefits and increased speed adoption of the recycling processes for Na-ion batteries, however until now those processes were not established for Na-ion batteries. Also in recycling of Li-ion batteries a number of materials is usually not recovered due to limited economic viability of the processes, even if technically possible.

In general the Na-ion batteries are assumed to be “environmentally friendly” meaning they are much less toxic if deposited to the environment, as do not contain elements like Co, Ni, Mn, Cu, Li. The same however means that there will be much less economical driving force to recycle those batteries, as the income from the secondary raw materials possible to recover will be limited. The separate issue that should be carefully analysed would be eventual release of the PBA compounds (containing cyanide ions in the structure) to the environment.

Recycling of sodium salt technically would be easy for its high solubility in water, however due to low price of the sodium salts the economy of the process needs to be looked up.

Recycling of metallic sodium should not be problematic; due to its reactivity with water, it could easily be converted into soluble alkali and easily leached out. However further conversion back into metallic sodium is an energy intensive process, requiring electrolysis of molten salt or hydroxide. Direct recycling of metallic sodium (in a process analogue to electrochemical copper refining) should also be possible, but it would require non-aqueous solvent similar to battery electrolyte for the process. Handling of metallic sodium needs to be done in inert atmosphere, without moisture and oxygen due to high reactivity of the metal. Thus, the economy of the process would need to be looked up.

Recycling other anode materials, like hard carbon is still requiring development, similarly like in the Li-ion batteries recycling, where direct recovery of graphite materials is still at the initial stage of development. The economy of this process would need to be looked up.

Recycling of cathode materials would be strongly depending on chemical formulation, there are known designs where sodium vanadium phosphate (NVP, $Na_3V_2(PO_4)_3$) can be directly reused in the regenerative process.[104] Recycling of vanadium, due to its price would be a driver of Na-ion batteries based on this chemistry. For other chemistries, based on iron the economy of the process would need to be looked up.

Recycling of the electrolyte would be the same as for Li-ion batteries as the same electrolytes are used. However, for the moment the process is not yet developed to the commercial level.

Recycling of current collectors – as aluminium is used for both current collectors, the recycling would be simpler than in case of Li-ion batteries (no copper used). However, if the pyrometallurgical process is used as initial step in Li-ion batteries recycling, the aluminium is not recovered.

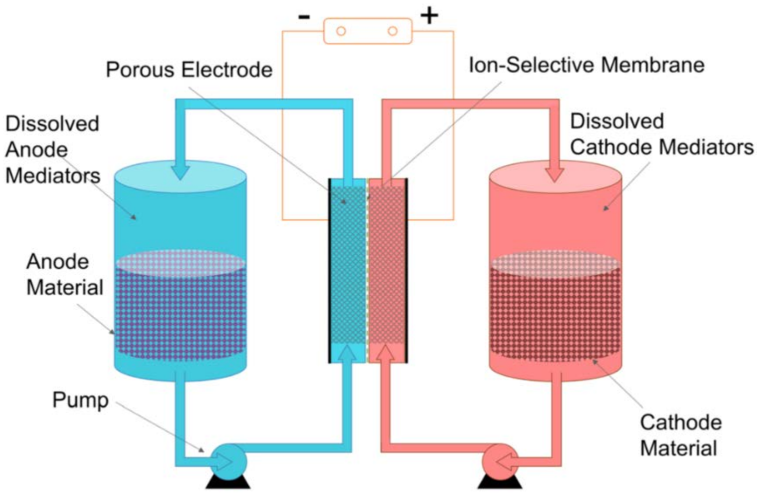
Plastic or iron casing – those materials might be separated via physical methods and separately recycled, they are identical like in case of Li-ion components. However, if the pyrometallurgical process is used as initial step in Li-ion batteries recycling, the casing materials (both, plastics and iron) are not recovered.

2.4 RedOx-Flow Batteries

RedOx flow batteries (RFB) is a type of electrochemical cell where chemical energy is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane. On charging, the electrical energy supplied causes a chemical reduction reaction in one electrolyte and an oxidation reaction in the other. The thin ion exchange membrane between the half-cells prevents the electrolytes from mixing but allows selected ions to pass through to complete the redox reaction. On discharge, the chemical energy contained in the electrolyte is released in the reverse reaction and electrical energy can be drawn from the electrodes. When in use, each of the electrolytes is continuously pumped in a circuit between the electrochemical cell and its storage tank.

Flow batteries allow thus storage of the active materials external to the battery with reactants circulated through the cell stack as required. The energy-bearing redox-active materials being the key component for RFBs are dissolved in liquid electrolytes stored in external reservoirs (Figure 5).

Figure 5. Schematic view of a RFB system. [Reproduced from an open source Ref. 105].



Flow batteries offer a variety of benefits. RFBs have emerged as prime candidates for energy storage on the medium and large scales, particularly at the grid scale and independent energy and power capacity. RFBs are promising stationary energy storage technologies with exceptional scalability and flexibility to improve the stability, efficiency, and sustainability of the power grid. The power and energy capacity of the system can be scaled independently from each other by separate sizing of the tank volume and the cell stacks (reaction cells). This allows an exact adaption to the associated generator unit. Flow batteries can switch between charging and discharging within a fraction of a second, but are actually designed for storing electricity for several hours.[106] In addition, modularised flow batteries, in the form of shipping containers, can be moved and set up as 'mobile' energy storage devices.[107]

RFBs show also great potential to overcome drawbacks inherent to Li-ion batteries, which dominate the global electrochemical storage market, namely irreversible aging due to phase transformations (even when not in use) and fire hazards due to the use of flammable organic electrolytes. Common flow batteries rely on aqueous electrolytes that are not flammable, and therefore a safe battery operation is guaranteed. The lifetime exceeds that of lead acid and lithium-ion/polymer batteries significantly. These advantages can be utilised for application possibilities, such as, peak shaving, as well as load and frequency balancing.[108]

Besides stationary energy storage, automotive applications are believed to be also potential application area for RFBs. Cost, safety, as well as the slow recharging of existing devices are considered to be the major hurdles for the widespread adoption of electrochemical energy storage as the main power source (such as lithium-ion batteries) in electric vehicles. Considering that the architecture of a RFB enables the charge to be stored within the electrolytes, ultra-fast recharging could be possible by simply 'refuelling' with charged electrolytes in the reservoirs. Several OEMs, such as Volkswagen, Toyota and Fiat have been experimenting with use of flow batteries.[109] Automobile applications open up an important new research direction for RFBs (including organic systems) and require further developments in performance (energy/power density), system architectures and durability, alongside overall cost per kWh.

The most promising and commercially available system so far is the Vanadium RedOx Battery (VRB) with TRL level around 9.[110] VRBs possess energy density of 25 Wh/L.[111] Conventional storage technologies such as lead-acid and lithium-ion/polymer easily outperform this value.[112] Hence, the space requirement of flow batteries is rather large to be competitive in the field of overall energy capacity. VRB uses four different oxidation states of the same element leading to minimal electrolyte cross-contamination and great long-term cyclability (>1,000 stable cycles). The system costs is relatively high with redox-active material comprising a major portion of the cost.

The key technical barrier therefore that still limits the widespread market penetration of RFB technologies is the generally lower energy densities (<50 Wh/l) for most RFB systems compared to their Li-ion battery competitors (>200 Wh/l). Only a few RFB chemistries such as zinc-based systems have energy densities of >50 Wh/l, but other concurrent drawbacks limit their practical applications, including dendrite growth on metal anodes, irreversible materials crossover, gas evolutions, and/or slow electrochemical kinetics. To overcome these limitations, strategies for improving the energy density of RFBs capitalise on developing new RFB designs and electrolytes to increase the cell voltage and effective concentration* of redox-active materials.

Indeed recent research and development in the redox flow battery community has focused on the identification, synthesis and modification of novel redox active molecules.[113-118] The redox-active materials are critically important for RFB systems because their properties determine the cycling performance. For example, the solubility, redox potential, chemical stability, and cost of redox-active materials directly impact the energy density, cell voltage, cycle life, and cost intensity of a RFB system, respectively. Corrosion processes due to the use of corrosive electrolytes is another issue encountered in metal-based RFBs.

The majority of studies have utilised metallic species in aqueous or non-aqueous systems. In non-aqueous electrolytes, active molecules mainly take the form of ligand modified inorganic species or metal coordination complexes in anion-exchange systems.[119-124] Although they can achieve relatively high overall cell voltages (>2.0 V), these systems are still based on expensive metals (e.g. nickel, ruthenium and cobalt) and are restricted by the limited solubility of their complexes.

Recent investigations have highlighted the use of organic† active materials in solid-state organic batteries.[125-129] In general, the advantages of using organic molecules are their abundance and the possibility of their extraction from diverse sources. One of the major challenges however is the search for promising redox organic materials with favoured combination of properties such as redox potential, solubility, and stability. Recent research efforts have been broadened to include tailored organic molecules that possess higher solubilities in non-aqueous electrolytes. Another important advantage of RFBs that utilise organic charge-storage materials is a possible cost benefit over metal-based RFBs.[118,124,130] As a consequence, the production costs for the organic active material have to be as low as possible. This requires low-cost starting materials, simple chemical reactions with full conversion, and no necessary purification steps. Flow batteries using electrolytes based on organic solvents are far from being cost competitive. Hence, water in combination with sodium chloride is the recommended electrolyte, both from a cost and also a safety point of view.

As already mentioned, conventional metal-based flow batteries have several drawbacks, which limit their commercial success. However, the development of RFBs based on inexpensive and sustainable redox-active organic materials can overcome these drawbacks. Therefore, new organic redox-active charge storage materials have to be discovered and investigated for application in RFBs. These materials can be low-molar-mass compounds or redox-active polymers, both with well-defined electrochemical properties.

* Active material per liter of total electrolyte volume.

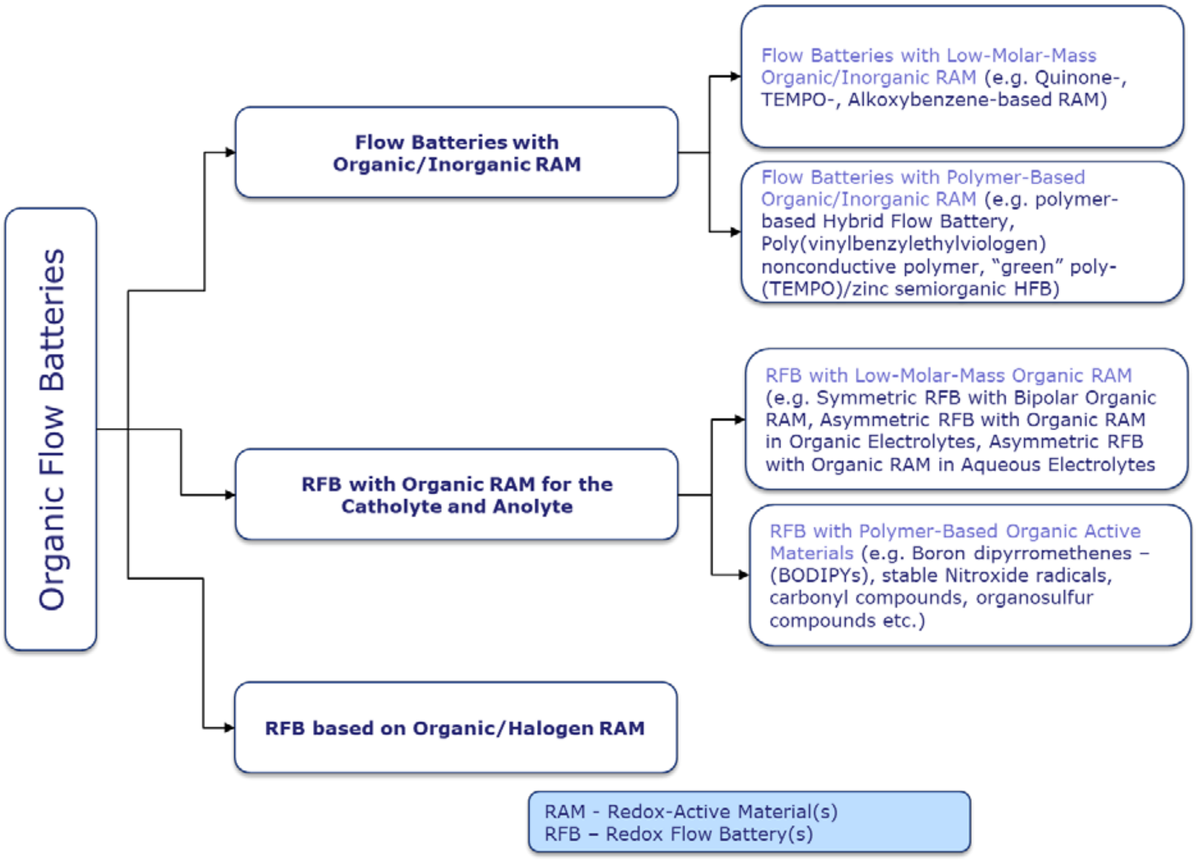
† When the terms "organic" or "all-organic" are used in association with flow batteries, it is referred only to the redox-active materials utilized and not to the solvent or the supporting electrolyte, which can be water or any organic solvent capable of dissolving the organic redox-active material.

Organic flow batteries types

There is no a strict classification of organic flow batteries. Some researchers are dividing them into three main categories, depending on the active material used: all-organic, organic-inorganic and organic-inorganic hybrid flow batteries.

Others are making more detailed sub-division of flow batteries (Figure 6).

Figure 6. Detailed classification of organic-based electrochemical power sources. JRC compilation.



The TRL level of metal-based RFB, such as Vanadium RedOx battery, Polysulphide–Bromide flow battery and Zinc–Bromine flow battery varies between 5 for Polysulphide–Bromide and 9 for Vanadium Flow Battery. Organic-based flow batteries are still under research and therefore have still low TRL level.

Recycling of flow batteries

Flow Batteries is a new technology with a variety of chemistries emerging. For zinc bromine batteries recycling is not currently available but should be relatively simple. Zinc bromine, plastics & acid could be recyclable. Zinc iron redox flow are potentially recyclable. From vanadium flow batteries vanadium, acid and plastics could be recovered.[131]

Vanadium RedOx battery is not as widely used as lithium-ion and lead-acid batteries, therefore the recycling process is not yet well-developed. Due to the high amount of plastic, reusable materials have a share of only around 18 % of the VRF battery. It has been shown that reduction or substitution of polytetrafluoroethylene in VRF should be in the focus of further research in order to continue decreasing the ecological impact of these batteries.[132]

Vanadium is uniquely useful as an electrolyte for flow batteries, providing some significant power and energy benefits over more common metal combinations (zinc bromine, iron chromium) used by competitors. But it is also far more expensive, with global market prices set by whatever steel industry customers are willing to bear. Vanadium can also be recycled from mining slag, oil field sludge, fly ash and other waste products, which is another area of research. The problem is to get recycled vanadium with high purity standard of 99.5 % required for most vanadium flow battery electrolyte formulations. Among others, companies such as Imergy Power Systems (USA), Fremont (USA), Gildemeister/DMG Mori Seiki (German-Japanese) are looking into innovative ways to use lower-grade recycled vanadium (98.5% instead of 99.5% purity) for battery production.[133]

Organic redox flow battery is in its infancy, therefore no recycling processes have been developed so far.

3 R&D Overview

3.1 Horizon 2020 projects

The analysis considers projects co-funded through EU's Horizon 2020 framework program and gives an overview of both the number of projects supported on a given battery technology and the corresponding EU public funding received by these projects. Additionally, national and regional programmes are also considered in this section.

Horizon 2020 has supported in total 34 projects on the four battery technologies discussed in this report with a total of ca. €118 million, roughly corresponding to 1/3 of the total funding (nearly €350 million) made available for battery-related research. The distribution by technology is as follows:

All Solid State Batteries with Li-metal anodes: 8 projects (total ca. €31 million)

Lithium-Sulfur Batteries: 5 projects (total ca. €32 million)

Sodium-ion Batteries: 5 projects (total ca. €15 million)

Redox-Flow Batteries: 9 projects (total ca. €25 million)

Cross-cutting projects relevant to several of the above-mentioned battery technologies: 7 projects (total ca. €15 million)

3.1.1 All Solid State Batteries with Li-metal anodes

In Horizon 2020 in total 8 projects addressing ASSB LiM have been funded through various programme parts (see Table 2). Only 2 projects, MONBASA and BATMAN, have come to a completion at the time of writing and the rest are ongoing.

The EC funding to R&D on ASSB LiM amounted to less than €31 million[‡], which represents roughly a 5.2% of total funds allocated to the topics mentioned in Table 2.

Table 2. Breakdown of Horizon 2020 supported ASSB LiM projects by funding call and topic.

Call **Topic**	**Title of the call** **(budget)**	**Topic** **(budget)**	**Number of projects (project name: budget)**	**Type of action**	**Project status**
H2020-COMPET-2015 COMPET-03-2015	Competitiveness of the European Space Sector: Technology and Science (€39 million)	Bottom-up space technologies at low TRL (€7 million)	1 (MONBASA: €1.26 million)	Research and Innovation action	Finished
H2020-SMEINST-1-2015 IT-1-2015-1	Horizon 2020 dedicated SME Instrument Phase 1 2015 (€26.6 million)	Small business innovation research for Transport (€26.6 million)	1 (BATMAN: €0.07 million)	SME Instrument	Finished

‡ This number indicates the total EC-contribution to the projects listed in Table 2. EC funding to ASSB LiM is difficult to calculate precisely as some of the projects address more than 1 topic/application and, as a consequence, not all of the EC contribution allocated to the project is spent on ASSB LiM research, but also on other research lines.

Call Topic	Title of the call (budget)	Topic (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-LC-BAT-2019-2020 LC-BAT-1-2019	Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries (€246 million)	Strongly improved, highly performant and safe all solid state batteries for electric vehicles (€25 million)	2 (SOLiDIFY: €7.82 million, SAFELiMOVE: €7.88 million)	Research and Innovation action	Ongoing
H2020-LC-BAT-2019-2020 LC-BAT-6-2019	Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries (€246 million)	Li-ion Cell Materials & Transport Modelling (€13 million)	1 (MODALIS[2]: €4.85 million)	Research and Innovation action	Ongoing
H2020-GV-2017 GV-13-2017	Green Vehicles 2017 (€133 million M)	Production of next generation battery cells in Europe for transport applications (<€133 million)	1 (IMAGE: €4.95 million)	Research and Innovation action	Ongoing
H2020-MSCA-ITN-2017 MSCA-ITN-ETN	Marie Skłodowska-Curie Innovative Training Networks (€430 million)	European Training Networks (€370 million)	1 (HYCOAT: €3.90 million)	Marie Skłodowska-Curie Actions	Ongoing
H2020-MSCA-ITN-2017 MSCA-ITN-EID	Marie Skłodowska-Curie Innovative Training Networks (€430 million)	European Industrial Doctorate (€28 million)	1 (POLYTE: €0.74 million)	Marie Skłodowska-Curie Actions	Ongoing

3.1.2 Lithium-Sulfur Batteries

The main R&D support instrument, Horizon 2020, has funded a total of 5 projects on Li-S batteries since 2015 via the calls listed in Table 3. All 5 projects fall under the support of RIA (Research Innovation Actions), where the EU contribution is 100% of project cost.

Projects funded via the calls H2020-NMP-GV-2014 and H2020-COMPET-2015 have come to a completion, whereas projects funded under H2020-NMBP-ST-IND-2018 are still active and have a forecasted end in the summer 2022. The EC has funded less than €32 million in total for Li-S batteries, which represents roughly a 5% of total funds forecasted in the calls/topics mentioned above.

Under the most recent call for battery funding, H2020-LC-BAT-2019, no funding has been allocated to Li-S batteries.

Table 3. Breakdown of Horizon 2020 funded Li-S battery projects by funding call and topic.

Call / topic	Title of the call (budget)	Topic (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-NMP-GV-2014 / NMP-17-2014	Nanotechnologies, Advanced Materials and Production (€482.7 million)	Post-lithium ion batteries for electric automotive application (€16 million)	2 (ALISE: €6.9 million, HELIS: €8.0 million)	Research and Innovation action	Finished
H2020-COMPET-2015 / COMPET-03-2015	Competitiveness of the European Space Sector: Technology and Science (€39 million)	Bottom-up space technologies at low TRL (€7 million)	1 (ECLIPSE: €1 million)	Research and Innovation action	Finished
H2020-NMBP-ST-IND-2018 / LC-NMBP-30-2018	Industrial sustainability (€79 million)	Materials for future highly performant electrified vehicle batteries (€25 million)	2 (LISA: €8 million, SPIDER: €8 million)	Research and Innovation action	Ongoing

3.1.3 Sodium-ion Batteries

For the Na-ion batteries technology under the Horizon 2020 activities, 5 projects have been supported (see Table 4). Out of those, 2 projects fall under the support of RIA (Research Innovation Actions), 2 projects are Maria Skłodowska-Curie individual fellowships and the last 1 is European Research Council grant (Proof of Concept Grant). In all cases the EU contribution is 100% of project cost.

Projects funded via the calls H2020-MSCA-IF-2016, H2020-ERC-PoC-2016 and H2020-LCE-2014-3 have already been concluded, whereas project funded under call H2020-LC-BAT-2019 is currently starting up (beginning 2020), and will last till 2022.

The EC has funded €15.02 million in total, which represents roughly a 2.5% of total funds forecasted in the calls/topics mentioned above.

Table 4. Breakdown of Horizon 2020 projects on Na-ion batteries by funding call and topic.

Call / topic	Title of the call (budget)	Topic (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-LCE-2014-2015 / LCE-10-2014	NA (€124.06 million)	Next generation technologies for energy storage (NA)	1 (NAIADES: €6.49 million)	Research and Innovation action	Finished

Call / topic	Title of the call (budget)	Topic (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-LC-BAT-2019-2020 / LC-BAT-2-2019	Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries (€246 million)	Strengthening EU materials technologies for non-automotive battery storage (€24 million)	1 (NAIMA: €8.00 million)	Research and Innovation action	On-going
H2020 ERC-2016-PoC / NA	European Research Council (ERC)-Proof of Concept-2016 (€20 million)	NA	1 (HiNaPc: €0.15 million)	European Research Council grant	Finished
H2020 MSCA-IF-2016 / MSCA-IF-2016-EF	Marie Skłodowska-Curie Individual Fellowships (€218.71 million)	Standard EF (€179.71 million)	2 (NExtNCNaBatt : €0.20 million NAPANODE: €0.18 million)	Marie Skłodowska-Curie Actions	Finished

3.1.4 Redox-Flow Batteries

For the Redox-Flow batteries technology under the Horizon 2020 activities, 12 projects related to non-conventional chemistries have been funded (see Table 5). Nine projects are related specifically to organic flow batteries. The information relative to the projects (e.g. deliverables, summary reports) has been gathered via Compass tool and more details can be found in sub-chapter 4.4.

Projects funded via the calls H2020-MSCA-IF-2014, H2020-FTIPilot-2015-1, H2020-LCE-01-2016-2017 and ERC-2017-PoC have come to a completion, whereas projects funded under ERC-2016-COG and H2020-MSCA-ITN-2017 are still active till 2021 and 2022, respectively. Projects funded under call H2020-LC-BAT-3-2019 and H2020-LC-BAT-4-2019 are currently starting (beginning 2020) and they will last for 3 or 4 years.

Table 5. Breakdown of Horizon 2020 projects on RedOx flow batteries by funding call and topic.

Call / topic	**Title of the call (budget)**	**Topic (budget)**	**Number of projects (project name: budget)**	**Type of action**	**Project status**
H2020-FTIPilot-2015-1	Fast Track to Innovation Pilot (€100 million)	Fast Track to Innovation Pilot (€100 million)	1 (GREENERNET: €2.0 million)	Research and Innovation action	Finished
H2020-LCE-01-2016-2017	COMPETITIVE LOW-CARBON ENERGY	Next generation innovative technologies enabling smart grids, storage and energy system integration with increasing share of renewables: distribution network (€20 million)	1 (EnergyKeeper: €4.0 million)	Research and Innovation action	Finished
H2020-LC-BAT-3-2019	Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries (€5 million)	Modelling and simulation for Redox Flow Battery development (€5 million)	2 (SONAR: €2.4 million; CompBat €1.75 million)	Research and Innovation action	Ongoing
H2020-LC-BAT-4-2019	Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries (€15 million)	Advanced Redox Flow Batteries for stationary energy storage. (€15 million)	4 (BALITH: €4.1 million; HIGREEW: €3.8 million; MELODY: €4.0 million; CUBER[1]: €4.0 million)	Research and Innovation action	Ongoing
ERC-2017-PoC	ERC-POC Proof of Concept Grant (€20 million)	Proof of Concept Grant (€20 million)	1 (ELECTRO-POM: €0.15 million)	European Research Council grant	Finished
ERC-2016-COG	ERC consolidator grant (€605 million)	Consolidator Grant (€605 million)	1 (MFreeB: €2.0 million)	European Research Council grant	Ongoing
H2020-MSCA-IF-2014	Marie Skłodowska-Curie Individual Fellowships (€240.5 million)	Individual Fellowships (€240.5 million)	1 (GLOBE: €0.2 million)	Marie Skłodowska-Curie Actions	Finished

Call / topic	Title of the call (budget)	Topic (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-MSCA-ITN-2017	Marie Skłodowska-Curie Innovative Training Networks (€430 million)	European Training Networks (€370 million)	1 (FlowCamp: €3.8 million)	Marie Skłodowska-Curie Actions	Ongoing

[1]Project related to copper-based RedOx electrolyte technology.

3.1.5 Cross-cutting projects relevant to several battery technologies considered in the present report

A number of projects addressing research questions relevant to several battery technologies considered in this report have been identified and summarised in the Table 6.

These projects aim, for example, at developing analytical methods for gaining a better understanding of electrolyte/electrode interface formation and dynamics, development of new materials that can be used both in Li-ion and Na-ion batteries and thin layer manufacturing techniques relevant for both ASSB LiM and Li-S battery chemistries.

Table 6. Breakdown of cross-cutting projects by funding call and topic.

Call / topic	Title of the call (budget)	Topic/project type (budget)	Number of projects (project name: budget)	Type of action	Project status
H2020-NMBP-TO-IND-2018-2020 DT-NMBP-08-2019	Foundations for tomorrow's industry (€433.1 million)	Real time nano-characterisation technologies (<€37.8 million)	1 (NanoBAT: €5 million)	Research and Innovation action	Ongoing
H2020 ERC-2016-ADG / NA	European Research Council (ERC) Advanced Grant 2016 (€540 million)	(ERC) Advanced Grant 2016 (€540 million)	1 (B-Phospho-Chem: €2.49 million)	European Research Council grant	Ongoing
ERC-2017-COG	European Research Council (ERC) Consolidator Grant 2017 (€575 million)	ERC Consolidator Grant 2017 (€575 million)	1 (FUN POLYSTORE: €2 million)	European Research Council grant	Ongoing
ERC-2017-ADG	European Research Council (ERC) Advanced Grant 2017 (€567 million)	(ERC) Advanced Grant 2017 (€567 million)	1 (ReSuNiCo: €2.4 million)	European Research Council grant	Ongoing
H2020 ERC-ADG-2014 / NA	European Research Council (ERC) Advanced Grant 2014 (€450 million)	(ERC) Advanced Grant 2014 (€450 million)	1 (ARPEMA: €2.25 million)	European Research Council grant	Ongoing
H2020 MSCA-IF-2014 / MSCA-IF-2014-EF	Marie Skłodowska-Curie Individual Fellowships (€240.5 million)	Standard European Fellowships (€240.5 million)	1 (ATMCinsituNMR: €0.18 million)	Marie Skłodowska-Curie Actions	Finished
H2020-MSCA-IF-2017 MSCA-IF-GF	Marie Skłodowska-Curie Individual Fellowships (€248.7 million)	Global Fellowships (€33.7 million)	1 (eJUMP: €0.25 million)	Marie Skłodowska-Curie Actions	Ongoing

3.2 International and national R&I programmes

Regions with a strong existing battery manufacturing base, such as China, Japan and South Korea, have a long-standing tradition in battery R&D across the entire value chain spanning from materials development to components and cell manufacturing and recycling.

Australia has recently joined these Asian countries as a major user of battery storage technologies in combination with renewable electricity generation and grid balancing.

Regions aiming at reinforcement of their position and establishing/expanding their domestic battery manufacturing base, such as USA and Europe, also run significant programmes on research and innovation in batteries. In Europe national programmes in Germany, France and the UK stand out for their large size and broad scope. Programmes in Finland and Sweden are worth-mentioning due to their focus on raw materials and battery recycling.

A brief overview of the battery research efforts in these regions, public, and when possible private, R&I programmes is given below.

CHINA

"**Made in China 2025**" program published by the Ministry of Industry and Information Technology (MIIT) and adopted in 2015 recognised automotive industry in China as one of the ten key national industries. A number of **technology roadmaps** including that **on traction batteries** were developed.[134] Very ambitious targets for energy density, cost and lifetime/durability of traction batteries were set based on the expectation that by 2020 an EV with a 400 km drive range would have a similar cost of ownership to that of a conventional internal combustion engine vehicle (see Table 7).[134]

Table 7. China's targets for traction batteries.[129]

Targeted characteristic	**2020**	**2025**	**2030**
Energy density at cell level, Wh/kg	350	400	500
Energy density at pack level, Wh/kg	250	280	350
Cost at pack level, USD/kWh	145	131	116
Calendar life, years	10	12	15

While the above-mentioned targets are not directly linked to any specific battery technology, it is expected that 2025 targets will be reached with advanced Li-ion batteries featuring e.g. Ni-rich NMC cathode and Si-containing anodes in combination with hybrid or solid-state electrolytes and those for 2030 will require development of all-solid state Li-ion batteries.[135]

Materials innovation is critical for the development of advanced Li-ion batteries, e.g. all solid state and Li-S, as well as for various other battery chemistries, e.g. Na-ion and RedOx flow batteries, capable of meeting requirements of a wide range of applications.[135] The **Strategic Priority Research Program of the Chinese Academy of Sciences**, launched in 2013, addresses materials research for Li-ion and Na-ion batteries, all solid-state batteries, Li-S, Li-air and Li-CO_2 chemistries. Associated targets for the development of Na-ion batteries are increase of energy density from ca. 100 Wh/kg currently to 150 Wh/kg in 2025 and up to 225 Wh/kg in 2030 for non-aqueous electrolyte batteries and from below 25 Wh/kg currently to up to 50 Wh/kg in 2025 and 75 Wh/kg in 2030 for aqueous electrolyte batteries.[135]

National Natural Science Foundation of China, National Key R&D Program of China and National Key Technologies R&D Program of China are other instruments funding research in batteries in China.[135] Many research organisations and universities, e.g. Ningbo Institute of Materials Technology & Engineering, Institute of Physics and Dalian Institute of Chemical Physics, Qingdao Industrial Energy Storage Technology Institute, Huazhong University of Science and Technology, Tsinghua University, Shanghai Institute of Ceramics and also battery cell manufacturers, e.g. CATL, BYD, Hefei Guoxuan High-Tech Power Energy, Ganfeng Lithium and Beijing WeLion New Energy Technology, work on the development of materials, electrode and cell concepts and manufacturing technology for all solid-state Li-ion batteries.[26] Institute of Physics, Institute of Process Engineering, Wuhan University and HiNa Technology Co. Ltd. are active in R&D&I and deployment of Na-ion batteries for both traction and stationary storage applications. Institute of Chemistry, Dalian Institute of Chemical Physics, Beijing Institute of Technology, Shanghai Jiao Tong University and Tsinghua University work on Li-S battery technology.[135]

SOUTH KOREA

In 2011 a **Strategy for energy storage technology development and industrialisation** has been established by the Ministry of Trade, Industry and Energy, which together with Ministry of Science and ICT, Ministry of SME' s and start-ups and others have funded the national R&D on batteries.[136,137] In the period between 2013 and 2015 in total USD 193.3 million have been invested in 619 projects focusing mainly on Li-ion batteries, but also supporting development of Na-ion, Mg-ion and RedOx flow batteries as well as supercapacitors.[137] Analysis of investments in R&D on batteries, presented in Ref. 137, showed that a significant part of the research and development work funded by the above-mentioned ministries is carried out by SME's. Another conclusion was that Korean research organisations would benefit from diversification and strengthening of their global research networks.

End of 2018 three large South Korean battery manufacturers **SK Innovation, LG Chem and Samsung SDI** announced the creation of a 100 billion won (USD 90 million) **fund** to promote R&D of battery-related materials, processes and equipment focusing on all solid-state batteries, lithium-metal batteries and lithium-sulfur batteries.[26,136]

Also researchers at the world-renowned Korea Advanced Institute of Science & Technology (KAIST) work on the development of lithium-sulfur batteries as well as on approaches to incorporate Si in Li-ion battery anodes and materials development for Na-ion batteries.[136] In 2018 Korea Electrotechnology Research Institute (KERI) announced a project for the development of the next generation lithium secondary battery, where lithium metal is used in place of graphite anode. Together with Australia's Protean Energy, the Korean Institute of Energy Technology Evaluation and Planning (KETEP) started a 4 MWh vanadium RedOx flow battery project.[136]

Since the adoption of Resource Circulation Framework Act in South Korea in 2018, much attention is being paid also to recycling of (EV) batteries.[138]

JAPAN

Japan has been at the cutting-edge of battery invention for more than a century. It currently runs a vast collaborative programme, called **Battery Research Platform** that brings together Japan's prestigious Waseda University and two of the country's flagship research institutes: the National Institute for Materials Science (NIMS) and the National Institute of Advanced Industrial Science and Technology (AIST).[139] NIMS is a facility for next-generation battery R&D covering everything from materials analysis and evaluation of battery properties to battery cell assembly.[140] In January 2020 AIST established an **International Joint Research Center for Zero-Emission Technologies**.[141] The centre conducts research for innovative environmental and energy technologies batteries and hydrogen.

In May 2018 a **Consortium for Lithium Ion Battery Technology and Evaluation Center (Libtec)** has been launched with the goal of development of all solid state batteries for traction applications. Chemical industry including Asahi Kasei, Toray Industries, Kuraray and others work in close collaboration with major Japanese automakers Toyota, Honda, Nissan, and battery manufacturers including Panasonic, GS Yuasa and others. Japan's

Ministry of Economy, Trade and Industry provided ¥1.6 billion (ca. USD 14 million) in funding to Libtec. Libtec hopes to develop a solid-state battery that doubles the range of electric vehicles to 800 km (497 miles) by 2030 over the current 400 km (249 miles). For the time being, it is targeting a more modest range of 550 km (342 miles) by 2025. The program is aimed at returning Japanese manufacturers to the forefront of automotive battery technology.[26]

In addition to its world-leading research on all solid-state batteries, Toyota develops a metal-air battery, which uses a metal such as lithium or zinc for the anode, and air drawn from the environment at the cathode.[142] The company is also working on developing recyclable batteries made from Earth-abundant materials.

In May-June 2018 Japan's **New Energy and Industrial Technology Development Organization (NEDO)** has launched the 2nd phase of a major solid-state Li-ion battery project for the development of traction batteries with high energy density and improved safety.[26] The ¥10 billion (USD 90 million) project, which involves 23 automobile, battery and materials manufacturers as well as 15 universities and public research institutes, will tackle challenges facing all solid-state Li-ion batteries such as the development of solid electrolytes, electrolyte coating with active material, and the sheet formation of the electrolyte-electrode layer. In addition, the project will develop simulation technology to predict the deterioration of all-solid Li-ion battery cells and battery packs, and test evaluation methods for durability and safety with international standardisation. The aim is to lower the battery pack cost to ¥10,000/kWh (USD 90/kWh) by around 2030.[26]

Universities in Japan play a very active role in the national research towards advanced battery technologies. Several universities, among which Osaka Prefecture University, Yokohama National University and Tokyo Metropolitan University are working in the area of "sulfide-based all-solid-state battery" and "oxide-based all-solid-state battery", in particular covering interface fabrication, materials processing, battery design and others. Tokyo Metropolitan University is conducting research on innovative Mg-based batteries for electrical vehicles' application. Doshisha University is involved in the development of metal hydride/air secondary battery, having as targets energy density over 1500 Wh/L or 500 Wh/kg, which is impossible to realise with Li-ion secondary batteries. The Tokyo University of Science is looking into sodium-ion batteries.[143] Shinshu University has emerged as a world leader in crystal growth research, with an emphasis on solution-based single-crystal growth for cutting-edge battery design: a new route to the fabrication of composite electrodes for all-solid-state lithium-ion batteries through the growth of single crystals of the active material from molten lithium-ion conducting glass (glass flux).

USA

The USA is a big market player for both cells production (however much smaller than Far East) and cells consumption. The country has ambitions to not only be self-sufficient regarding cell production, but also become an important producer at the world market. Programs supporting R&D activities hence aim at development of state-of-the-art Li-ion technology, but also at advanced, post-Li-ion chemistries.

The **Advanced Research Projects Agency-Energy (ARPA-E)** established by the U.S. Department of Energy (DOE) supports high-potential, high-impact energy technologies that are not yet developed to the point at which the private sector could engage with investment. ARPA-E targets the development of entirely new technologies of generation, storage and usage of energy. It runs several programs relevant to the battery R&D:[144]

Within ARPA-E **Advanced Management and Protection of Energy Storage Devices (AMPED)** programme support projects developing advanced sensing, control, and power management of battery systems. AMPED aims to improve the performance, safety, and lifetime of today's commercial EES systems through system-level innovations, not by development of battery materials or designs.[145]

Batteries for Electrical Energy Storage in Transportation (BEEST) programme started in 2010 and is already concluded; its aim was to develop a range of technologies for rechargeable batteries that would enable EVs and PHEVs to reach price and performance at least equal to ICE cars and enable mass production of electric vehicles.[146]

Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage (CHARGES) established two sites, where projects funded by ARPA-E can test their technologies under conditions required by today's and future electric grids. The focus is on the commercialisation of EES systems developed with ARPA-E funds.[147]

Duration Addition to electricitY Storage (DAYS) program aims to develop ESS that store enough energy to support the grid for a duration of 10 to 100 hours. The system location should be possible without restrictions and a fixed, extremely low cost per charge/discharge cycle should apply. This program is financing two projects developing RedOx flow batteries: Aqueous Sulfur Systems for Long-Duration Grid Storage (Form Energy) and High-Performance Flow Battery with Inexpensive Inorganic Reactants (UTRC).[148]

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) is an already concluded program that supported several projects developing RedOx flow batteries, and one, Advanced Sodium Battery (Materials & Systems Research, Inc. MSRI) targeting solid state Na-ion chemistry.[149]

Innovative Development in Energy-Related Applied Science (IDEAS) provides rapid support for early-stage applied research, new concepts and disruptive changes in energy technology. The grants are restricted to one year and USD 0.5 million. This programme was used to support several projects relevant for few battery technologies, including solid state batteries.[150]

Integration and Optimization of Novel Ion-Conducting Solids (IONICS) focused on high performance ion-conducting solids for battery and fuel cell applications. The program supports development of processing methods and device integration architectures to accelerate their commercial deployment.[151]

Open Funding Solicitation (OPEN 2018) is the fourth, most recent opening of the broad scope program, existing since 2009 and opening on three-years basis, that already gave support to 77 projects, and among them few projects developing battery related technologies and materials.[152-155]

Robust Affordable Next Generation Energy Storage Systems (RANGE) aims to develop electrochemical energy storage technologies able to accelerate the rate of adoption of electric vehicles by significant improve of their driving range and safety in parallel to cost reduction. RANGE focuses on four specific areas 1) aqueous batteries, 2) non-aqueous batteries that incorporate inherent protection mechanisms, 3) solid-state batteries that use no liquids, and 4) multifunctional batteries that contribute to both vehicle structure and energy storage functions.[156]

The Department of Energy, **Office of Energy Efficiency & Renewable Energy** (EERE) in cooperation with other federal agencies provides support to the projects working on the R&D and deployment of solutions in the area of energy efficiency and renewable energy. This support is provided via cooperative agreements or grants, after answering to the EERE's funding opportunity announcements (FOAs).[157] Under this scheme there are many funding opportunities covering a broad range of energy applications; including, for battery and battery materials developers:

Vehicle Technologies Office (VTO) supports development of novel batteries for the mobility sector, including solid state Li-ion, Li-S and Na-ion technologies.[158]

Advanced Manufacturing Office (AMO) supports development of innovative manufacturing processes for battery energy storage.[159]

Battery500 consortium is a multi-institution program, launched in 2017 and working to develop next-generation Li-ion cells based on metallic Li anode and providing energy density of 500 Wh/kg. The Battery500 brings together four National Laboratories and five universities.[160]

Office of Technology Transitions (OTT) - established in 2015 and supporting the development of energy related technologies along all their way from the idea to commercialisation. The office is also responsible for the Technology Commercialization Fund and the Lab Partnering Service, providing funding for the range of the energy technologies including batteries.[161]

Technology Investment Agreement is a dedicated tool to support technology development and technology transfer to the deployment stage, e.g. "EaglePicher Establishes Lithium-Ion Center of Excellence".[162]

Battery Recycling Challenge is a part of the American Made Grand Challenges program and focusses on development of cost-effective collecting, sorting, storing, transporting and recycling processes to recover to the maximum possible extent the economic value from spent lithium-ion batteries from EVs, consumer electronics, industrial, and stationary applications. The scheme is a USD 5.5 million staged competition directed to American entrepreneurs to develop and demonstrate processes that after upscaling will be able to capture 90% of all discarded or spent lithium-based batteries in the United States.[163]

The DoE **Energy Innovation Hubs** are the research centres that integrate basic and applied research with engineering to support early-stage research, accelerate discoveries that address critical energy issues and advance innovation in U.S. manufacturing.[164] Currently there are four hubs, and two of them are supporting projects relevant for batteries. Those are: the **Joint Center for Energy Storage Research** (JCESR) - improving battery technology for transportation and the grid; and the **Critical Materials Institute** (CMI) - developing solutions for materials critical to US energy technologies, in particular focussing on (battery part) recovery of Li, Co, platinum group metals (PGM) and rare earth elements from end-of-life (EoL) battery and electronics streams.[165,166]

The US Defense Advanced Research Projects Agency (DARPA), a research and development agency of the U.S. Department of Defense, that is responsible for the development of emerging technologies for use by the military. It's webpage does not list any programme dedicated to batteries development. However, one can find some information in other official media appearing from time to time and describing a battery projects financed by DARPA.[167-171]

AUSTRALIA

Australia does not have a dedicated tool supporting the development of batteries and especially the four technologies analysed in this report. Instead it has several more general funding schemes to which the battery developers and system integrators may apply, focused on a rather wide spectrum of applications, e.g. raw materials supply, grid services, deployment, recycling. Those are available at both federal and state levels. Australia is known for its raw materials supply capabilities, and this applies also for battery-relevant minerals and raw materials. Thus many of the R&D projects are focused on the materials supply chain, but Australia is also looking at the opportunities in other segments of the whole value chain, including development of new chemistries, technical solutions for different battery applications, integration of storage with the grid, deployment on the grid and user levels, recycling, safety and security, regulatory issues, IT market support solutions for distributed storage.

The **Cooperative Research Centres Projects** (CRC-P) Grants support short-term (3 years), industry-led collaborative research projects. Those projects must: develop a product, service or process that will solve problems for industry and deliver real outcomes; benefit small to medium enterprises (SMEs) and also include education and training activities. This is a recurrent support scheme built on yearly base. 2020 call is named Round 9.[172]

The **Advancing Renewables Program** (ARP) under **ARENA** (Australian Renewable Energy Agency) supports projects related to renewable energy technologies from early stage lab research to the demonstration stage in the field, including projects on batteries.[173]

Australia's national science agency, **Commonwealth Scientific and Industrial Research Organisation (CSIRO)** has established in Sep 2019 a new partnership with **Piotrek**, a Japanese specialist chemical manufacturer aiming at global commercialisation of Australian-developed solid state battery technologies within the next five years. The partnership will develop a next generation of Solid Polymer Electrolytes for lithium batteries based on CSIRO's Reversible Addition-Fragmentation chain Transfer (RAFT) polymer technology and Piotrek's Ion Conducting Polymers (ICP).[174]

The State Government of Western Australia has developed **Future Battery Industry Strategy** and set the **Local Capability Fund.**[175] Within this instrument a tool dedicated to SMEs - the **Future Battery Industry Round** - was established to increase SME's capability and competitiveness as suppliers of products, services and works.[176]

Smart Sodium Storage System (S^4) Project[177] – with a budget of AUD10.6 million aiming to develop and demonstrate a Na-ion battery for use in renewable energy storage application. It commenced in early 2016 and will conclude in 2020. The project is co-funded by the Australian Renewable Energy Agency (ARENA), and is led by the University of Wollongong. The Na-ion batteries demo sites are at the Illawarra Flame House[178] in Wollongong (5 kWh) and the Bondi Sewage Pumping Station[179] (30 kWh) - located in vicinity of Sydney's Bondi Beach. The project has published 7 scientific papers.[180-186] The consortium is strongly linked to the Chinese partners (with many staff involved from Chinese side), and is based on Na-ion cells provided by a Chinese manufacturer.[187]

GERMANY

The Federal Ministry for Economic Affairs and Energy (BMWi) and the Federal Ministry of Education and Research (BMBF) have recognised the research and development needs in the area of energy storage technology and are developing tailored promotional activities as part of the 6th Energy Research Programme of the Federal Government.[188] With the **Energy Storage Funding Initiative**, both ministries have been supporting innovations for a wide range of storage technologies since 2011. About €200 million was awarded to a total of around 250 projects in the **6th Energy research program** to 2017.

Since September 2018 the **7th Energy research programme** continues to fund technology-neutral innovation in the research field of electrical energy storage and sets out guidelines for energy research policy until 2022 with a budget of approximately €6 billion available for research institutions, universities, SMEs and businesses.[189,190]

In the inter-ministerial initiative for stationary storage facilities, funding can go to research in the following strategically important areas:[191]

- Electrical storage (batteries, pressurised air storage, virtual storage, condensers, flywheels and pumped storage);
- Material storage (conversion of flexible quantities of electricity into hydrogen and methane, geological storage, efficient reconversion of electricity stored in materials);
- Thermal storage (materials and design principles, concepts for solar thermal power stations, for supplying buildings, integration in heating networks);
- Overarching issues (management of distributed storage facilities, manufacturing processes, systems analysis and public acceptance of storage facilities).

The Federal Ministry for Economic Affairs and Energy's activities are mainly focused on the mobile applications, which are not covered by the joint funding initiative described above:

- Electrical storage with a focus on further development of the lithium technology;
- Material storage, particularly for the use of hydrogen;
- Thermal storage with a view to efficiency, availability and costs of application in power stations, industrial processes and buildings.

The results of the development work are discussed within the Energy Research Networks, so that the research field of electrical energy storage is strategically developed. The

Battery Forum Germany[192] continues to offer a platform, as part of the BMBF material research programme, for the strategic direction of battery research in Germany.

Batteries 2020 program is carried out under the Federal Ministry of Education and Research[193] The first call was launched on August 2014, a second in February 2016 and a third in October 2017. Till now 44 research projects and 1 associated research project have been granted funding. They are divided in the following thematic areas:

- Material and process engineering for lithium-ion batteries;
- Materials for secondary high-energy and high-power system;
- Possible game-changing battery systems for the future;
- Second-use and recycling of lithium-ion batteries;
- Comparative studies and interconnection of participants.

The **ProZell** competence cluster for battery cell production aims to provide the scientific basis for the establishment and sustainable development of an internationally leading, competitive battery cell production in Germany.[194] It is formed by 12 research projects.

The **FESTBATT** is a competence cluster for all solid-state batteries. It is formed by 21 research projects.[195]

UK

Faraday Challenge – The Faraday Institution is the UK's independent institute for electrochemical energy storage science and technology, supporting research, training, and analysis.[196] The Faraday Institution is the research vehicle for the Industrial Strategy Challenge Fund (ISCF) Faraday Battery Challenge,[197] which comprises a £246 million commitment to over 4 years, now enlarged to a £274 million commitment to March 2021 to develop, design and manufacture world-leading batteries in the UK. The programme is split into three separate elements, delivered in parallel, to provide connectivity across research and innovation strands: RESEARCH + INNOVATION + SCALE-UP.

The objective is to bring together scientists and industry partners on research projects to reduce battery cost, weight, and volume; to improve performance and reliability; and to develop whole-life strategies from mining to recycling to second use.

The main projects are:

Battery Degradation (**Degradation**),[198] Multi-scale Modelling (**MSM**),[199] Recycling & Reuse (**ReLIB**),[200] Electrode Manufacturing (**Nextrode**),[201] Lithium ion cathode materials (**CATMAT, FutureCat**),[202] Solid State batteries (**SOLBAT**),[203] Sodium-ion batteries (**NEXGENNA**),[204] Lithium-sulfur batteries (**LiSTAr**).[205]

Moreover the Faraday Institution announced £42 million for energy storage research at the Harwell Science and Innovation campus to speed up research into battery technologies.[206]

Funding competition, APC 15: developing the UK's low carbon automotive capability - The Advanced Propulsion Centre (APC) invests up to £30 million, 3 times a year, in collaborative research and development (R&D) projects which demonstrate a significant change in the reduction of CO_2 emissions and improvement in air quality compared to best in class. This can include batteries amongst other technologies (e.g. motors, power electronics).

FRANCE

Investments for the Future (Programme d'investissements d'avenir PIA) and the Joint actions of the SET-Plan - in order to achieve the identified targets of the implementation plans endorsed by the SET-Plan Steering group, France has made possible the development of joint research projects together with other European SET-Plan countries.[207]

Between 2010 and 2017 more than €2.5 billion were allocated through French Environment & Energy Management Agency (ADEME) to 750 R&D projects, covering a wide scope of topics: energy, storage, energy efficiency, circular economy, transportation and mobility. In 2018, the third round of the PIA was launched with an endowment of €1 billion for innovation in the field of the energy and ecological transition.

On July 31st 2019, the French government launched 3 calls for projects which are part of the action "Demonstrators" of the third Investment Program for the Future (PIA3), endowed with €300 million. One to the 3 calls is dedicated to projects on "Energy Systems -Sustainable Cities and Territories". The projects must relate to: optimised energy systems, production / supply of renewable energies and renewable energy vectors and environmental optimisation at the scale of a building / island (under construction or renovation) or of a territory.

Agence Nationale de la Recherche (ANR) – the Generic Call for Proposals is the French National Research Agency's (ANR) main annual call with a substantial budget of roughly €400-500 million. It is directed towards all scientific communities and all public and private actors involved in French research, including small and medium-sized enterprises (SMEs) and very small enterprises and funds amongst others battery research projects. Relevant research projects include:

CASSIOPES In situ/operando characterisation tool for 3D Li-ion solid state microbattery (2017);

SELPHy Single-ion hybrid polymer electrolytes for Li-metal battery (2017);

V-S-L New aqueous 'all Vanadium-Solid-Liquid redox flow batteries for conversion and storage of renewable energies (2017);

SHUTTLE All solid lithium-sulfur battery with a polymer electrolyte (2019);

Energy-4S Redox flow batteries for sustainable storage intermittent energies (2019);

DESTINaion_Operando Study of the Dynamics of Sodiation within Individual Particles of Active Materials for Operando TEM Na-ion Batteries (2019).

BPIFrance - French agency for innovation, delivering programs to innovative entrepreneurs.

ADEME - Environment and Energy Management Agency Climate change - ecological, energy transition

STOCK_CONV, Stock - Investments for the future: Call for Expressions of Interest Storage and Energy Conversion (2015 and 2017). The objective of these calls for expressions of interest is to support the development of projects in the field of energy storage and the conversion of energy carriers in order to exploit fluctuating renewable energies and guarantee stability of the electricity network. One of the 2 themes was devoted to Energy storage, including "Reversible storage of electricity (in electric charge-discharge cycles)"

Concours d'innovation - ADEME created the funding scheme "Concours d'innovation" (Innovation competition) I-Nov in 2019. This is a support system financed by the Investments for the Future Program (PIA) aimed at supporting innovative projects carried out by start-ups and SMEs and leading to foster the accelerated emergence of leading companies in their field which can claim in particular on a global scale. It makes it possible to co-finance research, development and innovation projects whose total costs are between €0.6 and 5 million and which contribute to accelerating the development and marketing of innovative solutions and technologies. Two of the themes of the Innovation competition is devoted to "Renewable energy, storage and energy systems" and "Transport and sustainable mobility".

Bilateral French-German call for proposals in the domain of "sustainable energy" – 2018-2019 - funding was provided to collaborative projects between German and French partners that conduct application-oriented basic research (TRL 1-5) aiming at highly innovative, cross-sectoral solutions for economically, ecologically and socially sustainable and secure energy storage and distribution in France, Germany and Europe. This call features two main topics: *Conversion and storage of energy from renewable sources* (with a special mention to new batteries) and *Smart Grids at transmission and distribution levels.*

DESCARTES - challenge on electro-chemical storage associated with remote controlled robots. The challenge of energy storage DESCARTES (organised over three years) is in partnership with the DGA (Direction Générale de l'Armement) and it aims to improve the storage of electrical energy (electrochemical batteries, supercapacitors, fuel cells, or their hybrids, etc.) for both military and civilian applications. Projects, starting 2014, with a maximum budget of €0.5 million were funded. That included projects on advanced Li-ion batteries, nickel-zinc and sodium-ion batteries for robots.

SPAIN

Funding for research on batteries has been made available by the Spanish Ministry of Science and Innovation in various programmes (please see below for a summary). No data on funding of the four specific battery technologies discussed in this report have been found, as programmes usually cover all battery types and chemistries. However, some relevant projects focusing on the types of batteries discussed in the current report could be identified and are listed below.

Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016 - (€217 million).

ENE2013-44330-R - Li-ion and Na-ion battery technologies for transportation and storage applications on electrical networks (2014-2016; €205.000)

ENE2014-52189-C2-2-R - graphite nanofibers: design and application as anode in sodium-ion batteries for renewable energy storage (2015-2017; €121.000)

MAT2014-56470-R - post Li-ion batteries: from sodium to aluminium (2015-2017; €182.000)

MAT2014-59907-R - graphene as a base for advanced Li-S and Na-S batteries for storage of renewable energies in smart electrical grids (2015-2017; €60.500)

ENE2015-64907-C2-1-R – Li-S solid state battery (2016-2018; €133.100)

MAT2016-78362-C4-2-R - materials for lithium, post-lithium and fuel batteries: from the laboratory to the prototype (2016-2019; €121.000)

MAT2016-78362-C4-1-R - materials for lithium, post-lithium and fuel batteries: from the laboratory to the prototype (2016-2019; €151.250)

ENE2016-75242-R - advances in Na-ion battery technology (2016-2019; €252.000)

Plan Estatal de Investigación Científica y Técnica y de Innovación 2017-2020 - (€268 million).

RTI2018-095425-B-I00 - electrical storage devices guided by environmental aspects: from materials to prototypes of sodium-ion batteries (2020-2022; €140.360)

RTI2018-093712-B-I00 - design and preparation of carbon materials for use in cathodes of Li-S batteries (2020-2022; €176.760)

RTI2018-099228-A-I00 - injectable batteries of semi-solid electrodes (2020-2022; €121.000)

RTI2018-094550-A-I00 - novel materials like anodes to make potassium-ion-based, low-cost rechargeable batteries viable (2020-2022; €72.600)

FINLAND

In 2018, a three year activity, "Batteries from Finland" and a four year program "Smart Mobility", were launched. The budget of these programs is over €100 million.

BatCircle - EU pilot project with the goal of recovering as much of the battery materials as possible for the use of battery manufacturing in a financially viable manner and thus integrating recycling and initial production. 30 companies, universities and research Institutes are involved. Finland was asked to lead the Battery Recycling sub working group under the Battery Implementation plan. Business Finland is funding the consortium with approximately €10 million.

SWEDEN

The Swedish Energy Agency supports research and development projects on supply, conversion, distribution and use of energy.

The **Batterifondsprogrammet** Battery Fund Program is a research program with a focus on battery recycling and batteries for electrical system and vehicle applications.

The program is funded by the Swedish Energy Agency through funding from the Swedish Environmental Protection Agency. About SEK280 million will be distributed during the period 2017-2027 through annual calls.

TURKEY

Turkey has been associated to the EU research framework programmes since 2003 and it is the third EU partner country to become associated to Horizon 2020. Under the previous programme (2007-2013) over 1,000 participations from Turkish public and private institutions in some 950 projects received almost €200 million of EU funding. These included world-class science projects selected by the European Research Council and support for younger researchers under the Marie-Skłodowska Curie Actions. There were also more than 200 participations in joint research projects by Turkish Small and Medium-sized Enterprises (SMEs).[208]

No consistent and structured information has been found in English regarding battery research programmes in Turkey. The R&D and industrial deployment in Turkey seems to be focused on the conventional lithium-ion battery technology. Different sources are referring to lithium-ion batteries manufacturing on Turkey's soil, including academia. Sakarya University won EU funding of €0.98 million out of a €22.5 million total budget under the ERA-Net Smart Energy Systems initiative of the EU research and innovation funding program Horizon 2020. It was selected out of more than 300 applicants from 18 countries. The project aims to decrease Turkey's import battery technology dependence in the energy sector by producing battery components locally.[209]

Another example is the Energy Institute Battery Technologies Laboratory, which works in all phases of manufacturing of electrodes and batteries that are the target outputs of the battery technologies R&D projects. Beside the laboratory activities such as the development of battery materials and cells, electrochemical specification and prototyping, battery testing activities are performed within the scope of industrial test and analysis services.[210]

Turkey is interested in lithium-ion battery storage system to reduce day ahead bid changes and market integration issues that exist due to sporadic disposition of wind power in Turkey. The establishments for Turkey's first lithium-ion battery manufacture facility were laid in the country's central province of Kayseri.[211]

The Chinese electric vehicle battery manufacturer Farasis has signed a letter of intent with Turkish automotive company Turkiye'nin Otomobili Girisim Grubu to jointly develop and supply energy storage products through a Turkey-based joint venture. The two companies will produce battery modules and packs in Turkey using battery cells provided by Farasis through the joint venture that will focus on providing energy storage solutions for Turkey and the surrounding countries. Farasis will also develop and supply lithium-ion batteries for electric vehicles to Turkiye'nin Otomobili Girisim Grubu.[212]

4 Impact assessment of H2020 co-funded projects

This chapter together with associated tables in the Annex present an assessment of completed Horizon 2020 projects. The impact assessment is limited to the project's goals and achieved results as well as scientific outputs, such as peer-reviewed publications, presentations at conferences etc. Also some information available on the ongoing projects is included.

4.1 All Solid State Batteries with Li-metal anodes

In this analysis projects related to ASSB LiM, listed in Table 2, are considered and a summary of each project is presented below.

MONBASA - Monolithic Batteries for Spaceship Applications[213]

This project was funded via the call H2020-COMPET-2015 (Competitiveness of the European Space Sector: Technology and Science) and had a duration of 24 months (start date 01/06/2016; end date 31/05/2018; budget €1.3 million). For an overview of the project, please refer to Table 9 in the Annex.

The overall ambition of MONBASA was to develop a novel energy storage system for small satellites (nano-/microsatellites) that outperforms existing solutions on various levels. The specific needs identified by the MONBASA consortium were:

- high energy efficiency and density,
- small size and low weight,
- high reliability,
- compliance with safety regulations and existing standards,
- high cost-efficiency.

BATMAN - Feasibility study of a high energy BATtery with novel Metallic lithium Anode[214]

This project was funded via the call H2020-SMEINST-1-2015 (Horizon 2020 dedicated SME Instrument Phase 1 2015) and had a duration of 6 months (start date 01/09/2015; end date 29/02/2016; budget €0.05 million). For a detailed analysis of the project, please refer to Table 10 in the Annex.

The overall objective of the innovation project was to develop a novel anode technology, which would allow Li-ion batteries to achieve energy density up to 300 Wh/kg and capacity cycle efficiency more than 99.998%.

The core novelty of the solution lied in the approach to solving the problem of irreversible phase formation on carbon and metallic lithium battery anodes through synthesis of protective nanostructures. This has thus far prevented the usage of new metallic materials (such as mixed Li, Sn, Sb, Si nanostructures) in commercial rechargeable batteries, as well as current state high energy carbon materials at high cycle rates in case of metallic lithium dendrites growth.

Ongoing Projects

SOLiDIFY - Liquid-Processed Solid-State Li-metal Battery: development of upscale materials, processes and architectures[215]

This project is funded via the 2019 call H2020-LC-BAT-2019-2020 (Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries) and will have a duration of 48 months (start date 01/01/2020; end date 31/12/2023; budget: €7.8 million).

The SOLiDIFY project proposes a unique manufacturing process and solid-electrolyte material to fabricate ASSB LiM known as Gen. 4b on the EU battery roadmap. The concept is based on a solid nanocomposite electrolyte or nano-SCE. It is made by a sol-gel reaction which is used advantageously for a liquid-to-solid approach in the fabrication of the composite cathode and the solid-electrolyte separator. The general strategy to reach the target energy density of 1200Wh/L (400Wh/kg) in 20 minutes charging time is: (1) enabling the integration of high-energy NMC active materials and (2) development of new electrode architectures for high mass loading and enabled by the liquid-to-solid approach. An added imposed challenge is a water-based cell assembly process. To this end, suitable protection of the high-energy NMC powder with ALD thin-film coatings is pursued. Finally, thin lithium foils with protective artificial interphase coatings will be developed for lamination on the nano-SCE separator.

The main goal of SOLiDIFY is to bring the liquid-processed solid-state cell fabrication concept from demonstration in the lab (TRL 3) to prototype demonstration in pilot line (TRL 6) with upscaling of the liquid-to-solid concept both towards (1) the development of manufacturable materials and processes and (2) the development of full cell assembly schemes with ultimate demonstration of 1 Ah pouch cell prototypes.

The research will focus on (1) solutions enabling the upscaling process and manufacturability and (2) further improvement of cell integration steps to enhance performance. Parameters such as cost, environmental impact and recycling will also be considered. The larger scope of the SOLiDIFY project entails the development of a novel and potentially European-lead solid-state battery technology with fully covered EU value chain.

SAFELiMOVE – Advanced all solid state safe lithium metal technology towards vehicle electrification[216]

This is another project funded via the 2019 call H2020-LC-BAT-2019-2020 (Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries) and it will also have a duration of 48 months (start date 01/01/2020; end date 31/12/2023; budget: €7.9 million).

SAFELiMOVE project aims to support a market-driven disruptive technology change towards high energy density batteries (450 Wh/kg or 1200 Wh/L) and improved safety in a cost-effective manner. SAFELiMOVE delivers innovations in five main technology areas: development of nickel-rich layered oxide cathode materials; high specific capacity, lithium metal anode materials; advanced hybrid ceramic-electrolyte with improved ion conductivity at room temperature; interface adoption for effective Li transport by surface modification and/or over-coatings, and knowhow creation for the development of scale up production of all-solid-state batteries. By higher energy density batteries towards 450 Wh/kg, faster charging and longer cycle life, SAFELiMOVE aims to meet future battery requirements for EVs.

MODALIS² – MODelling of Advanced LI Storage Systems[217,218]

MODALIS² is a project funded via the 2019 call H2020-LC-BAT-2019-2020 (Building a Low-Carbon, Climate Resilient Future: Next-Generation Batteries) with duration of 36 months (start date 01/01/2020; end date 31/12/2022) and a budget of €4.8 million.

MODALIS² will make a significant contribution to a cost-down for EV battery cells through an all-integrated development process based on numerical tools relying on extensive measurement data and material characterization all the way down to micro-structures.

The main goal of MODALIS² is to develop and validate modelling and simulation tools for the following next generation batteries:

- Gen 3b: aiming for higher capacities for the positive and negative electrodes
- Gen 4b: enabling the use of solid electrolytes for improved safety and to facilitate the use of Li-M for the negative electrode

Next generation cells pose new and significant challenges, such as:

- Volumetric expansion of materials
- Mechanical stresses
- Ionic conductivities in solid electrolytes
- Solid-solid interfaces that behave differently than currently used solid-liquid interfaces

With the integrated modelling and simulation, MODALIS² will provide degrees of freedom for the cell and battery development processes that allows to address the following design challenges: i) faster development of batteries with higher energy density with new materials; ii) faster development of materials with higher optimized performances for higher-energy battery applications; iii) improved battery safety during transport and operation; iv) optimization of cyclability; v) lower development costs; and vi) better understanding of material interactions within the cell.

MODALIS² will address the material characterization of next-generation (3b and 4b) Li-Ion cells in different physical domains, then expanding a carefully chosen set of models towards integrating new cell generations and implementing the models into a numerical simulations toolchain scalable to mass production. The modelling & simulation toolchain will allow faster time-to-market for next-gen cells.

IMAGE – Innovative Manufacturing Routes for Next-Generation Batteries in Europe[219,220]

IMAGE is a project funded via the H2020-GV-2017 call (Production of next generation battery cells in Europe for transport applications) with duration of 42 months (start date 01/11/2017; end date 30/04/2021) and a €4.9 million.

The main goal of IMAGE is to push European's Li-battery industry and academia to take over a leading role in the development and manufacturing of Next Generation Li-Ion cells. IMAGE has the following major objectives:

1) Develop generic production techniques for next generation battery cells based on high specific energy Li-metal battery cells. This includes a modular development approach that is easy to up-scale while remaining flexible and safer to replace in case of any contingencies and market/ manufacturer configuration changes.

2) Identify energy and resource efficient cell manufacturing technologies and assets tailored to the existent European industrial infrastructure. This includes the identification of bottleneck factors and challenges that could be addressed in the present European industrial context.

3) Develop a progressive, multiple-tier technological and production framework that is able to cope with the inherent technological changes and advancements characteristic to this dynamic field. Thus, several technologies are covered by IMAGE, each having different technological maturity level.

HYCOAT – A European Training Network for Functional Hybrid Coatings by Molecular Layer Deposition[221,222]

HYCOAT is European training network funded via H2020-MSCA-ITN-2017 call (Marie Skłodowska-Curie Innovative Training Networks) with a duration of 48 months (start date 01/01/2018, end date 31/12/2021) and a budget of €3.9 million.

HYCOAT is the first European Training Network at the intersection of chemistry, physics, materials science and engineering dealing with the synthesis and applications of hybrid coatings grown by Molecular Layer Deposition (MLD). HYCOAT targets the development of novel precursor chemistries, processes, characterisation and modelling of MLD and the demonstration of hybrid coatings in four key high impact fields of application relevant for European industries, in packaging, biomedical, electronics and batteries.

The key objective of HYCOAT is to create a group of well-trained young researchers who have a deep understanding of all aspects of MLD technology, as well as a broad vision on the application potential of hybrid coatings.

Therefore, via training-through-research projects and training events, the consortium aims to:

- establish novel MLD deposition chemistries and process schemes,

- enable fabrication of hybrid thin films with tailor-made and novel properties,
- gain a deep understanding of the molecular mechanisms during MLD processes, and to
- develop dedicated, industrially scalable reactor concepts for MLD-type processes.

Hybrid materials engineered at the molecular scale can have synergetic properties, i.e. surpassing the performance of their individual inorganic and organic components. Thin films of hybrid materials will enable breakthroughs in several economically and socially relevant technological application areas.

Combining inorganic and organic building blocks on a molecular scale is challenging due to the different preparative conditions needed for forming inorganic and organic networks. Current routes are often based on solution chemistry, e.g. sol-gel synthesis combined with spin-coating, dipping or spraying. Liquid-based techniques lack the level of control (thickness, composition, etc.) and sophistication (avoiding contamination, corrosion, etc.) required to fully enable the potential of hybrid coatings, especially on complex surfaces.

Molecular Layer Deposition (MLD) is a vapour phase deposition technique for hybrid thin films based on successive self-limiting surface reactions. In several aspects, MLD resembles the now mainstream technique of Atomic Layer Deposition (ALD). However, where ALD is limited to exclusively inorganic coatings, the precursor chemistry in MLD is expanded to include organics and enables linking both types of building blocks together in a controlled way to build up organic-inorganic hybrid materials.

POLYTE – European Industrial Doctorate in Innovative POLYmers for Lithium Battery Technologies[223]

POLYTE is a European industrial doctorate innovative training network funded via the H2020-MSCA-ITN-2017 call (Marie Skłodowska-Curie Innovative Training Networks) with a duration of 48 months (start date 01/01/2018, end date 31/12/2021) and a budget of €0.7 million.

POLYTE-EID European Industrial Doctorate offers excellent training opportunities to 3 Early Stage Researchers in multidisciplinary areas of research, including polymer chemistry, ionic liquids, polymer physics, advanced characterization methods, electrochemistry and electrochemical energy storage technologies, such as lithium metal, lithium-ion or lithium-air battery technologies.

POLYTE-EID puts together the expertise in batteries for automotive applications of Toyota Motor Europe (TME) with the academic excellence in polymers of the University of the Basque Country (POLYMAT). The project represents a well-balanced combination of fundamental materials & polymer science with applied research in electrochemical energy storage technologies.

The overall objective of the project is the development of new polymeric materials to increase the performance and safety of the current and future batteries.

4.2 Lithium-Sulfur Batteries

In this analysis we consider the following 5 projects related to Li-S batteries: ALISE,[224] ECLIPSE,[225] HELIS,[226] LISA,[227] and SPIDER.[228] A summary of each project is presented below.

ALISE – Advanced Lithium Sulphur battery for xEV[224]

This project was funded via the call H2020-NMP-GV-2014 (Post-lithium ion batteries for electric automotive applications) with a duration of 48 months (start date 01/06/2015; end date 31/05/2019; budget €7 million). For an overview of the project, please refer to Table 11.

The project focused on the development of new materials and on the understanding of electro-mechanical processes involved in the technology. The objective of the project was a very challenging one; achieving 500 Wh/Kg Li-S stable cell. The goals needed adjustment to meet the timing of the project.

The project involved durability, safety testing and LCA activities aiming at producing new materials and processes at a competitive cost from lab scale to pilot scale (at TRL 4). Efforts were made to optimise anode, cathode, electrolyte and separator, as well as in developing associated modelling from the unit cell to the battery pack.

Safety issues found with battery pack testing identified for first generation cells, necessitated a considerable effort in terms of safety testing for this type of technology.

Relevant partner in the project was OXIS Energy,[73] major player in the field, which has developed Li-S cells at commercial level since 2015 in its own production plant.

The project delivered an improved scientific and technical understanding of the Li-S battery technology and confirmed its TRL 3 status.

ECLIPSE – European Consortium for Lithium-Sulphur Power for Space Environments[225]

This project was funded via the call H2020-COMPET-2015 (Competitiveness of the European Space Sector) and had a duration of 24 months (start date 01/12/2015; end date 30/11/2017; budget €1 million). For an overview of the project, please refer to Table 12.

This project focused on Li-S batteries at three different levels: i) cell level, including research to optimise the four main cell components: anode, cathode, separator and electrolyte aiming at achieving 400 Wh/kg cells compatible with space cycling profiles ii) battery and encapsulation level, including prototyping and theoretical studies, and iii) system level for integration in satellite and launcher architectures taking into consideration the harsh conditions of such applications.

An electrical model of the cell (including ageing effects) was used for system level analysis.

HELIS – High energy lithium sulphur cells and batteries[226]

This project was funded via the call H2020-NMP-GV-2014 (Post-lithium ion batteries for electric automotive applications) with a duration of 48 months (start date 01/06/2015; end date 31/05/2019; budget €8 million). For an overview of the project, please refer to Table 13.

The project focused on fundamental aspects of the development of the technology, and it is somehow a continuation of a previously funded FP7 EUROLIS[229] (having same project coordinator, the National Institute of Chemistry Ljubljana, Slovenia). Main focus of the project was on the stability of lithium anode during cycling to avoid formation of dendrites, which have serious implications on safety.

Actually, safety had a main role in this project with considerations for safety testing of aged cells. In this project, the aspect of recycling was also considered. This work performed the modelling of quasi solid state Li-S batteries.

Ongoing Projects

The next two projects are currently ongoing and expected finalisation is summer 2022. Therefore, the summary here presented only corresponds to roughly the first 8-12 months of project (corresponding to the timing of the first reporting period).

LISA – Lithium sulphur for SAfe road electrification[227]

This project is funded by the call H2020-NMBP-ST-IND-2018 on Industrial sustainability and builds on the results from ALISE with a duration of 43 months (start date 01/01/2019; end date 31/07/2022; budget €8 million), but in this case more industrial material producers are present which, in principle, might help in the upscaling of technologies. For a detailed overview of the project please see Table 14 in the Annex.

The project proposes the development of high energy and safe Li-S battery cells with hybrid solid-state non-flammable electrolytes validated at a 20 Ah cell according to EUCAR industrial standards for automotive battery integration. The development of a chemical system that can block ion mobility by means of solidification of the catholyte at elevated temperatures through thermally switchable chemical crosslinking can be an important achievement in terms of safety.

Having REN and VDL as partners in the project, will in principle enable the assessment of the technology for light duty vehicles and buses for full electric drivetrains.

SPIDER – Safe and Prelithiated hIgh energy DEnsity batteries based on sulphur Rocksalt and silicon chemistries[228]

This project is currently being funded by the call H2020-NMBP-ST-IND-2018 on Industrial sustainability with a duration of 44 months (start date 01/01/2019; end date 31/08/2022; budget €8 million).For a detailed overview of the project please see Table 15 in the Annex.

SPIDER technologies will be implemented on 4 successive advanced Li-ion cell generations in which several concepts will be successively introduced: high capacity anode and cathode materials, prelithiation and advanced electrolyte formulations.

Several prelithiation methods will be evaluated as part of the project in order to have a lithium buffer.

4.3 Sodium-ion Batteries

In this analysis we consider the following projects related to Na-ion batteries: NAIADES,[230,231] NAIMA,[232,233] HiNaPc,[234] NAPANODE,[235] NExtNCNaBatt.[236]

NAIADES – Na-Ion bAttery Demonstration for Electric Storage[230,231] project was funded via the H2020-LCE-2014-3 call with a duration of 48 months (start date 01/01/2015; end date 31/12/2018; budget €6.49 million). For a detailed overview of the project please see Table 16 in the Annex.

The NAIADES project is one of the first large research projects aiming to develop and demonstrate a Na-ion battery for stationary EES and grid applications. Such a system is expected to work at ambient temperature and bring a radical decrease of cost with respect to the Li-ion technology while ensuring sustainability and performance in terms of safety, cycle life, and energy density.

According to the most recent information available on the project website:

The main expected impact of this project is the following: an enlarged energy storage portfolio, an increased efficiency of the storage technologies, and a facilitated electric energy management in the grid. So far, as this project is focused on the long term evolution of the electric grid, it is still difficult to provide specific final evidence of the impact. However, some significant results can already give promising answers. First of all, the manufacturing of the first 1 Ah cells have already proven the feasibility of this technology, and from this point of view, it seems very likely that this battery technology will be available soon on the market. However, it must first meet the requirements of specific applications in terms of performance, cost and safety. This is one of the purposes of the test plan of the NAIADES project. Secondly, preliminary results show encouraging values in terms of environmental impact of this material along all its life. Finally, the Integration of this storage technology into the management of the distribution grids to provide increased grid security and stability, will be evaluated during the last year of NAIADES, when the module will be integrated in a smart secondary substation as a backup power source.

The project has published 12 articles in scientific journals, contributed to 3 conferences, received 1 patent, issued 1 report and organized 1 summer school. The NAIADES was a collaborative European project involving 10 partners: CEA, CSIC, CNRS, Vito, Chalmers University of Technology, VDE Institut, Solvay (Rhodia Operations), SAFT, Estabanell Energia, MAST Carbon Int. LTD (bankrupted in 2016) and was led by CEA.

In 2017 CNRS, a partner of the NAIADES project established a spin-off company **Tiamat** developing and manufacturing Na-ion battery cells basing on the results of NAIADES.

NAIMA – Na ion materials as essential components to manufacture robust battery cells for non-automotive applications[232,233] – was funded via the call H2020-LC-BAT-2019 (Strengthening EU materials technologies for non-automotive battery storage (RIA)), NAIMA is an INDUSTRIAL LEADERSHIP type of project with a duration of 36 months (start date 01/12/2019; end date 30/11/2022; budget €8 million). For a detailed overview of the project please see Table 17 in the Annex.

NAIMA is a follow up project of NAIADES, led by Tiamat and created around the same group of core partners. It is based on results and lessons learnt from the NAIADES project operation and is expected to move further the technology development (TRL 6 is aimed at the end of NAIMA project). It is still in the early stage of the development.

According to the most recent information available on the project website:

NAIMA project will develop and validate a new generation of Sodium-ion (Na-ion) based batteries to unseat the current Li-based technologies, nowadays controlled by Asian industry. This disruptive technology is already supported by a solid European battery value chain, preserving the ownership and industry strength around European countries.

The European Union is transitioning to a secure, sustainable and competitive energy system based on renewable sources. The non-dispatchable renewable generation requires a higher flexibility in the energy system, where the weight of much more decentralised installations grow day-to-day.

In fact, the flourishing of a wide portfolio of renewable energy installations is allowing the deployment of large to small scale industrial electricity grids, and an increased share of electricity produced in private households.

In the whole of these business scenarios, without any exception, the role of energy storage technologies is crucial.

At present, the European industry depends on the import of Asian Lithium-ion batteries. The EU share for cell manufacturing is only a 3%, while the Asian share of cell manufacturing is an 85%. For this reason, it is mandatory to create a new industry value chain capable to ensure the production and supply of 100% European batteries.

NAIMA project will demonstrate that a new generation of high-competitive and safety Na-Ion cells is one of the most robust and cost-effective alternatives to Li-based batteries.

Within the framework of the project, Na-ion batteries prototypes will be tested in 3 multi-scale Business Scenarios to provide solid evidences about the competitiveness of the technology in 3 real Energy Storage Systems environments (renewable generation, industry and private household).

With an overall budget of 8 million euros funded by the European Commission through the Horizon 2020 programme, NAIMA, which began on 1st of December 2019, will gather 15 partners working together until 30 November 2022.

The project has started in Dec 2019 and did not produce any publication nor patent yet. The NAIMA is a collaborative European project involving 15 partners: Accurec-Recycling GMBH, Biokol Sverige AB, CNRS, CEA, Dil Diel, Electricite De France, Gestamp Navarra SA, Stichting Ihe Delft Institute For Water Education, Innovative Energy And Information Technologies Ltd, Kemijski Institut, Rhodia Operations (Solvay), Tiamat, Umicore, VITO, Zabala Innovation Consulting, S.A.

HiNaPc – Sodium-ion pouch cells with high energy and power density[234] – was funded via the call H2020-ERC-2016-PoC (Proof of Concept) and is a project with a duration of 18 months (start date 01/01/2017; end date 30/06/2018; budget €0.15 million). For details please refer to Table 18 in the Annex.

According to the most recent information available for the project, its objective is: “The growing market appeal of rechargeable lithium ion batteries (LIBs) for electric vehicles and portable electronics as well as the high cost and scarcity of lithium are driving research towards developing alternatives to LIBs. Sodium ion batteries (SIBs) have attracted considerable scientific and industrial attention as a potential alternative to LIBs with great economic benefits, which mainly attributes to the low cost and natural abundance of sodium. Moreover, SIBs share many similar characteristics with LIBs, from charge storage mechanism to cell structure, thus facilitating the production of SIBs with the existing LIB production technique and equipment. Currently, the key challenge of commercializing SIBs is to improve their performance to be comparable to LIBs. During the ERC ThreeDSurface project, we have performed both the material designing and 3D electrode designing for largely enhancing the SIB performance.”

The project has published 2 articles (on supercapacitors and on K-ion batteries) in scientific journals. The HiNaPc is a one partner project executed by Technische Universitaet Ilmenau.

NAPANODE – Molecular Foundation of Structural and Dynamic Transformations in Novel Sodium-Ion Battery Materials[235] – was funded via the call H2020-MSCA-IF-2016 (Marie Skłodowska-Curie Individual Fellowships, IF-EF), NAPANODE is a Nurturing excellence by means of cross-border and cross-sector mobility type of project with duration of 24 months and terminated after 16 months (started on 01/03/2017; terminated in 06/2019) with a budget of €0.18 million. For a detailed overview of the project please see Table 19 in the Annex.

The project was focused on basic science aiming in understanding the degradation processes relevant to Na-ion cell chemistry. The new Na and P binary and ternary anode alloys behaviours were studied (paired with well-known cathode material[237]), and resulting cell performance characteristics. Finally, the goal was also to develop an *in situ* NMR spectroscopy technique for non-invasive real-time studies of batteries under operating conditions, which task was successfully completed.

The most recent information available for the project, extracted from its webpage is:

“The future of widespread clean energy relies heavily on understanding, developing, and optimizing materials for electrochemical energy storage. The influence of short-range structure on macroscopic device properties during operation has hindered implementation of promising technologies such as Na-ion batteries. Na-ion batteries offer a more sustainable solution for energy storage compared to their Li-ion counterparts because Na is cheaper, more abundant, and more widespread in the Earth’s crust. Efforts to develop Na-ion batteries have led to the discovery of cathode materials for Na-ion batteries, but the identification of suitable anode materials has been more arduous. Many intercalation and alloying anode materials that work well in Li-ion batteries fail in Na-ion chemistries, such as graphite or Si. Phosphorus is an exceptionally promising anode material for Na-ion batteries because it offers the highest theoretical capacity of any known anode material, with the end member composition Na3P corresponding to a capacity of 2596 mAh/g. Unfortunately, P-based anodes suffer from performance degradation issues such as low conductivity and poor capacity retention over multiple cycles. Correlating changes in material structure with specific electrochemical signatures in the charge-discharge profiles allows us to understand which processes immediately precede and follow degradation in anodes for Na-ion batteries. Here, we used solid-state NMR in combination with powder X-ray diffraction (XRD) and theoretical calculations to monitor the evolution of NaxP phases that form on (de)sodiation in black P anodes in Na-ion batteries. We identified key structural units in the amorphous intermediates (P helices) as well as provided the first assignment of the final discharge product of the crystalline architecture, Na3P, in Na-ion batteries.

The work completed in this project is the first study that provides a detailed assignment of the amorphous NaxP intermediates that form during cycling black P anodes. Numerous studies have shown the tremendous promise of black P for use in Na- and Li-ion batteries, yet a detailed assignment of the chemistry in these systems had remained elusive. Our work reported the combined use of advanced solid-state NMR (specifically, 2D 31P phase-adjusted spinning sideband experiments to correlate 31P isotropic and anisotropic chemical shift) and density functional theory (genetic algorithm, ab initio random structure searching, and prototyping to sample a vast composition space) to determine the intermediate structures. Further, with the use of NMR, XRD, and DFT, we correctly assigned the crystalline architecture of the final discharge product, Na3P, for the first time. These results have the potential to impact how anodes for Na- and Li-ion batteries are designed in next generation batteries that offer higher capacity and longer cycle life. By improving our options for batteries that offer optimal performance, we can transition to clean energy sources more rapidly."

The project has published a study on the structural transformations that occur during repetitive sodiation and desodiation of black phosphorus anodes. NAPANODE used solid-state NMR, XRD and DFT calculations, and provided insight into the reaction pathways.[238] The amorphous Na_xP intermediate structures were identified and two crystalline architectures were assigned to the final discharge product, Na_3P, for the first time.

The project has published one article in a scientific journal and contributed to five others (non Na-ion related) and contributed with 4 talks and 1 poster to the conferences. The NAPANODE is a one partner project executed by The Chancellor, Masters and Scholars of the University of Cambridge (for details please refer to Table 19 in the Annex).

NExtNCNaBatt – Novel Extended solids based on N=C chemistry for future Na-ion Batteries[236] – was funded via the call H2020-MSCA-IF-2016 (Marie Skłodowska-Curie Individual Fellowships, IF-EF), NExtNCNaBatt is a Nurturing excellence by means of cross-border and cross-sector mobility type of project with duration of 24 months, terminated after 13 months of work (started on 01/03/2017; suspended on 15/04/2018; terminated on 31/08/2018 without being resumed) and a budget of €0.2 million. For a detailed analysis of the project, please refer to Table 20 in the Annex.

The project was focused on the fundamental understanding of the chemistry between Na and N=C compounds with application as electrodes for sodium ion batteries as long-term objective. The proposal was built upon promising achievement of 200-600 mAh/g reversible capacity as published earlier by the applying researcher.[239]

The most recent information available for the project:

"The large and increasing demand for energies with a low CO2 footprint has prompted intense research and development on renewable energies as well as on sustainable electrochemical energy storage systems to fully utilize them. This requires the development and understanding of battery chemistries from earth abundant low-cost raw materials, which can be easily synthesized, with Na-ion batteries at the forefront of meeting these requirements.

While in Na-ion batteries most efforts are made to investigate materials that are essentially derivatives of Li chemistry, there are opportunities to look at very different chemistries which were not explored for Li ion batteries or just work better in Na batteries.

Na-ion batteries are just at the birth of commercialization, and therefore materials developed in this project could be timely incorporated into next generation prototypes and first commercial Na-ion batteries. Additionally, these new materials and the understanding of the alkali to NC interactions will be relevant to many other areas of research where electrochemical transformations occur, such as other battery chemistries, capacitors, electrochromic displays, and as photocatalysts, all systems where the understanding of the heterogeneous reactions between the solid electrode and ions from a liquid electrolyte are of critical importance.

NExtNCNaBatt project has largely improved the electrochemical performance of N=C containing electrodes by avoiding first cycle coulombic inefficiency, approaching these materials to their application in real low-cost Na-ion batteries. A better understanding of some of the issues related to the deployment of NC containing solids of different families will allow better design of next generation low cost Na-ion batteries."

The project did not published any article in scientific literature. The NExtNCNaBatt was a single host project – lead and executed by The Chancellor, Masters and Scholars of the University of Cambridge.

4.4 Redox-Flow Batteries

In this analysis we consider 9 projects in total, related to organic flow batteries: GREENERNET (closed), GLOBE (closed), EnergyKeeper (closed), MFreeB (ongoing), FlowCamp (ongoing), SONAR (ongoing), CompBat (ongoing), BALIHT (ongoing), and HIGREEW (ongoing). The information relative to the projects (e.g. deliverables, summary reports) has been gathered via Compass tool. Below a review of each project is presented.

GREENERNET – Advanced Flow Battery Energy Storage Systems in a Microgrid Network[240,241]

The project was funded via H2020-FTIPilot-2015-1 call (Type of action: IA) with a duration of 30 months (start date 01/07/2016; end date 31/12/2018). Budget: €2.7 million. For details please refer to Table 21 in the Annex.

The GREENERNET project aimed to develop a new highly innovative organic redox flow battery, integrated in an optimised microgrid infrastructure operated by an intelligent Energy Management System.

It involved development and commercialisation of a storage system module of 10 kW, 40 kWh based on a breakthrough technology, originally developed by Harvard University and implemented in the 1 kW battery prototype, that relies on the electrochemistry of naturally abundant, inexpensive, small organic (carbon-based) molecules called quinones. In addition, it targeted development of an innovative Microgrid Management Platform to optimise the use of the AQDS (Anthraquinone disulfonic acid) flow battery, able to monitor microgrid components (loads, energy sources, storage) and to continuously perform a multi-objective optimisation of the energy flows between them and the Power Distribution Grid whose requests will be taken into account by dynamically adhering to Demand Response programs.

The GREENERNET project has fully achieved its objectives:

- optimise the performances of the system's components;
- reduce technology overall costs;
- realise a scalable technology platform.

The project has made an impact in seven key stakeholder fields, namely 1) education/research; 2) commercial; 3) investment; 4) social; 5) environmental; 6) policy making; 7) standard and regulation. In terms of knowledge sharing, the GREENERNET project has disseminated its activities at worldwide, European and national level, including professional stakeholders, policy-makers and public bodies and general public. Project web-site, brochure, leaflet, press-releases and social networks were used as tools for knowledge dissemination.

GLOBE – All organic redox flow batteries[242,243]

The project was funded via H2020-MSCA-IF-2014 call (Type of action: MSCA-IF-EF-ST) with a duration of 24 months (start date 01/09/2015; end date 31/08/2017). Budget: €0.2 million. For detailed analysis please refer to Table 22 in the Annex.

The GLOBE project aimed to provide a low-cost solution for electrical energy storage (EES), based on organic redox active species for both redox flow and solid-state batteries.

The overall project objectives have been met. The research developed a new method to improve the cell potential of organic redox flow batteries with pH dependent redox potential. As result a semi organic redox flow battery was developed and directly fully charged using solar energy and the home-made semiconductor. Overall, a sound knowledge has been gathered on organic redox active species and their application in redox flow, solid-state and directly solar charged redox flow batteries.

The outcomes of the project is promising as it expected to have both social and economic future impact. The project results are expected to promote innovation in the field of organic redox flow and solid-state batteries, given the developed new types of species. Several collaborations have been set up. Dissemination has been adequately performed through publications as well as participation in international conferences and meetings. Training and transfer of knowledge objectives have been adequately pursued.

By sharing the new insights publicly and by using the current knowledge to establish foundations for a new type of semi organic redox flow battery, there are considerable chances to explore commercial applications within short terms. The results are expected to strengthen the global competitiveness of the European electrical energy storage industry.

Though no direct impact on the SME's are evident from the project, the SMEs could play an important role in a future commercialisation if the redox flow battery model is further developed.

EnergyKeeper – Keep the Energy at the right place![244,245]

The project was funded via H2020-LCE-01-2016 (Type of action: RI) with a duration of 36 months (start date 01/01/2017; end date 31/12/2019). Budget: €4 million. For detailed analysis please refer to Table 23 in the Annex.

The project is to provide a new battery-based energy storage system which should enhance innovation capacity, create new market opportunities, strengthen competitiveness and growth of companies, and address issues related to climate change.

In particular, the EnergyKeeper project aimed to design, develop and test a novel, scalable, sustainable and cost competitive battery based on organic reduction–oxidation (redox) active materials, equipped with an interoperable battery management system enabling plug-and-play integration into a smart grid. Communications architecture, grid control and demand side management systems are designed and demonstrated to show the added value of using energy storage systems to provide ancillary services to the distribution grid. The main expected impact is an enlarged energy storage technology portfolio for stationary applications enabling integration of large capacities of variable renewable generation into the electrical grid of the EU, provision of services to the distribution grid and the consumer at affordable cost and deferral of investments in grid reinforcements.

The work carried may have an impact on SMEs in the future especially given that 3 SMEs are partners in the consortium.

The EnergyKeeper project has been recently finalised and has fully achieved its objectives of installing the world's first metal-free redox flow battery in an interoperable smart grid in the Netherlands. Although the project ended half a year ago, the work continues. JenaBatteries has made great progress to further advance the flow battery technology. The installation of a new test system is progressing rapidly. This is an important milestone on the way to mass production.

Ongoing Projects

MFreeB – Membrane-Free Redox Flow Batteries[246]

This project was funded via the call ERC-2016-COG with a duration of 60 months (start date 01/06/2017; end date 31/05/2022). Budget: €2 million.

The most unique objective of this project is to eliminate the membrane that causes multiple problems such as high investment and maintenance cost and poor battery performance; insufficient separation of electrolytes (crossover), high resistance (low power) and low durability. Moreover, the research proposes to substitute the metal redox pairs by organic redox molecules of different families including quinones and other aromatic compounds such as methoxybenzenes, phenothiazines, quinoxalines, nitroxides (TEMPO), and viologens.

FlowCamp – European Training Network to improve materials for high-performance, low-cost next-generation redox-flow batteries[247,248]

This project was funded via the call H2020-MSCA-ITN-2017 with a duration of 48 months (start date 01/09/2017; end date 31/08/2021). Budget: €3.8 million.

Research in FlowCamp aims to improve materials for high-performance, low-cost next-generation redox-flow batteries, including organic RFBs.

Expected impact: In its SET-Plan the EU Commission seeks to improve new storage technologies and bring down costs by applying a coordinated strategy to the national research efforts. Therefore cross-national research teams have more impact on complex and highly interdisciplinary research topics like energy storage than national initiatives. Within the Flow Camp project the exchange of ideas on flow battery storage has already led to new project ideas. All partners have reported that FlowCamp has attracted interest within the RFB community, and led to enquiries by further institutions that wish to participate or contribute. The updated Horizon 2020 program on energy storage allows some opportunities to strengthen these already tight bonds.

SONAR – Modelling for the search for new active materials for redox flow batteries[249]

This project was funded via the call LC-BAT-4-2019 with a duration of 48 months (start date 01/01/2020; end date 31/12/2023). Budget: €2.8 million.

SONAR will develop a framework for the simulation-based screening of electroactive materials for aqueous and nonaqueous organic redox flow batteries (RFBs). It will adopt a multiscale modelling paradigm, in which simulation methods at different physical scales will be further advanced and linked by combining physics- and data-based modelling. SONAR will develop a screening framework to determine levelised cost of storage, starting from the automatic generation of candidate structures for the electroactive material, then iterating through molecular-, electrochemical interface-, porous electrodes-, cell-, stack-, system- and techno-economic-level models. To increase the throughput of the screening, SONAR will exploit advanced data integration, analysis and machine-learning techniques, drawing on the growing amount of data produced during the project. Project results are expected to reduce the cost and time-to-market of redox flow batteries, thus strengthening the competitiveness of the EU battery industry.

The project is addressing the following specific challenges:

- cost;
- use of abundant, safe and environmentally friendly active materials;
- protic and aprotic systems;
- modelling, simulation and high-throughput screening;
- experimental validation.

CompBat – Computer aided design for next generation flow batteries[250]

This project was funded via the call LC-BAT-3-2019 with a duration of 36 months (start date 01/02/2020; end date 31/01/2023). Budget: €1.8 million.

CompBat aims to take flow batteries to the next level, identifying new prospective molecules for their chemical composition. Tools will be developed to this end, using machine learning paired with a high-throughput screening method to enable large-scale automated testing. Targeted molecules are bio-inspired organic compounds, as well as derivatives of a specialty bulk-manufactured chemical. Sophisticated calculations will be deployed to obtain data on molecules and their properties. Based on the results, The EU-funded CompBat project will perform modelling of flow battery systems to allow for predictions on performance, and a cost estimation approach will be applied. Furthermore, the team will examine the possibility of using solid boosters to enhance battery capacity.

BALIHT – Development of full lignin based organic redox flow battery suitable to work in warm environments and heavy multicycle uses[251]

This project was funded via the call H2020- LC-BAT-4-2019 (Advanced Redox Flow Batteries for stationary energy storage) with a duration of 36 month (start date 01/12/2019; end date 30/11/2022). Budget: €4.1 million.

BALIHT project aimed to develop a new organic redox flow battery suitable to work up to temperatures of 80 ºC, that has a self-life similar (or even better) than current organic ones, but with an energy efficiency 20% higher than current RFB due to cooling system is not required, need less pump energy & has a high power. Such new concept of organic RFB would make this technology suitable for applications where the requirements are more challenging like: smoothing of non-dispatchable renewable power plants (like solar or wind), support for ancillary services, high performance electric car recharge points, improvement of grid flexibility and stability (at both transmission and distribution level), avoid cooling needs in RFB placed in warm countries (between 40 º Latitude North & 40 º Latitude South).

The BALIHT project is totally aligned with Integrated SET-Plan Action 7 where Batteries are a key enabling technology for e-mobility and stationary energy storage applications. Energy storage solutions will require batteries that have higher performance (e.g. energy density), extended life, reduced costs, larger capacity and can be scaled-up to competitive manufacturing. For example, BALIHT proposed an advanced redox flow battery capable to work in warm or heavy cycles environment and it is fully recyclable (using thermoplastic, miscible materials, non-toxic electrolytes, easy to regenerate and suitable to generate heat or fertiliser at the end of the life). The work with less corrosive environment than in Vanadium batteries will permit to use cheap materials.

HIGREEW – Affordable high-performance green redox flow batteries[252]

This project was funded via the call LC-BAT-4-2019 (Advanced Redox Flow Batteries for stationary energy storage) with a duration of 40 month (start date 01/11/2019; end date 31/03/2023). Budget: €3.8 million.

The main objective of the HIGREEW project is to develop, demonstrate and validate a sustainable, low cost and safe advanced redox flow battery technology. The specific technical objectives and targeted key results are:

- to develop and optimise the aqueous organic electrolyte-membrane-electrode tandem;
- to design, build, test and validate efficient aqueous organic RFB cells and stacks;
- HIGREEW prototype engineering and validation in pilot facilities;
- demonstrate the use of aqueous organic RFB through the integration with renewable energy sources;
- ensure safety and sustainability of the HIGREEW technology;

HIGREEW overall methodology to bring the technology from TRL 3 to TRL 5 focuses on the materials that mainly influence redox battery performance (electrolyte, membrane and electrode) with different strategies for their optimisation.

Project results should contribute to reach the targets set in the SET Plan, putting the energy storage cost on the path to fall below 0.05 €/kWh/cycle by 2030.

4.5 Cross-cutting projects relevant to several considered battery technologies

In this analysis we review projects potentially relevant to several battery technologies considered in this report and also to other fields, not limited to batteries or energy storage: NanoBAT,[253] FUN POLYSTORE,[254] ReSuNiCo,[255] eJUMP,[256] ARPEMA,[257] ATMCinsituNMR,[258] B-PhosphoChem.[259] The information relevant to the projects (e.g. deliverables, summary reports) has been gathered via Compass tool.

NanoBAT – GHz nanoscale electrical and dielectric measurements of the solid-electrolyte interphase and applications in the battery manufacturing line[253]

NanoBAT is a project funded via the H2020-NMBP-TO-IND-2018-2020 call (Real time nano-characterisation technologies) with duration of 36 months (start date 01/04/2020; end date 31/03/2023) and a €5.0 million budget.

NanoBAT aims at establishing an RF-nanotechnology toolbox for Li-ion batteries and beyond lithium batteries. The specific focus is on the nanoscale structure of the 10-50 nm thick SEI (solid electrolyte interphase) layer, which is of pivotal importance for battery performance and safety, but which is difficult to characterize and optimize with currently available techniques. The toolbox contains new nanoscale high-frequency GHz methods that are ultra-fast and capable of testing and quantifying the relevant electrical processes at the SEI, several orders of magnitude better than currently available techniques. Nanoscale imaging of the SEI electrical conductivity at high GHz frequencies will be done for the first time, and impedance changes are measured during electrochemical processes, supported by advanced modelling and simulation techniques. Several methods are tested in pilot-lines, including advanced electrochemical impedance spectroscopy and a newly developed self-discharge method that shortens the electrical formation process in battery production from 2 weeks to 10 min. Finally, the new methods will be used for high-throughput incoming quality control in the battery module production at our automotive end users, where 30.000 cells will be tested per day. In summary, we develop a solid basis of GHz-nanotech instrumentation to improve cell production and testing, resulting in major advantages for manufacturers and customers, for instance reduced waste and energy consumption, and longer lasting batteries that are safer with 90% improved thermal runaway.

FUN POLYSTORE – FUNctionalized POLYmer electrolytes for energy STORagE[254]

FUN POLYSTORE a project funded via the ERC-2017-COG (European Research Council (ERC) Consolidator Grant 2017) with a duration of 60 months (start date 01/09/2018; end date 31/08/2023) and a budget of €2.0 million.

The conventional liquid battery electrolytes pose a problem already for the mature Li-ion chemistries due to safety and cost, but are particularly destructive for future battery types such as Li-metal, organic electrodes, Li-S, Li-O_2, Na- or Mg-batteries, where rapid degradation and loss of material are associated with incompatibilities with the electrolytes. In this context, solid state polymer electrolytes (SPEs) could provide a considerable improvement.

This application regards moving out of the established poly(ethylene oxide)-paradigm and exploring alternative polymer hosts for SPEs, primarily polycarbonates and polyesters. These ‘alternative’ polymers are comparatively easy to work with synthetically, and their possible functionalization is straightforward. The work aims at exploring functionalized alternative polymer host for mechanically robust block-copolymer systems, for alternative cation chemistries (Na, Mg, etc.), for extremely high and low electrochemical potentials, and for unstable and easily dissolved electrode materials (sulfur, organic).

Moreover, since the ion transport processes in the host materials are fundamentally different from polyethers, there is a need for investigating the conduction mechanisms using simulations.

ReSuNiCo – Inverted Reactive Spray Processes for Sulphide/Nitride High Surface Area Electrode Coatings[255]

ReSuNiCo a project funded via the ERC-2017-ADG (European Research Council (ERC) Advanced Grant 2017) with a duration of 60 months (start date 01/01/2019; end date 31/12/2023) and a budget of €2.4 million.

Highly pure, binary and ternary metal sulphides/nitrides are increasingly important materials for energy storage, electrocatalysis, optoelectronics and battery materials. To fully use their potential, radical new technologies that allow the synthesis of complex, and multicomponent crystalline materials with specific size and morphology are required. While the reactive spray technology is already a key element for the scalable and economic synthesis of metal oxides, ReSuNiCo project will fundamentally advance the strength of the reactive spray processes by generating a knowledge-base for sulphide/nitride materials.

Reactive spray systems with a fast, safe, versatile, time and resource-efficient high throughput single droplet combustion screening that identifies complete new reaction schemes and processes will be developed. The method is highly flexible and adaptable to a large variety of reactive liquids and gas atmospheres that readily comply with the safety requirements via small volumes, small liquid streams and gas flows.

An in-situ process diagnostics in order to identify droplet reactions, particle formation pathways and product characteristics will be established. Acquired knowledge will be used to build standard and inverted (fuels and sulfidizers/nitridizers are exchanged in the reactive spray) lab-scale reactors that serve as demonstrators to transfer the first material samples into performance evaluations in specific applications.

The objectives and work packages of ReSuNiCo reach far beyond the state of the art materials synthesis exploration and call for new process innovations in reactive spraying technologies, aerosol and gas phase characterizations, process model formulations and particle synthesis.

eJUMP – Organic Ionic Plastic Crystal Nanocomposites for Safer Batteries[256]

eJUMP is an individual fellowship funded via the H2020-MSCA-IF-2017 call (Marie Skłodowska-Curie Individual Fellowships) with a duration of 36 months (start date 01/01/2019, end date 31/12/2021) and a €0.25 million budget.

The eJUMP Global Fellowship aims to develop innovative nanocomposite electrolytes based on Organic Ionic Plastic Crystals (OICPs) – a novel class of solid state electrolytes with intrinsic safety and high ionic conductivity. The eJUMP approach is to prepare composites materials from OIPCs and polymer nanoparticles – which can act both as reinforcement but also add function via a purposely designed nanoparticle interfaces. The knowledge generated by eJUMP will help to establish specific design criteria for the fabrication of this new class of solid electrolytes.

ARC Centre of Excellence in Electromaterials Science (Deakin University, Australia) will host the assignee during the outgoing phase. The incoming phase will take place at POLYMAT (University of the Basque Country, Spain) at the Innovative Polymer Group.

ARPEMA – Anionic redox processes: A transformational approach for advanced energy materials[257] – was funded via the call H2020-ERC-2014-ADG (Advanced Grant), ARPEMA is a Frontier Research Grant type of project with a duration of 60 months (start date 01/10/2015; end date 30/09/2020) and a €2.25 million budget. For details please see Table 24 in the Annex.

The project is focused on investigating layered oxide systems based on Ni, Mn and Co with excess of Li; so called Li-rich NMC, e.g. $Li[Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13}]O_2$.[260,261] Their extraordinary high capacity was explained as due to cumulative cationic ($M^{n+} \leftrightarrow M^{n+1}$) and anionic ($2O^{2-} \leftrightarrow (O_2)^{n-}$) reversible redox processes. Some evidence of similar anionic redox process in Na-based compounds suggests that this approach could be equally attractive for designing high capacity Na-based insertion materials.[262]

The project has published 18 articles in scientific journals. The APREMA is a single host project – lead and executed by College de France.

ATMCinsituNMR – Next level real-time characterisation of Li- and Na-ion batteries by – Automatic Tuning Matching Cycler (plus Goniometer) – ATMC(+G) *in situ* NMR[258] – was funded via the call H2020-MSCA-IF-2014 (Marie Skłodowska-Curie Individual Fellowships, IF-EF), ATMCinsituNMR is a Nurturing excellence by means of cross-border and cross-sector mobility type of project with a duration of 24 months (start date 01/03/2015; end date 28/02/2017) and a €0.18 million budget. For details please see Table 25 in the Annex.

The project was focused on developing an *in situ* NMR spectroscopy technique for non-invasive real-time studies of batteries under operating conditions – to track the formation of intermediate phases and investigate electrolyte decomposition during cycling of Li-ion batteries and Na-ion batteries. This task was successfully completed including development of ATMC in situ NMR, of an external automatic tuning/matching (eATM) ROBOT and a plastic cell capsule allowing not only for performing the measurements, but also for automatising reducing the time of investigations.[263] The hardware developments have been made available to the researchers via an industry partner.

ATMC in situ NMR was applied to LFP, NFP, and NVPOF cathodes giving insights into structural changes of these materials during cycling.[264] The same technique was also used to investigate Na-metal anode reactions to monitor formation of a range of Na-metal species as well as to quantify the electrolyte consumption.

The ATMC in situ NMR was used to study the intercalation of Na-ions into hard carbon anodes. It was reported that "capacity results from ''diamagnetic'' sodium ions first adsorbing onto pore surfaces, defects and between expanded layers, before pooling into larger quasi-metallic clusters/expanded carbon sheets at lower voltages".[265]

The project has explained alluaudite sodium iron sulfate $Na_{2+2x}Fe_{2-x}(SO_4)_3$ intercalation reaction mechanism.[266] The single-phase, solid-solution reaction occurs involving an irreversible rearrangement reaction during the first charging (the Na extraction from the Na1 site is accompanied by Fe migration from the Fe1 to Na1 site) followed by reversible processes at later discharging and charging steps, resulting in minor, 3.5% volume change. Sodium extraction occurs sequentially, at Na3, followed by Na1 and then Na2 sites during the initial charging. During subsequent discharging, sodium insertion occurs at Na2, Na3, and Na/Fe1 sites and is reversible in subsequent cycles. This mechanism is similar to that of $Li_2FeP_2O_7$ and $Na_4Fe_3(PO_4)_2P_2O_7$. The studied material is a promising candidate for a Na-ion cathode, composed of earth-abundant elements, with high redox potential of Fe^{3+}/Fe^{2+} reaction (3.8 V vs. Na/Na^+), good cycle performance, and high rate capability.

The project has published 8 articles in scientific journals. The ATMCinsituNMR is a single host project – lead and executed by the University of Cambridge.

B-PhosphoChem – Exploration of the 2D-Chemistry of Black Phosphorous[259] – was funded via the call H2020-ERC-2016-ADG (Advanced Grant) and is a project with a duration of 60 months (start date 01/08/2017; end date 31/07/2022) and a €2.49 million budget. For details please refer to Table 26 in the Annex.

The project is focused on investigating the chemistry of black phosphorus (BP) and its derivatives, such as intercalation compounds of BP for instance. Among them, the BP intercalation compounds with Li and Na are of interest for battery applications. The theoretical calculations show 2596 mAh/g theoretical capacity for Li_3P and slightly less for Na_3P.[267] The practically realised P/C nanocomposite Na-ion anode – however obtained from amorphous phosphorus – had exhibited 1,765 mAh/g capacity, good capacity retention after 100 cycles, and high power capabilities.[268]

The project has synthesised a BP Na intercalation compounds at different Na:P ratios and characterised using a combination of in situ X-ray diffraction, Raman spectroscopy, and

DFT calculations.[269] The structural behaviour of the compound at different intercalation stages has been demonstrated for the first time. The synthesis was performed both, in bulk by solid-state reaction, as well as vapour-solid phase reaction. The project results give insight into the new family of intercalation compounds, with a distinct behaviour if compared to its graphite analogues, showing a remarkable structural complexity and dynamic behaviour, but demonstrating also a tenability of its properties, e.g. direct band gap ranging from about 0.3 eV for bulk to approximately 2 eV for monolayers.

The project has published 8 articles in scientific journals. The B-PhosphoChem is a single host project – lead and executed by Friedrich-Alexander-Universitaet Erlangen Nuernberg.

5 Technology development outlook

Battery storage of electricity can play an important role facilitating full decarbonisation of the European energy system by 2050 as targeted by the European Green Deal.[1]

Depending on the exact decarbonisation approach and the corresponding 2018 LTS scenario, stationary battery storage is expected to grow from around 4 GWh globally in 2018 to ca. 144 GWh in the EU in 2030 and between 270 GWh and 890 GWh in the EU in 2050.[§,3] These projections are supported by the findings of the JRC-EU-TIMES dedicated SET-Plan scenario, where the EU's stationary battery storage is predicted to amount to 150 GWh in 2030 and to grow further to 300 GWh in 2040 and 800 GWh in 2050.[270,271]

Transport electrification will continue to be the main driver behind the battery deployment. According to the JRC's SET-Plan scenario, the EV fleet battery storage capacity is expected to reach 1800 GWh in 2030 corresponding to a 10 times increase compared to ca. 180 GWh in 2020,[7] 4000 GWh in 2040 and 6800 GWh in 2050.[270,271] However, only a part of this capacity will potentially be contributing to the power system balancing.

Facing this explosive growth of demand for battery storage capacity, novel battery chemistries, such as the ones considered in the present study, have a high deployment potential in both the transport electrification and stationary energy storage sectors.

5.1 All Solid State Batteries with Li-metal anodes

It is commonly agreed that a noticeable market uptake of the ASSB LiM cannot be expected before 2030,[17,272] especially in applications with a large GHG emissions reduction potential such as electrification of transport and stationary energy storage to aid an inherently intermittent generation of renewable power.

According to Faraday Institution solid state batteries are likely to take a 7% share of the global battery market for consumer electronics and a 4% share of the global EV battery market, with total demand volume in both segments of less than ca. 70 GWh in 2030.[272] The demand for ASSB in the EV market is expected to grow significantly to ca. 1600 GWh in 2040.[272] According IDTechEX demand for ASSB will grow significantly faster and reach 250 GWh by 2029; transport electrification will be the main driver behind this quickly growing demand for ASSB.

Many large Li-ion battery cell manufacturers such as CATL (CN), BYD (CN), Samsung SDI (KR), Panasonic (JP), Toshiba (JP), SAFT (FR) are currently working on ASSB LiM technology. Also automotive OEMs, e.g. Toyota (JP), BMW (DE), Volkswagen (DE), Hyundai (KR), BYD (CN), Enovate Motors (CN), either have their own in-house R&D programmes on ASSB LiM or partner with materials and cell developing companies (please see below for details). A number of (start-up) companies have been making significant steps towards commercialisation of this battery technology, a list of most significant players is given below.

<u>(Start-up) companies working on ASSB LiM</u>

<u>Solid Power</u> (USA) was founded in 2012. The company uses market-available cathode materials, in combination with a lithium-metal anode and a solid electrolyte made up of lithium, sulfur, and phosphorus. The main innovation behind Solid Power's technology is its solid-state electrolyte/separator, based on the sulfur chemistry. This can be processed through standard roll-to-roll, slurry-based techniques. As of September 2018, Solid Power is scaling up its pilot production facility. Since 2017 the start-up has a partnership with BMW to develop and test its technology.

§ Estimate based on the electricity storage capacities for 2050 reported in [3] and assuming a 5 hours usage. Please note that scenarios considered in [3] aim at 80-100% reduction of GHG emissions by 2050, while the European Green Deal aims at achieving no net emissions of GHG in 2050. As a consequence, mentioned battery storage capacities may be lower than the newly set target requires.

QuantumScape (USA) was founded in 2012. In terms of all-solid-state battery regime, QuantumScape is developing through two technical directions. One is on sulfide-based material "LGPS" jointly developed by Tokyo Institute of Technology and Toyota. Another is on garnet-type oxide inorganic electrolyte LLZO. Volkswagen has acquired 5% stake in QuantumScape in 2015 and invested USD 100 million in 2018.

Ionic Materials (USA) have developed a polymer-based solid electrolyte, whose ion conduction mechanism does not require polymer chain mobility (contrary to, for example, PEO) and with room conductivity claimed as high as 9 mS/cm.[273] ASSB LiM cell development takes place in collaboration with Toyota, targeting 5 mA/cm^2 anode footprint current density.

Solid Energy (USA) was founded in 2012. Its cells have a very thin lithium metal anode coated with a very thin protective coating. The electrolyte is a combination of two layers: a solid electrolyte consisting of a polymer, inorganic material and fibers coated on the anode, and a high efficiency quasi-ionic liquid (IL) electrolyte in contact with the cathode. The company uses a conventional NMC cathode. First markets where cycle life is not of prime importance are targeted, like aeronautics, space, drones and wearables. Nevertheless, company plans to supply ASSB LiM also for the EV market at a later stage and has a partnership with General Motors. 450 Wh/kg and 1200 Wh/l were achieved at cell level in 2018.

Seeo (USA) was founded in 2007. Block co-polymer-based ASSB LiM cells used coated NCA or LFP as cathode and lithium metal anode. Energy density of 220 Wh/kg was achieved in 2017. Acquired by Bosch in 2015, but after relinquishing all efforts in manufacturing of batteries Bosch stepped out of this partnership. Company closed down in 2019.

Sakti3 (USA) was founded in 2007 and was developing a LiPON-based electrolyte ASSB LiM. Sakti3 was acquired by Dyson in 2015, but the partnership was abandoned in 2017.

ProLogium (Taiwan): ProLogium has been working on inorganic lithium ceramic solid-state-electrolyte based batteries (possibly oxide-based system). Current energy density at cell level reached 535 Wh/L (255 Wh/kg) and the target figure is about 650 Wh/L. Roll to roll manufacturing is available with 50 MWh production capability and in 2020 Q3, 2 GWh production line is expected to be ready. Targeted markets are: wearable devices, smart belts, smart watches, smart helmets, consumer electronics such as power jackets of smartphones, e-books, tablet keyboards and cover IoT like smart cards, etc. and EV as well.

Polyplus (USA) works on a cell concept that incorporates a novel solid-state electrolyte made up of a thin (20-50 µm) Li-rich glass membrane, NMC or NCA cathode, and a thin Li metal (10-30 µm) anode. Targeted energy density is 500 Wh/kg, 1700 Wh/l with NMC cathode.

Sion Power (USA): have historically been developing Li-S battery technology (please see below), and in 2015 decided to include ASSB LiM into their portfolio. In January 2020 Sion Power announced that a ASSB LiM cell with 500 Wh/kg and 1000 Wh/l has successfully been developed.[274] Ultra-thin Li metal anode is protected by a ceramic/polymer layer and is in contact with a “thin separator moistened with electrolyte to allow ionic conductivity while preventing short circuits”.[274] Conventional lithium metal oxide is used as active cathode material.

Hydro-Québec (CA)[275] has pioneered in the LiM polymer technology since 1979 and it was the first company who brought the LiM dry polymer rechargeable battery to commercialisation, thereby acquiring extensive knowledge on manufacturing and handling of LiM anodes. This technology was transferred and licensed to Bolloré (FR) and now is installed in the EV-Bluecar.

SCE-France, a subsidiary of Hydro-Québec, has set up a laboratory dedicated to research and technology transfer in the Aquitaine region in France to carry out research on new battery technologies that use advanced materials.[276] Up to now Hydro-Québec has no equivalence in Europe in terms of know-how and expertise on LiM anodes.

5.2 Lithium-Sulfur Batteries

Li-S battery technology is still some way from being fully commercialised for applications including battery electric vehicles and plug in hybrids.

Commercial opportunities are forecasted to achieve sales around USD 100 billion per annum by 2025 and an expected uptake around 2025-2030.[277] The global Li-S battery market is expected to grow at a CAGR of 71.06% during 2019-2022 (as forecasted by Technavio).[278]

However, more work and research is needed to fully understand Li-S chemistry in order to overcome technical challenges still need to be addressed if commercialisation is to be achieved.

Cell cost. If the scale of production reaches a considerable number, the cost per unit is expected to be lower than current cell cost (as sulfur is widely available and inexpensive compared to the cathode materials required for the Li-ion chemistries). It has been assumed that a cell cost lower than USD 100 per kWh can be reached.[55]

Regarding the industrial interest, only a couple of companies are at commercialisation stage on this technology: OXIS Energy and Sion;[279] however the door is open to more: LG Chem (in partnership with Sion), Sony[280], with Polyplus[281] in the frontrun. A summary of these companies and their spectrum of solutions is presented below. This list is not exhaustive, as there are other companies that have some in-house R&D either at component level (e.g. cathode, anode, electrolyte) or at full cell / prototyping level, such as Eaglepicher Technologies LLC,[282] NOHMs,[283] Lithops,[284] Blue Solutions,[285] Vorbeck Materials,[286] PATHION,[287] but have not made it yet to commercial products.

OXIS Energy:
Established in 2004 to develop, manufacture and commercialise Li-S pouch cells. Headquarters and research & development centre near Oxford, cathode and electrolyte manufacture facility in Wales, international test centre in Abingdon (UK). Currently establishing new facilities in UK and setting up a manufacturing cell facility in Brazil.[288] Plans for a phase I with 1-2 million cells /annum and a phase II with 5 million cells /annum.

One main technological advantage of Oxis is that they develop their own cell components: anode, cathode and electrolyte, plus battery management systems for integration, making them dominant in the market.

Commercial products: pouch type (both high energy cells and high power cells); up to 50 Ah; 400-500 Wh/kg; 1,500 cycles.

Patent portfolio: 110 patents granted, 77 patents pending.

Number of employees: 80 employees in 2019.

Sion Power:

US based company, spin-off from Brookhaven National Laboratory in 1989; was one of the leading companies in lithium-sulfur technology (powered the Airbus Zephyr aircraft). Since 2019 they shifted focus to Lithium metal technology - high-energy NCM (Ni-rich), commercialising Licerion® lithium metal rechargeable battery cells and packs (modular approach). UN 38.3 certification was achieved.

The knowledge gained on lithium metal protection in their Li-S batteries research was very valuable in their transition to ASSB LiM rechargeable technology (please see above).

The company announced November 2018 the construction of a new test facility (>3,000 cell test channels, abuse room with safety test equipment, and an altitude chamber).[289]

Commercial products: pouch type; 20 Ah; 500 Wh/kg and 1000 Wh/l, >450 cycles

Patent portfolio: 197 patents granted, 86 patents pending.

Number of employees: 60 employees

Polyplus Battery:

PolyPlus was founded early 1990s upon the invention of the lithium/organosulfur battery at Lawrence Berkeley National Laboratory.

The company claims that nearly all Li-S batteries sold use their proprietary non-aqueous electrolyte developed and patented in the 1990s. PolyPlus also developed inexpensive water-based Li-S chemistry, greatly improving the capacity and cycle life of sulfur electrodes in the process.

Commercial products: not yet achieved commercialisation stage. They state that they will likely work with a partner and/or license the technology.

Patent portfolio: 42 patents granted, 2 patents pending Number of employees: 18 employees

LG Chem:

LG Chem and Sion Power announced partnership back in 2016, however no recent evolution on this has been found.

Commercial products: not yet achieved commercialisation stage

LG Chem is the company with the strongest patent portfolio worldwide.

Patent portfolio: 143 patents granted, 353 patents pending

Sony:

Sony announced targets for their Lithium Sulfur Battery back in 2016 with plans for commercialisation by 2020.[280] Up to the time of writing this report no concrete evolution on this has been made public.

Commercial products: not yet achieved commercialisation stage

5.3 Sodium-ion Batteries

The Na-ion battery technology has a potential to develop in multiple directions, covering a wide range of applications. However, it is mostly seen in applications compatible with lower energy density ESSs (e.g. as a potential successor of lead-acid batteries). This technology is capable providing enhanced performance (up to 5-fold higher energy density respective to lead-acid batteries, better efficiency, safety, cycling stability and faster charging/discharging rate) at comparable cost. Such application could be stationary energy storage systems, like grid services, renewables integration, domestic energy storage, smart grids, telecom applications etc., but also less demanding automotive applications like starting, lighting, and ignition (SLI) batteries, traction batteries for low speed electric vehicles, e-bikes, e-scooters, e-busses where lower cost would be an asset. Also, power tools sector could be of interest for Na-ion technology.

It is of lower probability that Na-ion batteries will be seen in applications requiring high energy density batteries like long-range electric vehicles or consumer electronics; however, those applications cannot be excluded provided significant development of the technology.

Table 8. Basic comparison of Na-ion batteries with lead-acid and Li-ion battery technologies.

Parameter	Na-ion	Li-ion	lead-acid
Cost	+	-	+
Energy density	+/-	+	-
Safety	+	-	+/-
Materials	+	- (scarce)	- (toxic)

Parameter	Na-ion	Li-ion	lead-acid
Cycling stability	+	+	+/- (self-discharge)
Efficiency	>90%	>90%	<75%
Temperature range	-40°C to 60°C	-25°C to 40°C	-40°C to 60°C
Other	infant technology, development likely easy transportation	mature technology, development likely at significant cost transportation safety issues	mature technology, development limited fast charge limitations environmental concerns

In last years, renaissance of research interest in Na-ion batteries is observed. This trend is driven by concerns regarding availability of Li, Co, Ni and thus their future costs (driving costs of main alternative, the Li-ion technology). In contrast, Na is the sixth most abundant element of Earth crust and can be extracted from seawater, which removes risks related to limited resources or geopolitical supply issues. Due to such supply characteristics the consensus is that the cost of Na-ion batteries will always remain low, provided that cathode and anode materials will base on cheap, abundant materials.

Moreover, the electrochemical window of operation of Na-ion batteries allows to use Al for both, anode and cathode current collectors, substituting in this way Cu otherwise used as anode current collector in Li-ion batteries, contributing to costs reduction and increasing energy density.

Na-ion technology in principle uses the same technology of manufacturing; hence, there is a significant synergy with current Li-ion production technology. This implies a little or no additional cost if an existing Li-ion battery manufacturer is to switch to Na-ion technology.

Na-ion batteries are not expected to exhibit the same high energy density as Li-ion batteries. This rationale is supported by higher molecular weight of Na (23 g/mol vs. 6.9 g/mol for Li) and a higher standard electrode potential of Na/Na^+ redox couple (-2.71 V vs. standard hydrogen electrode SHE and respectively to -3.02 V for Li/Li^+). However, for Metal-ion batteries the weight fraction of Na or Li is rather small, electrodes electrochemical capacity depends on active materials capabilities to host the relevant metal and electrode potentials are related to actual compound working potentials rather than to potential of pure M/M^+ couple. Replacement of Cu current collector with the Al one promotes Na-ion batteries. Indeed, the electrical performance of developed prototypes places them only just a bit behind the state-of-the-art Li-ion cells.

With reference to lead-acid batteries the energy density of Na-ion batteries is 1 - 5 times higher, depending on actual chemistry used.

Contrary to Li-ion batteries, the Na-ion technology using Al anode current collector do not suffer from too low battery voltage. It was demonstrated that keeping Na-ion cell shorted (at 0 V) over prolonged time periods does not hamper its cycle life at all.[290] This feature clearly favours the Na-ion batteries over the Li-ion for transportation and storage of the cells, which can be done at fully discharged state. (Generally, the higher SOC of the metal-ion cell, the lower is its stability and the more risky, and thus costly its transport.)

Moreover, Na-ion batteries may use electrolyte containing a higher fraction of more thermally stable propylene carbonate as opposed to Li-ion batteries using electrolyte richer in highly flammable diethyl carbonate and/or dimethyl carbonate. This feature also improves safety of Na-ion technology.

Presently there are few companies worldwide developing commercial Na-ion batteries for some niche applications:

Faradion Limited:[291] Founded in 2011 in UK is an owner of >20 patent families (2019) covering a range of materials, technologies and system designs. Its main product uses high energy density oxide cathode with hard carbon anode and liquid electrolyte. Its pouch cells have demonstrated 140 – 150 Wh/kg at cell level with good rate performance up to 3 C and cycle life 300 (100% DoD) to 1,000 (80% DoD).[88] It demonstrated viability of its solution for e-bike and e-scooter applications. Faradion also patented a concept of transport of Na-ion cells in a shorted state (at 0 V) eliminating risk during transport of cells.[290]

Tiamat:[292] Founded in 2017 in France is an owner of several patents from CNRS and CEA. It is a spin-off from CNRS and CEA, linked to RS2E network and NAIADES project. The Tiamat solution[293,294] is a 18650 cell based on polyanionic materials, with energy density 100 – 120 Wh/kg at cell level. The company targets fast charging applications for both mobility and stationary storage use. Durability of more than 4,000 cycles and rate capability of >80% retention for a 10 C rate have been recorded. With a nominal operating voltage of 3.7 V its cells are expected to find application in the developing power market. The company has demonstrated working prototypes of e-bikes, e-scooters, start & stop 12 V batteries and 48 V batteries.

Aquion Energy: in 2014 developed aqueous Na-ion battery and offered it at cost per kWh comparable to Pb-A chemistry for use in a back-up application of micro-grid.[295] According to the company the efficiency was 85%. The company went into bankruptcy in Mar 2017.

Novasis Energies Inc.: originated from University of Texas at Austin (prof. John B. Goodenough), further developed at the Sharp Laboratories of America. Based on PBAs as the cathode and hard carbon as the anode its battery delivered 100 – 130 Wh/kg with cyclic stability of 500 cycles and rate capability up to 10 C.

HiNa Battery Technology Co LTD:[296] A spin-off from the Institute of Physics, Chinese Academy of Sciences (IOP-CAS), established in 2017. Its batteries are based on Na-Fe-Mn-Cu oxide cathodes, anthracite carbon anode and can deliver 120 Wh/kg. In 2019 it was reported that HiNa installed a 30 kW/100 kWh Na-ion battery in East China.[297,298] This installation is intended to store off-peak electricity from the grid and partially cover the electricity demand from the building of Yangtze River Delta Physics Research Center during peak time or the power grid down time. The company has installed the lines for production of cathode and anode materials at ton-level and a NIB cell fabrication line with MWh production capacity. Its NIB pouch cells with a cycle life of 2,000 cycles have been developed and demonstrated in E-bike, mini electric vehicle and household energy storage system applications.

Natron Energy:[299] A spin-off from Stanford University, USA. The company uses PBAs for the cathode and an aqueous electrolyte. The company targets solutions for stationary applications: data-centre, UPS, electric forklifts, smart- and micro-grids, and support of renewable energy sources. Natron claims its batteries can "survive tens of thousands of deep discharge cycles, can be fully charged or discharged in just minutes, and cost significantly less than incumbent lead acid batteries". In June 2019 the company has been awarded a USD 3 million grant by the California Energy Commission (CEC) to develop manufacture and install "Advanced Energy Storage for Electric Vehicle Charging Support" which will utilise a high power, long cycle life energy storage system at an EV Fast Charging station.[300]

Altris AB:[301] A spin-off company from the Ångström Advanced Battery Centre with links to Uppsala University and EIT InnoEnergy. The company is selling Fennac®, an iron based Prussian blue analogue for the positive electrode in non-aqueous sodium ion batteries. Batteries containing Fennac® utilise hard carbon as the anode.

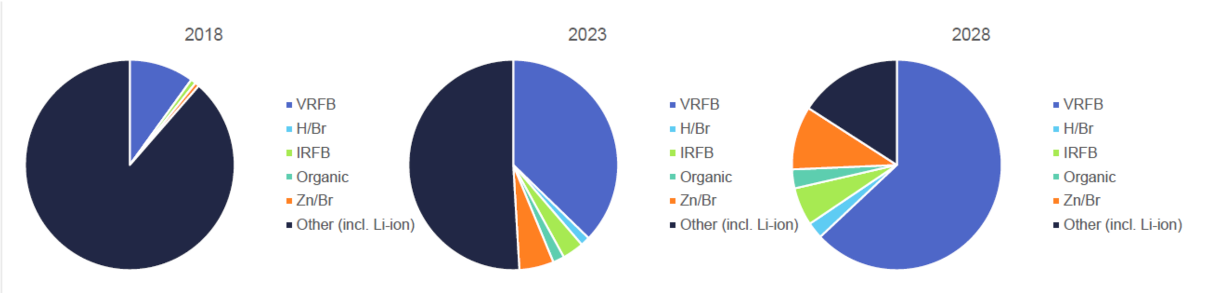
5.4 RedOx-Flow Batteries

Several RFB chemistries, such as vanadium (V/V), iron/chromium (Fe/Cr), sulfur/bromine (S/Br), zinc/bromine (Zn/Br), and zinc/chlorine (Zn/Cl) RFBs are already commercialised.

A number of RFB, such as hydrogen/bromine and quinone/bromide are still at R&D level, attracting a lots of research interest.

The flow battery technologies market is projected to rapidly increase until 2028 with Vanadium RedOx being the main RFB technology (Figure 7).

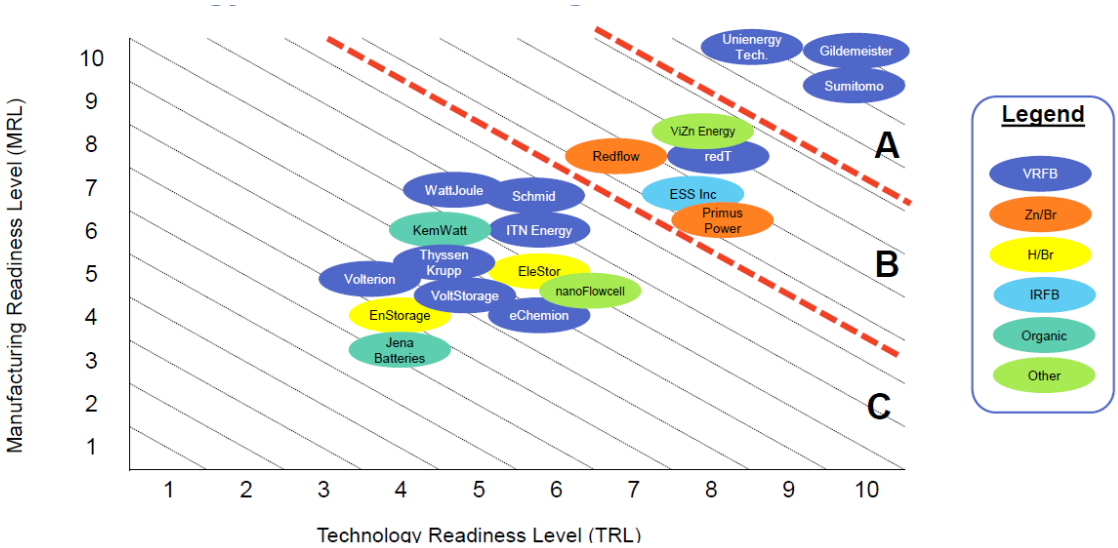
Figure 7. Battery technologies market shares until 2028. [Reproduced with permission from Ref. 302].



According to experts, over the coming years, Li-ion batteries for stationary storage (mostly Commercial & Industrial and grid markets) will be gradually replaced by RFBs. The residential market is expected to remain dominated by Li-ion, unless more RFB companies appear on the market. The market share of Vanadium RFB technology is steadily increasing over the period and represents the predominant battery type in 2028.

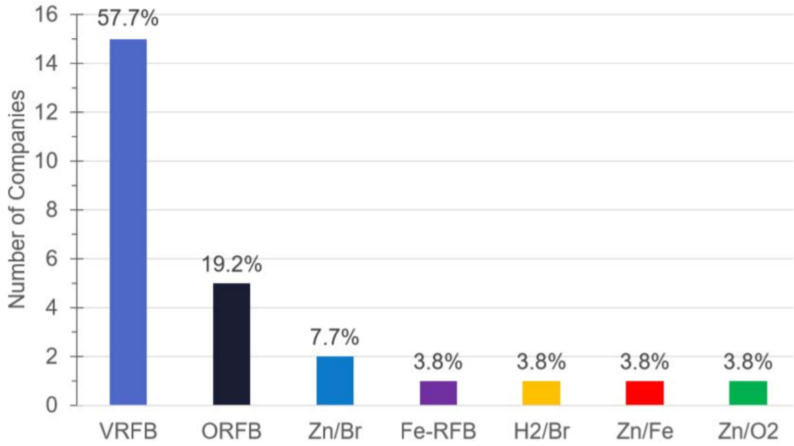
The share of organic flow batteries remains relatively small until 2028; the current TRL for organic batteries is 4 to 5, while the manufacturing readiness level (MRL) varies between 3 and 6 on the scale of 10 (Figure 8).

Figure 8. Technology and manufacturing readiness level of companies involved in flow batteries. [Reproduced with permission from Ref. 302].



The number of RFB companies on the market per type chemistry is shown in Figure 9. 16 companies are producing VRFB, which is the leader technology. Organic RFB accounts for almost 20% with 5 companies developing this technology.[303]

Figure 9. Number of RFB companies on the market per type chemistry. [Reproduced with permission from Ref. 303].



There are several European companies active on the market of organic flow batteries.

- **JenaBatteries GmbH**: German company working on polymer type batteries with aqueous electrolyte; the intention was to begin with large scale production in 2019. The foreseen applications are storage of solar energy, grid-scale energy storage, scalable batteries for stationary applications (from houses to industrial plants), load levelling and peak-shifting, emergency power supply. German utility EWE is partnering with the University of Jena (home to Jena Batteries GmbH) to incorporate an organic-based RFB inside some unused caves to turn them into electrolyte tanks for a massive organic RFB. The size of the project is not known yet, but EWE claims that the storage system could be large enough to "supply a major city such as Berlin with electricity for an hour".[303]
- **KemWatt**: French company developing organic molecules from the quinone family that undergo a redox reaction inside a flow battery. The molecules are dissolved in an aqueous alkaline solution. The company has developed a 10 kW prototype, as well as a 20 kW demonstrator – the plan was to be ready by 2017. These batteries can be connected in series or parallel up to MW scale. The company produces the stacks in-house, as well as batches of electrolytes. The company wants to address the off-grid market, particularly solar farms.
- **CMBlu**[304] is a pioneer and market leader in the field of organic flow batteries, which are used as energy storage systems in the power grid. In collaboration with leading university working groups and industrial partners, CMBlu develops the key technology for a sustainable energy transition and enables a comprehensive charging infrastructure for electric mobility. The company headquarters in Alzenau near Frankfurt am Main and employs 70 people. CMBlu is one of 100 solution providers worldwide selected for their particular potential for very large CO_2 savings. Organic energy storage of CMBlu is based on the vegetable raw material lignin, which is produced annually in the production of paper and cellulose in the million ton scale and is burnt so far due to a lack of alternative utilisation.

6 Conclusions

Recent major European effort to establish of a sustainable and competitive battery value chain in the EU have resulted in massive investments in R&D&I on batteries, including the advanced Li-ion, post Li-ion and non-Li-ion technologies considered in this report. As a result, many Horizon 2020 projects are still ongoing and are expected to deliver results in the near future; other projects are finalised and are analysed in detail in this report. A number of cross-cutting recommendations can be given that are applicable for all four battery technologies considered in this report:

1. Closer collaboration between R&D organisations, cell producers, pack and system integrators and recycling companies can deliver an essential contribution in meeting the sustainability and circularity goals, and also ensure a proper scale up of novel materials.
2. End of life disassembly of batteries and recycling of materials need to be taken into account already at a product design stage. This will help improve materials circularity and sustainability of the future generations of batteries, which are critical to the whole Green Deal approach.
3. Development of *in situ* and *in operando* research methods helping to gain a deeper insight into interfacial and other processes occurring in battery cells during cell operation, but also at various manufacturing stages, can aid in development of novel, improved batteries and corresponding manufacturing processes.
4. It is important to continue funding demonstration projects, aiming at faster transition from proof-of-concept to (semi-)commercial products. Here SMEs and start-ups can play an important role in gathering first hands-on experience and knowledge exploring many research routes. This approach is proven to be effective, e.g. in the US for the development of ASSB LiM.
5. Large-scale support in the form of R&D financing, production support and deployment actions should be focused on a few most promising and closest-to-the-market solutions to quickly reach market availability and meaningful market penetration.

Recommendations specific to a given considered battery technology are listed below.

Future research challenges for ASSB LiM

To quote the Faraday Institution, “ASSB LiM are the technology of the 2030s but the research challenge of the 2020s”.[272] This battery technology is seen as a direct successor of the contemporary Li-ion battery technology for many applications, including those with high GHG reduction potential such as transport electrification and stationary energy storage. A coordinated and well-supported R&D programme on ASSB LiM at the EU level can help further strengthen Europe’s position and reinforce the efforts in establishing a sustainable domestic battery value chain.

R&D needs to advance the ASSB LiM technology

1. Li metal anodes:
   a) Fabrication and handling of thin lithium metal layers (foils and/or Li deposits onto an anode current collector),
   b) Integration of (protected) Li metal anodes into ASSB LiM cells ensuring controlled anode/solid electrolyte interface,
   c) High lithium plating rates (C-rate for charging, anode footprint current density up to 10 mA/cm^2) without formation of dendrites.
2. Development of novel solid electrolyte materials meeting the following requirements:

a) Chemically and electrochemically stable in contact with Li metal and cathode materials in a broad range of operating temperatures and cell voltages,
b) Sufficient conductivity for Li ions (at least $>10^{-4}$ S/cm and better $>10^{-3}$ S/cm), while being non-conductive electronically $<10^{-12}$ S/cm,
c) Adequate mechanical properties to withstand mechanical stress a.o. at interfaces caused by insertion/de-insertion of Li ions into the electrodes during battery cycling, and also to enable their incorporation into the ASSB LiM cells,
d) Good charge transfer kinetics and low interfacial resistance between electrodes and ionic conductor phase,
e) Ideally insensitive to water vapour and CO_2 in the air to facilitate their manufacturing and handling.

3. Interface design and stability:

   a) Methods to gain a deeper insight into the electrode/electrolyte interface formation and dynamics are needed. Lack of knowledge on interfacial phenomena in solid-state battery systems and the complexity of "visualising" such phenomena using *in-situ* methods, limit the progress of this novel and promising solid-state battery technology,

   b) Development of new approaches and manufacturing processes to form intimate and low-impedance contact between solid electrolytes and active electrode materials, which remains (electro)chemically and mechanically stable throughout the lifetime of a ASSB cell.

4. Full cell design and manufacturing:

   a) New cell designs and manufacturing processes to achieve low electrolyte/electrode interfacial resistance and optimal electrochemical performance, while reducing manufacturing costs and improving process sustainability compared to the contemporary manufacturing of Li-ion battery cells,

   b) Harmonised protocols for testing of cell performance, durability and safety are needed to enable technology benchmarking and reliable inter-laboratory comparisons.

Future research challenges for Li-S batteries

Lithium-sulfur batteries have attracted great attention in the battery community in the past decade. One of their main advantages is their low cost, and high potential gravimetric capacity, although only a fraction of the theoretical values could be achieved in reality. Their main challenge is to overcome the polysulfide shuttle effect.

1. Research at materials level is critically needed. Increased conductivity of cathode materials, improved electrolytes (e.g. high polysulfide solubility, low viscosity, reduced polysulfide shuttle effect) and better protection of the anode (lithium metal) are fundamental to achieving improved levels of safety and cyclability,

Emphasis must be given to the evaluation of safety, and the effect of mechanical expansion of Li-S cell electrodes needs thorough assessment,

The modest number of funded projects for this technology compared to the others assessed in this report may indicate that more funding for Li-S batteries is needed.

Future research challenges for Na-ion batteries

Na-ion battery technology can be attractive for applications such as, for example, stationary energy storage, from behind-the-meter to grid scale. The main advantages of the type of batteries are avoiding costly and critical raw materials such as Co and Li, relatively good tolerance to over-discharge, potential to reduce costs and manufacturing processes similar to already mature Li-ion technology. The main issue of Na-ion batteries is their lower energy density.

1. Research at materials level and cell design is needed, especially to improve the cyclic stability and to increase the energy density,
2. The synergy with Li-ion batteries production process should be practically demonstrated – a project aiming at setting a Na-ion production facility using production line designed for Li-ion (new or recovered form Li-ion small production facility) should be funded,
3. Due consideration must be given to safety - risk of hydrogen cyanide gas release from PBA materials contained in some Na-ion cells should be evaluated – see details in paragraph 2.3. Supporting PBA-containing chemistries should be carefully considered both from the point of societal risk associated with such a release and in view of the forthcoming regulation on requirements for battery sustainability.

Future research challenges for flow batteries

While Vanadium RedOx Battery is the most promising and commercially available flow battery system so far, organic RedOx batteries are still at early research stage. Only few projects dedicated to organic RFB have been finalised as of today. The majority of the projects will deliver in few years from now, which will allow for better tailoring of the future research needs. Very generic recommendations can however be made.

Research and development should focus, in general, on development of a RFB using non-corrosive, safe, and low-cost redox-active organic storage materials. Promising redox-active low-molar-mass compounds as well as redox active polymers are of interest. Additionally, a special focus on the system safety, in regard to the flammability and toxicity is required. In particular, safe battery systems are absolute necessary for household-sized RFBs, which can be used in combination with decentralised roof-top photovoltaic electricity production.

More specifically, the following needs have to be addressed by future research:

1. An increase in energy density: e.g. by developing redox-active materials, capable of transferring more than just one electron, as well as bipolar materials with a large difference between their redox potential,

2. An increase in current density: e.g. by accelerating the kinetic reactions on the electrodes. This can be realised by choosing appropriate electrode materials and/or their activation/modification. The modification of the electrodes is a completely novel approach, particularly for organic compounds,

3. An increase in lifetime: e.g. by the utilisation of highly reversible redox couples, which undergo no side reactions and offer thousands of charge/discharge cycles,

4. An increase in overall system efficiency: e.g. by expanding the temperature range in which no precipitation of either active material or supporting electrolyte occurs. This is also required for common metal-based RFBs (e.g. VRFBs, Fe/Cr, and Zn/B_{r2}) and would consequently reduce the energy demand for heating or cooling the electrolyte,

5. A cost decrease is an important, if not the most important, driving force to enable market penetration for RFBs. This goal can be accomplished by the utilisation of organic materials or earth-abundant metals for the storage process.

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List of abbreviations and definitions

18650	one of typical cell designs, having form of hard case cylinder of 18 mm diameter and 65 mm height
AIST	National Institute of Advanced Industrial Science and Technology (Japan)
AMO	Advanced Manufacturing Office
AMPED	Advanced Management and Protection of Energy Storage Devices programme (part of ARPA-E)
ARENA	Australian Renewable Energy Agency
ARPA-E	Advanced Research Projects Agency-Energy
AQDS	anthraquinone disulfonic acid
ASSB	all-solid-state battery
ATMC	automatic tuning matching cycler
BMBF	Bundesministerium für Bildung und Forschung - The Federal Ministry of Education and Research (Germany)
BMS	battery management system – electronic system controlling the battery
BoL	beginning of life
BoP	balance of plant
BP	black phosphorus - the orthorhombic, least reactive allotrope of phosphorus
CAGR	compound annual growth rate
CAS	Chinese Academy of Sciences
CEA	Commissariat À L'energie Atomique Et Aux Energies Alternatives
CEC	California Energy Commission
CEI	cathode electrolyte interface
CMI	Critical Materials Institute
CNRS	Centre National de la Recherche Scientifique (French National Centre for Scientific Research)
CNT	carbon nanotubes
COF	covalent organic framework
CRC-P	Cooperative Research Centres Projects
CRMs	critical raw materials
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DFT	density functional theory – a computational quantum mechanical modelling method used to investigate the electronic structure of many-body systems, like atoms, molecules, and the condensed phases.
DIOX	1,3-dioxolane; IUPAC name: 1,3-dioxolane ($(CH_2)_2O_2CH_2$)
DMC	dimethyl carbonate; IUPAC name: dimethyl carbonate ($OC(OCH_3)_2$)
DME	dimethoxyethane; IUPAC name: 1,2-dimethoxyethane ($CH_3OCH_2CH_2OCH_3$)

DoD	depth of discharge
EC	ethylene carbonate; IUPAC name: 1,3-dioxolan-2-one ($OC(OCH_2CH_2O)$)
EERE	Office of Energy Efficiency & Renewable Energy
EES	electric energy storage
EOL	end-of-life
ESS	energy storage system
EU	European Union
EUCAR	European Council for Automotive R&D
EV	electric vehicle
FEC	fluoroethylene carbonate; IUPAC: 4-Fluoro-1,3-dioxolan-2-one ($OC(OCH_2CHFO)$)
FOAs	funding opportunity announcements
FP7	Framework Programme 7
H2020	Horizon 2020
HALE UAVs	high altitude long endurance unmanned aerial vehicles
HRTEM	high resolution transmission electron microscopy (analytical technique)
IC	inert-cation
ICP	ion conducting polymers
IF-EF	Individual Fellowship-European Fellowship
ILE	ionic liquid electrolyte
IPR	intellectual property rights
JCESR	Joint Center for Energy Storage Research
JRC	Joint Research Centre
KERI	Korea Electrotechnology Research Institute
KETEP	Korean Institute of Energy Technology Evaluation and Planning
LATP	$Li_{1+x}Al_xTi_{2-x}(PO_4)_3$, ceramic materials used as solid electrolytes
LCA	life-cycle assessment
LCC	life-cycle costing
LFP	lithium iron phosphate - chemistry of batteries ($LiFePO_4$)
LiM	lithium metal (anode)
LiPON	Lithium phosphorus oxynitride, a solid Li-ion conductor of general formula $Li_xPO_yN_z$
Li-S	lithium sulfur - chemistry of batteries
LLZO	$Li_7La_3Zr_2O_{12}$, ceramic material used as solid electrolyte
LMP	Li Metal Polymer, type of ASSB LiM developed by Bolloré (FR)
MEMS	microelectromechanical systems
MLD	Molecular Layer Deposition
MSCA	Maria Skłodowska Curie Actions
Na-ion	sodium ion battery - chemistry of batteries, synonymous to SIB and NIB

NaTFSI	sodium bis(trifluoromethanesulfonate)imide, IUPAC: bis(trifluoromethane)sulfonimide
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NFP	sodium iron phosphate - chemistry of batteries ($NaFePO_4$)
NIB	sodium ion battery - chemistry of batteries, synonymous to SIB and Na-ion
NIMS	National Institute for Materials Science (Japan)
NMC	lithium nickel manganese cobalt oxide ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$) the simplest Li Ni Mn Co mixed oxide called also NMC111. As the Ni Mn Co ratios may vary other representatives of the series may appear, e.g. NMC532, NMC622, NMC811.
NMR	Nuclear Magnetic Resonance (analytical technique)
NVPOF	sodium vanadium phosphate fluoride ($Na_3V_2(PO_4)_2F_3$)
OEM	original equipment manufacturer
OER	oxygen evolution reaction (leading to water split)
OIPC	organic ionic plastic crystals
Pb-A	lead-acid battery - chemistry of batteries
PBA	Prussian blue analogues (Prussian blue = $KFe^{III}[Fe^{II}(CN)_6]$
PC	propylene carbonate; IUPAC name: 4-Methyl-1,3-dioxolan-2-one ($CH_3C_2H_3O_2CO$)
PEO	poly(ethylene oxide)
PGM	platinum group metals
PHEV	plug-in hybrid electric vehicle
PLD	pulsed laser deposition
PoC	proof of concept
RAFT	Reversible Addition-Fragmentation chain Transfer
RF	radio-frequency
RFB	redox flow battery
Organic RedOx	RedOx flow batteries with organic shuttles
RIA	Research and Innovation Action
SCE	solid composite electrolyte
SEI	solid-electrolyte interface
SHE	standard hydrogen electrode
SIAT	Shenzhen Institutes of Advanced Technology
SIB	sodium ion battery - chemistry of batteries, synonymous to NIB and Na-ion
SLI	starting, lighting and ignition (battery)
SME	small-medium enterprise
SOC	state of charge
SOH	state of health

SPE	solid polymer electrolyte
TEA^+	tetraethylammonium ion
TEM	transmission electron microscopy
TEMPO	2,2,6,6-Tetramethylpiperidin-1-yl)oxyl
TFSI	bis(trifluoromethane)sulfonimide
TRL	technology readiness level
UAV	unmanned aerial vehicle
UPS	uninterruptible power supply
VRB	vanadium redox battery, synonym to VRFB
VRFB	vanadium redox flow battery, synonym to VRB
VTO	Vehicle Technologies Office
WiS	water-in-salt
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
ZIF	zeolitic imidazolium framework

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Annexes

Annex 1. Analyses of H2020 projects and their impact

Table 9. MONBASA project.

Project name	**MONBASA**
Target application	Space, micro and nanosatellites
Main goals	The overall ambition of MONBASA is to develop an energy storage system for small satellites (nano-/microsatellites) that outperforms existing solutions and can be integrated with MEMS technology. To be both, applicable and competitive, the novel solution will have to respond to specific needs, namely: (1) High energy efficiency and density; (2) Small size and low weight; (3) High reliability; (4) Compliance with existing standards and regulation; (5) High cost-efficiency.
Achievements	During MONBASA project, most of the effort was devoted to tune processing methods for thin film battery components. Remarkable results were achieved with hybrid cells using thin film electrodes and liquid electrolyte. Cathode: - Different deposition parameters were explored to obtain the high voltage cathode with best performances, specific capacities at 85% of the maximum theoretical value were obtained. - In addition, the high cathode showed an outstanding cycle life keeping more than 80% of its initial capacity during more than 2030 cycles; even if cycled at rather high current rates, e.g. full charge or discharge in 1 hour. As a reference, commercial cathodes of the same material can deliver the same performance only during 150 cycles. Solid electrolyte: - For the ceramic electrolyte, three different fabrication routes were explored. The difficulties to obtain a functional cell pushed the consortium to explore new materials and processing methods such as transition metal accommodation layers and glassy electrolytes. Anode: - Metallic Li was selected as starting material. High quality and high purity Li metal films have been obtained and tested with reference commercial solid electrolytes. The thin film Li anodes have shown an outstanding performance reducing the operating temperature of the solid electrolyte from 70 ºC to 45ºC. Interfaces: - Physical and chemical properties of the battery interfaces have been analysed employing the most advanced analysis tools. - Different accommodation interlayers between cell components were also explored in order to guarantee higher stability during cycling. Battery integration with state-of-the-art satellite sensors such as microelectromechanical systems (MEMS), a crucial technology for sensors and actuators in advanced satellites, has been studied. The solution was tested and validated under space-like conditions.
Main deviations	Functional thin film all solid state full cell was not obtained
Grant amount (round up € million)	1.3
Duration of the project (years; start-end dates)	2; 01/06/2016 - 31/05/2018

Number of scientific publications	A brochure and two policy briefs have been published
Participation in conferences	Three events were organized: - an open ethic training given by Dr. Lluis Montoliu, - an open seminar titled “Space Technologies for non-space actors” delivered by Nanospace’s CEO at M18 meeting, - the „Workshop on space batteries“ held within The Battery Show Europe 2018 in Hannover at M24. The first two events were recorded and spread through the MONBASA web page.
Number of patents	N.A.

Table 10. BATMAN project.

Project name	**BATMAN**
Target application	Energy storage systems (ESS) for residential and industrial users and electric vehicle (EV) batteries
Main goals	The specific objective of project was to define the technical and business conditions for successful commercial application of Li-ion batteries with the new nanostructure coated anode. In particular, the following goals were set: 1) Elaboration of a long-term business plan to define the most profitable market entry strategies as well as further development and commercialisation directions. 2) Determining the key technological limitations, such as the maximal content of added nanostructures to anode material, its chemical composition, increasing of charge/discharge current and cycling efficiency to determine the power and capacity characteristics of the Li-ion battery. 3) Conducting a freedom-to-operate study to ensure no other patents are infringed by the proposed innovation project.
Achievements	1) As a result of the economic feasibility assessments carried out within the project, a strategic partnership was established for further development and commercialisation of the proposed coating technology. The core business model foresees direct sales of full ESS solutions to the residential and industrial users: while the production of the developed coating material will remain in-house, the deposition of the coating and the assembly of full ESS systems will be performed at our partner's premises. The first market that will be addressed is Germany, after which Scandinavia, Baltics and other European countries will be targeted. The selection of target markets is based on the usage of renewable energy in gross inland energy consumption as well as the overall purchasing power of the residents. 2) The technological feasibility study primarily focused on conducting various tests for optimizing and determining the precise chemical content of the coating material. Specific tasks included identifying the key technological parameters of the solution in by conducting tests in the following domains: maximal thickness of protective layer, the layer's precise chemical composition, maximal charge/discharge current, and stability during cycling. Detailed specifications of the envisioned anode coating material characteristics and its manufacturing technology have been documented and will feed into the core product development activities of Phase 2 of the innovation project. 3) The IPR study was performed in collaboration with a renowned patent specialist and indicated that most of the relevant patent applications have been filed in US, China, Japan, Europe and are still in application phase. The most appropriate IP strategy identified for the project was to combine different protection instruments: non-disclosure of confidential information or regulating the treatment of sensitive information by specific contracts, trademark protection in the target markets, and patent protection.
Main deviations	N.A.
Grant amount (round up € million)	0.05
Duration of the project (years; start-end dates)	0.5; 01/09/2015 - 29/02/2016
Number of scientific publications	N.A.
Participation in conferences	N.A.

Number of patents	N.A.

Table 11. ALISE project.

Project name	**ALISE**
Target application	Electric traction
Work plan	Anode, cathode, electrolyte, separator Cell (pouch and 18650) - module – pack assembly Safety, cycle life testing Ageing modelling LCA, LCC
Main goals	New materials and processes at TRL 4 level 500 Wh/Kg cell level Stability Prototype (100 km driving range for PHEV)
Achievements	- WP1 on specification has been closed after 3 months project with associated D1.1 (Cell Requirement Document) and D1.2 (Report on specifications and definition of reference cell/parameters). - WP2, 3 and 4 are dedicated to the elaboration of new materials for their integration in LiS technology at the cell level (pouch and cylindrical). WP2, dedicated to the anode, shows early stage development (TRL3) relating to coatings onto metallic lithium. - WP3 is summarizing the works done on the cathode during this first period where ALISE target planned at the laboratory scale have been already reached and maintained for 100 cycles with >80% of the initial specific capacity (S content >70wt %, specific capacity of 4mAh/cm2 and >1200mAh/g of S). - WP5 and WP6 are dedicated to the cell integration and associated validation at the module level. Specific tasks on Cycle Life Assessment (WP6) and research activities onto the module construction have been realized. On May 2017, first generation of hundreds pouch cell has been built at OXIS facilities. The cell developed is currently half weigh and comparable volumetric energy density respect commercial lithium ion at same format, at low C-rate only (up to 1C), and for a limiting number of 50 cycles at 80% BOL. - On November 2017, first living module designed for PHEV is built at Williams Advanced Engineering facilities from 82 real lithium sulphur cell (13.55kg) to be assessed by 2018. - Actual technical readiness level of ALISE lithium sulphur pouch cell is TRL3
Room for improvement	- The scale of the materials synthesis is still insufficient for the implementation in cell modules, mostly related to anode protection. - Critical challenges for these components are linked to the adequate formulation for the electrolyte adapted to the superficies and electrochemistry of the other components of the cell. - Studies are ongoing new organic based electrolyte and less toxic candidate have been reach promising performance respect the reference electrolyte used initially. - Safety issues has been detected mostly related to the short circuit test which do not allow ALISE partners to realize the integration at battery pack level because of the important number of samples (328 cells) and risk associated. The issues are attributed to the use of non protected lithium specific to this first cell generation and the new selected electrolyte allowing higher charge and discharge rate. - ALISE partners aim to develop a solution allowing the best balancing possible between safety and performances for the last 18 months of the project: is to maintain >75% of the C/5 capacity at 2C, high energy density 400Wh/kg and high cyclability 300-500 cycles including protective layer at the anode
Grant amount (round up € million)	7
Duration of the project	4; 01/06/2015 - 31/05/2019

(years; start-end dates)	
Number of scientific publications	10
Participation in conferences	>50 (47 oral, 17 poster)
Number of patents	4

Table 12. ECLIPSE project.

Project name	**ECLIPSE**
Target application	Spacecraft batteries
Work plan	Anode, cathode, electrolyte, separator Cell – module – system level Cycle life testing Ageing modelling Definition of the future roadmap for space applications Costs/benefits analysis
Main goals	- To demonstrate the feasibility of the optimized Lithium-Sulphur cell technology so that it can make its way towards space applications - At cell level: Maximising the high energy density (>400 Wh/kg) offered by the Lithium-Sulphur chemistry - At battery and cell encapsulation level: Building a prototype battery module and checking its suitability for the space environment - At system level: Creating an electrical model of the cell that takes into account ageing effects. The detailed cell design, the experimental results and the assessment of system-level impacts will also have to be developed
Achievements	- Specifications : elaboration of specifications to define the needs for cells components, cells and battery performances as well as model features have been edited as input to the different workpackages to ensure the work is in accordance to ECLIPSE objectives - Dissemination : creation of a website including a private access for ECLISPE members, creation of a project brochure and presentation of the project in some conferences - Electrochemistry development : different materials solutions have been evaluated at both material and cells levels in order to define the best options for ECLIPSE cells - System analysis: a first version of system analysis has been edited to identify the LiS cells features and the potential impacts on space systems. This analysis will be continued in 2017 with new data from cells and models developed in ECLIPSE - Modeling: a first issue of beginning of life model has been issued based on the current LiS cells Some first assessments regarding the ageing behavior of cells have been. The complete model will be updated with new data from cells developed in ECLIPSE - Battery design: some specific tests have been performed to evaluate the cells series or parallel connection and the needs of balancing functionality. A module design has been proposed for ECLIPSE cells - Consolidation of an independent European industrial supply chain for Lithium-Sulphur batteries - An increased maturity of the technology with the goal of achieving Technology Readiness Level (TRL) of 5 at the end of the project.
Grant amount (round up € million)	1
Duration of the project (years; start-end dates)	2; 01/12/2015 - 30/11/2017
Number of scientific publications	1
Participation in conferences	13
Number of patents	2

Table 13. HELIS project.

Project name	**HELIS**
Target application	Electric traction
Work plan	Anode, cathode, electrolyte, separator (ion-selective) Scale up materials obtained in Eurolis Safety – gas evolution Ageing modelling Pack level (BMS) LCA and recycling
Main goals	- Addressing issues connected with a stability of lithium anode during cycling, with engineering of complete cell and with questions about lithium sulphur batteries cells implementation into commercial products (ageing, safety, recycling, battery packs) - Development of three different series of Li-S cell prototypes, all of which will be tested according to specifications for automotive use - Final cell price is estimated to be below 150 €/kWh - Achieving 500 Wh/kg energy density
Achievements	- Formulation of new carbon host matrices which will enable decrease of electrolyte/sulphur ratio and enable high areal capacities (utilization of more than 1000 mAh/g capacity with loadings higher than 4 mg of sulphur per cm2. - First results from modelling were implemented into the positive electrode formulation and experimental results are in the agreement with modelling results. - Electrolyte used in the first set of prototypes is based on formulation within EUROLIS project. A lot of activities in the first reporting period were performed in order to determine the optimal quantity of electrolyte which will than determine the thickness and porosity of the separator. New solvents and combination of different solvents are under testing, including some new types of glymes which are not cancerogenic. Activities are focused on solvents with low solubility of PS in order to have soluble PS as redox mediators and at the same time to prevent electrolyte saturation with PS and related transport problems. These activities are supported by modelling part, where interactions between PS and different solvents are studied. In the first generation of prototype cells protection of lithium surface will be performed only through addition of LiNO3 into electrolyte, however activities for the next generation of prototypes have started. - Preliminary studies using ALD (atomic layer deposition) coating and polymer coatings show promising direction which in the combination of presence of low concentration of PS can prolong cycle life of lithium. Another promised strategy is protection of lithium with graphene based materials either chemically modified or within the composite in the polymer matrix. Separator development is based on the achievements within EUROLIS project and additional activities are devoted to the tests of commercial separators coated with inorganic layers by ALD technique. Aim of the first generation of prototypes is also to check the problem related with safety and potential evolution of H2S gasses. - Performed controlled thermal runaway of one Li-S cell and checked gaseous products formed during the thermal runaway. Further research is required in order to stabilize Li-S battery. For that reason also some additional safety rules were required at the production line for prototypes and as well in the partner's laboratories where electrochemical tests will be done. - Work performed in the work package dealing with recycling is on time and some additional activities are planned with cells that were prepared and characterised within EUROLIS project.
Grant amount (round up € million)	8

Duration of the project (years; start-end dates)	4; 01/06/2015 - 31/05/2019
Number of scientific publications	14
Participation in conferences	41
Number of patents	5

Table 14. LISA project.

Project name	**LISA**
Target application	Electric traction
Work plan	Anode, cathode, electrolyte (solid state), separator Safety – gas tests SOC and ageing estimators Supporting the future development of BMS for EV pack integration and 2nd life to validate PLD processes for multi-layered and multi-material ceramic deposition To validate coating process using polymers (ICP) blended with garnet type (LLZO) ceramic doped oxide Recycling LCA and LCC
Main goals	- To reduce the lithium excess, the weight, and thicknesses of unit cell stack layers - To deliver Li-S cells prototype reaching the following performance targets: 20 Ah, 450 Wh/kg, 700 Wh/l, 700 W/kg maintaining at least 77% of the C/5 beginning of life load (BoL) at 2C, 1.000 cycles maintaining 80% DoD and 80% of BoL and < 70 € kWh-1 at cell level - To develop State-of-Charge and ageing estimators supporting the future development of Battery Management System for EV pack integration and 2nd life use assessment - To achieve 50 wt%. recyclability and demonstrate economic viability at lab-scale
Achievements	In WP2 (Specification), Cell and Test Definition and Production Processes Definition reports have been produced. These documents outline all specifications, such as material, component, cell, simulation, application, and recycling which will be required as commune document between the partners for the subsequent WPs. Specific interlaboratory Round Robin tests have been run between the laboratories and allowed to consolidate a reference set up based on liquid electrolyte. No reference has been reached for polymeric electrolyte in LiS system which requires further investigation. In WP3 (Lithium anode and solid-state electrolyte), Lithium and ceramic solid-state electrolytes physical deposition are being developed and tested. Successful depositions of lithium have been realized on metallic current collector in an upscaled process by roll to roll. Ceramic deposition appears more challenging to reach the targeted chemical composition. Also, research is dedicated to find the optimum separator substrate fitting with the thermal parameters of the physical deposition. Up 1 component parameter produced impacting at stack level construction. WP4 (Stand-alone dielectric) focuses on the fabrication of a stand-alone dielectric layer to be incorporated as separator/solid electrolyte in the final cell. The WP includes the development of a hybrid ceramic-polymeric electrolyte, the improvement of the liquid component of the electrolyte, the evaluation of alternative separators and its modification solutions to improve commercial options, and the upscaling of the most promising solutions for batch production and subsequent building of Li-S pouch and cylindrical cells. A major issue is related to the challenging discovery of a stable polymeric matrix compatible with lithium, LLZO and PS. Relevant development on the thermal fuse led to the patentability study of the development is ongoing. In WP5 (S/C cathode), CNF-based carbon scaffolds have been prepared and exchange to partner working on Lithium infiltration to produce lighter anode and to reduce the lithium excess. Partners have been further adapted the co-extrusion carbon/CNT/sulfur composites. Results show 1200 mAh/ g sulfur utilisation, 50-55 cycles, and the projected specific energy is ~430 Wh/kg. WP6 (Modelling, cell prototyping and validation) covers three distinct activity groups: the application of theoretical techniques to support design and operational improvements; carbon synthesis and cell

	manufacture; and electrochemical and safety testing. Partners have continued attempts to develop a mechanistic model to improve understanding of how porosity affects LiS behaviour, although implementation of the theory is presenting significant issues. Partners have used existing LiS cell to develop new methods for SOC/SOH determination, which will be applied to the LISA cell as it becomes available. In the second activity group, partner has characterization on a selection of carbons, leading to a demonstration of how varying porosity alters the cycling characteristics of cells. WP7 (Circular economy) This WP's focuses on the principles of the circular economy. During the first RP, the work performed have focused on Li-S batteries recycling process, from a preliminary draft test to the acquisition of Li-S cells and testing the first three steps regarding the recycling process. WP8 (Communication, Dissemination and Exploitation) covers the communication, dissemination, and exploitation of the project results. The progresses during this period are the creation of dissemination and communication materials and the launch of communication channels. The first technology and IPR monitoring report for the project was prepared while exploitation and business planning activities have focused on the development of a preliminary business model for the LISA project.
Grant amount (round up € million)	8
Duration of the project (years; start-end dates)	4; 01/01/2019 - 31/07/2022
Number of scientific publications	Early in the project to be assessed
Participation in conferences	Early in the project to be assessed
Number of patents	Early in the project to be assessed

Table 15. SPIDER project.

Project name	**SPIDER**
Target application	Electric traction
Work plan	Sulfur rocksalt cathode (titanium and sulfur) and silicon anode Several prelithiation methods will be evaluated Li-ion cells of 1-5 Ah Highly conductive liquid electrolyte (easier to transfer to the industry compared to solid electrolytes) Recycling LCA and LCC
Main goals	- Increase cell energy density by 65% vs. State of the Art with non-critical, sustainable materials - Reach power density of 800W/kg - Reach 50% cost reduction for batteries by 2022 - Increase cycle life to 2000 cycles by 2022 - Increase cell safety by increasing thermal runaway temperature above 200°C and limiting the thermal energy dissipation to 4 kW/kg - Develop a circular value chain for sustainable, recyclable (60 wt%) batteries in Europe
Achievements	- First results for mechanical prelithiation show that lithium was successfully introduced to the cell, the initial capacity loss in full cells could be reduced by 15% and the cycle life was increased by 5-7% - Replacing NMC622 with NMC811 can allow more than 10% increase in specific energy density (with graphite) and the capacity retention is similar with 95% after 300 cycles. In addition, replacing graphite with silicon composite allows for an initial increase in specific energy density of ~14% - WP3 worked on fixing all synthesis parameters for high capacity cathode material Li_2TiS_3 - Formulation of a benchmark electrolyte able to outperform the reference electrolyte with a gain of 20% in cycle life - Development of Si-Carbon composite slurry formulation and optimization and a cathode formulation screening of three different Ni-rich NMC811 commercial active materials - Preparation of the recycling process started
Grant amount (round up € million)	8
Duration of the project (years; start-end dates)	4; 01/01/2019 - 31/08/2022
Number of scientific publications	Early in the project to be assessed
Participation in conferences	Early in the project to be assessed
Number of patents	Early in the project to be assessed

Table 16. NAIADES project.

Project name	NAIADES
Target application	Stationary energy storage and grid applications
Work plan	anode material cathode material electrolyte formulation electrodes Na-ion cells BMS Demo module Development active materials synthesis processes Upscaling of the processes Cells design Development of cells assembly processes characterization of cells Module design and manufacturing processes Module performance characterisation in real working environment
Main goals	to develop and demonstrate a Na-ion battery for stationary EES applications
Achievements	A two cathode materials, polyanionic and a layered oxide were compared and rated;[305-308] polyanion presents a very high average discharge voltage; however, its theoretical capacity is quite modest. It presents also very good cycling behaviour and power rate capability. Layered oxide presents one of the highest theoretical capacity, >200 mAh/g, but the average voltage is rather low, and the rate capability and cycling behaviour are both poor. The layered oxide was chosen as giving higher cell energy density. The selected layered oxide syntheses route was optimized, so that process could be scaled-up to the production level of kg/batch while maintaining the electrochemical performance similar to that of the smaller laboratory batches. For the negative electrode, hard carbon was selected, commercially available hard carbon anode materials were screened,[309] and the one prepared by the project[310] outperform "battery grade" commercially available samples. However, the consortium encountered difficulties with upscaling the process, and a very high irreversible capacity due to synthesis temperature conditions was observed. A large number of electrolyte compositions was developed, screened and evaluated.[311-315] The project produced high energy density electrodes, developed cells (84070 and larger, 10 Ah) to be implemented in the larger module. The module design: 12s2p (12 cells in series and 2 in parallel of 10 Ah cells). Total energy content: 960 Wh; nominal voltage of the battery: 48 V; nominal cell voltage: 4 V; maximum cell voltage: 4.33 V. The produced cells show good capacity and rate capability - a wide range of tests was used to master cell assembly and formation process, including also post-mortem characterization and the analysis of electrodes thermal behaviour to understand and predict capacity fading due to ageing processes.[316] BMS and the battery module development. Final system integration and battery prototype test in the grid environment.
Grant amount (round up € m)	6.49
Duration of the project	4; 01/01/2015-31/12/2018

(years; start-end dates)	
Number of scientific publications	12
Participation in conferences	3
Number of patents	1

Table 17. NAIMA project.

Project name	**NAIMA**
Target application	Stationary energy storage grid applications
Work plan	anode: bio-sourced or at the least EU-made hard carbon cathode: low price EU-made oxides and advanced polyanions, no Li, Ni nor Co novel, commoditised and EU-available electrolyte electrodes Na-ion cells functional and unique Na-ion-tailored BMS demo modules technology development roadmap upscaling of the processes sustainability and recyclability development of cells assembly processes characterization of cells modules design and manufacturing processes module performance characterisation in real working environment
Main goals	To achieve the main NAIMA goal, "to develop a new generation of high-competitive and safe Na-Ion battery cells for a more competitive European Industry", the project has identified 8 specific targets: 1. To develop and test 2 enhanced configurations of Na-ion cells conceived by the perfect combination of novel advanced materials and chemistries, to demonstrate the fulfilment of KPIs directly linked with the technological competitiveness of the technology. 2. To apply a set of cost reduction strategies to pave the way towards a high competitiveness with the aim of reaching a cost target of 0.05€/kWh0.05€/kWh/cycle and 0.04€/kWh/cycle by the end of the project. 3. To design, assembly and test 6 Sodium-ion batteries (SIB) prototypes as a full system, in 3 different Business Scenarios where the role of storage technologies is considered vital for the end-users. 4. To introduce novel strategies such as eco-design, circular economy, high recycling and 2nd life applications to guarantee the development of a sustainable SIB and to demonstrate it's environmental, social and economic impact by the development of a full low cost cell design and high power cell design for industry application. 5. To contribute the creation of a new EU battery industry by the commitment of investments in manufacturing plants, especially in the component production and cell assembly stages of the SIB value chain, reducing the EU dependence of the raw materials for Li-ion batteries. 6. To create a detailed technology development roadmap to establish the product development strategies required to achieve the target KPIs by 2030: – 200 Wh/kg (gravimetric energy density. – 1 500 W/kg (gravimetric specific power). – > 750 Wh/l (Volumetric energy density). – 10 000 cycles and >50% recycling rate. 7. To create an industry upscaling roadmap enabling the strengthening of the European Battery Industry by addressing the whole value chain. 8. To establish the main pillars of a precise refined feasibility study and business plan as a strategic tool to get a smooth market penetration and proper orientation of the future products and services in 2023.
Achievements	NA

Grant amount (round up € m)	8.00
Duration of the project (years; start-end dates)	3; 01/12/2019-30/11/2022
Number of scientific publications	NA
Participation in conferences	NA
Number of patents	NA

Table 18. HiNaPc project.

Project name	**HiNaPc**
Target application	Electric vehicles and portable electronics. Impact on K-ion and supercapacitor technologies.
Work plan	New cathode material Na-ion pouch cell Cell electrochemical characterisation Production scalable process IPR protection Industry contact development of SIB pouch cells through upscaling the prototype SIB coin cells without deterioration the performance
Main goals	1. Scale up of the coin cell Na-ion cell 2. PoC pouch battery development 3. Characterisation of the battery performance
Achievements	According to the project webpage "A prototype of rechargeable SIB coin cells with high energy density and supercapacitor-like power density has been achieved, with performance indices that are comparable with the commercial LIBs. In particular, its supercapacitor-like high power density and superior rate capability allow ultrafast charge and discharge without deteriorating the energy density." The project published two papers, not relevant for Na-ion chemistry.
Grant amount (round up € m)	0.15
Duration of the project (years; start-end dates)	1.5; 01/01/2017-30/06/2018
Number of scientific publications	2
Participation in conferences	NA
Number of patents	NA

Table 19. NAPANODE project

Project name	**NAPANODE**
Target application	Basic science focused on understanding the degradation processes relevant to Na-ion chemistry.
Work plan	Anode materials: phosphorus and metal phosphides (M_xP_y; M = Sn, Cu) composites with graphene Cathode material: well settled[317] $Na_{1-x}M_y(PO_4)_z$ (M = Ti, V) Electrolyte: 1 M sodium bis(trifluoromethanesulfonate)imide (NaTFSI) in propylene carbonate experimental methods – TEM, XPS, NMR, XRD and electrochemical analyses computational modelling – DFT
Main goals	1. To correlate changes in material structure at atomic level with specific electrochemical signatures in the charge-discharge profiles aiming to understand processes of material degradation in anodes for Na-ion batteries for designing high capacity Na-based insertion materials. 2. Upscale the SIB coin cells into SIB pouch cells with low cost (< US$ 200 per kWh) and high energy capacity, 30-50 Ah (compared to <1 Ah for coin cell). The proposed pouch cell shall be applicable in battery systems with large-scale commercial applications. 3. Establish a production-scalable process for mass production of the SIB pouch cells, and hence paving the way towards further developing full SIB battery system for electric vehicles and portable electronics.
Achievements	The structural transformations that occur during cycling in black P anodes for Na-ion batteries were tracked with solid-state NMR, XRD, and DFT calculations. 1. We found new NaxP structures via a computational genetic algorithm that allowed the assignment of various P motifs present in amorphous NaxP (a-NaxP) intermediates. During the first sodiation, P atoms at the end of a chain are observed as early as 0.60 V (Na0.52P) showing that P−P cleavage begins at this composition. In a-NaxP, P motifs that correspond to both P helices and the terminal unit in phosphorus zig-zags are observed. Once the potential drops below 0.22 V, c-Na3P-P63cm, which was predicted to form a priori, appears and persists during desodiation until >0.60 V. 2. We find that Na3P-P63cm is formed in both Na-ion batteries and solid-state synthesis, indicating that both routes access the thermodynamically favorable structure. Slight differences in P-containing environments in a-NaP during sodiation/desodiation may result from different pathways that form extended P structures from the pristine black P vs isolated P atoms in c-Na3P-P63cm, respectively. 3. At the end of desodiation, we find that black P is not re-formed, which may contribute to the poor capacity retention in this material. 4. The combined approach of analyzing both experimental and theoretical chemical shift anisotropy can be extended to understand other structural transformations on (de)lithiation/(de)sodiation in not only P-containing materials, but also systems, such as Si, where distinct structural motifs, such as clusters and chains, play an important role in the battery chemistry of these largely amorphous phases.
Grant amount (round up € million)	0.18
Duration of the project (years; start-end dates)	2; 01/03/2017-28/02/2019 (terminated in Jun 2018; month 16 out of 24 planned)
Number of scientific publications	1 (contributed to 5 publications in other area)

Participation in conferences	5 (4 oral, 1 poster)
Number of patents	NA

Table 20. NExtNCNaBatt project.

Project name	**NExtNCNaBatt**
Target application	Basic science focused on understanding the interactions between Na and N=C compounds relevant to Na-ion chemistry.
Work plan	Anode materials: novel materials - ternary carbodiimides with TM^{2+} and an alkali ion in the structure, COFs, ZIFs – synthesis via multiple routes materials characterization experimental methods – TEM, NMR, XRD and electrochemical analyses computational modelling – DFT confronting of the material characteristics with the experimentally obtained electrochemical performance
Main goals	The overall objective of NExtNCNaBatt project is the investigation of designed novel materials based on the N=C derived anions and their application as electrodes for sodium ion batteries. The major objective is the establishment of a fundamental understanding of the Na to N=C interactions in Novel Extended solids based on the NC chemistry for Na-ion batteries which will be achieved through the study of structural changes in the bulk by in-situ x-ray diffraction studies, as well as local changes in the atomic environment followed by advanced spectroscopic studies.
Achievements	1. The crystal structure of a new Schiff Base molecule has been determined. The molecule is electrochemically active as electrode for Na-ion batteries with performance comparable to state-of-the-art organic anodes for Na-ion batteries. 2. A novel electrolyte formulation largely supresses first cycle coulombic inefficiency in Schiff Base electrodes, bringing these materials closer to their implementation in Na-ion batteries for large scale stationary applications.
Grant amount (round up € m)	0.20
Duration of the project (years; start-end dates)	2; 01/03/2017-16/07/2019 (suspended on 15/04/2018; month 13 out of 24 planned and terminated on 31/08/2018 without being resumed.
Number of scientific publications	0
Participation in conferences	7 (5 oral presentations, 2 posters)
Number of patents	NA

Table 21. GREENERNET project.

Project name	**GREENERNET**
Target application	Advanced Flow Battery Energy Storage Systems in a Microgrid Network
Work plan	2 main steps: • Scaling up of AQDS Storage System: battery components (electrodes, membranes, electrolytes, bi-polar plates, pumps) are analyzed with the aim to optimise the battery performance in terms of cost and performance. • Development of Innovative Microgrid Management Platform for the AQDS flow batteries, able to monitor microgrids components (loads, energy sources, storage) and to continuously perform a multi-objective optimisation of the energy flows among microgrids components and with the Power Distribution Grid.
Main goals	To develop a new organic redox flow battery (AQDS) suitable to work up to temperatures of 80 ºC, that have a self-life similar (or even better) than current organic ones, but with an energy efficiency 20% higher than current RFB due to cooling system is not required, need less pump energy & has a high power.
Achievements	Upscaling and the pre-commercial design of the main components of the 1 kW flow battery already developed, including electrodes and stacks, pumps and balance of plants (BoP), electrolytes, the battery control system, to a 10 kW system validated. The upscaling considered aspects such as manufacturability, cost reduction, performance and lifetime improvement. • Design of Battery Control System (BCS) and final risk assessment; • Development a test bench for flow battery stack and test stack Building up a 10 kW test stand for stacks with AQDS/Bromine chemistry for initial specs testing of the stack; • AQDS 10 kW battery laboratory validation; • Development of a marketable Battery: modular architectural structure of the battery was developed to facilitate possible commercial purposes. • Implementation Micro Grid HW Components: the project has developed an innovative Microgrid Management Platform for the AQDS flow batteries, able to monitor microgrids components (loads, energy sources, storage) and continuously perform a multi-objective optimisation of the energy flows among microgrids components and with the Power Distribution Grid; • On field tests: case studies and assessment scenarios were defined; • Organic Battery standalone field test was done with the objective qualification and validation of the battery in a real environment. • Microgrid energy Mgmt. System field testing to verify the following aspects: functional tests of the microgrid control, performance of operation, reliability of the system, HMI and usability of the system and testing functions to be controlled.
Main deviations	None
Room for improvement	N.A.
Grant amount (round up € million)	2.7
Duration of the project (years; start-end dates)	2.5; 01/07/2016 - 31/12/2018
Number of scientific publications	N.A.

Participation in conferences	4 (scientific presentations)
Number of patents	N.A.

Table 22. GLOBE project.

Project name	**GLOBE**
Target application	Electrical Energy Storage (EES)
Work plan	Includes 4 main steps: • Selection of electrolyte: selection of water soluble organic electrolytes based on E-pH diagrams, chemical stability and solubility of organic electrolytes at different temperatures. • Selection of membrane: selection of optimal (low cost) membrane type based on diffusion coefficients and electrical resistances measurements. • Chemical synthesis of mono and pentahydroxy AQDSs to be used as a replacement for AQDS in organichalide and AQDS/TEMPO RFB. • Performing Lab scale RFB tests to evaluate low cost potential of All Organic RFB and improved organic-halide RFB.
Main goals	Provide a low-cost solution for electrical energy storage (EES), based on organic redox active species for both redox flow and solid-state batteries.
Achievements	Electrochemical techniques were successfully adapted and a large screening of a commercially available organic redox species were performed to learn about their redox potential, water solubility and chemical stability. This allowed to determine better the project direction. GLOBE's results are expected to promote innovation in the field of organic redox flow and solid-state batteries, given the developed new types of species. The results will strengthen the global competitiveness of the European electrical energy storage industry.
Main deviations	Adaptation and/or redirection of some of the experiments
Room for improvement	N.A.
Grant amount (round up € million)	0.2
Duration of the project (years; start-end dates)	2; 01/09/2015 - 31/08/2017
Number of scientific publications	2 papers published in peer reviewed journals
Participation in conferences	4 conferences and a lecture organised by Danish Battery Society on organic redox flow batteries
Number of patents	N.A.

Table 23. EnergyKeeper project.

Project name	**EnergyKeeper**
Target application	Electrical Energy Storage (EES)
Work plan	• Lab-scale demonstration of advanced storage solutions • Technical design and construction of the upscaled storage system • Metering system, control interface and Smart Grid intercommunications network • Integration, testing and optimisation • Policy, Standards and Data protection • Prosumers business models • Dissemination Communication and Exploitation
Main goals	Design, develop and test a novel, scalable, sustainable and cost competitive battery based on organic reduction–oxidation (redox) active materials.
Achievements	• Research to identify the most promising redox compounds in order to synthesise new polymers; • Define test protocols for assessing the performance and addressing the lifetime behaviour of different redox flow battery configurations and materials; • Completing specification documents detailing requirements for the construction of the redox-flow battery and the preparation of the testing site; • Identification of all components for the battery management system; • Specification and design of communication protocols; • Defining potential business models • Review and gaps identification of the existing standards.
Main deviations	• Delay in the construction and shipment of the redox-flow-battery system to the test site; • Issues experienced with the scale-up process of the polymer electrolyte which introduced additional delays (additional tests needed); • Higher cost for the construction of the battery system than originally planned due to experienced technical issues. To stay within the project's budget, the battery was downscaled from 100 kW and 350 kWh (originally promised) to approximately 30 kW and 100 kWh, respectively.
Room for improvement	Better coordination from the project coordinator was needed especially in the beginning of the project to assure the timely delivery of the work.
Grant amount (round up € million)	4
Duration of the project (years; start-end dates)	3; 01/01/2017 - 31/12/2019
Number of scientific publications	
Participation in conferences	Several conference papers, presentations, press releases, articles in magazines and newspapers have been published
Number of patents	N.A.

Table 24. ARPEMA project.

Project name	**ARPEMA**
Target application	Basic research focused on new cathode materials. Primary application: Li-ion; impact on: Na-ion, PEC water splitting
Work plan	Cathode material Basic science to understand mechanisms of ion and electron transport in Li- and Na-driven anionic redox reactions involving $(O_2)^{n-}$ peroxo-groups. Identifying the fundamental processes that enable anionic redox activity. New materials (transition metal and anion) showing anionic redox chemistry, Experimental methods - structural and electrochemical analyses Computational modelling - first-principle DFT
Main goals	1. Development of a new generation of Li-ion batteries based on sustainable electrode materials enlisting both cationic and anionic redox activities, and exhibiting substantial increases (20 - 30%) in energy storage capacity. 2. Implementation of the anionic redox concept to Na-ion battery electrodes, a technology with presently only a few well-performing materials offering modest capacities (140 mAh/g), 3. Design of water splitting catalysts able to surpass current water splitting efficiencies.
Achievements	1. The first direct visualization of the (O-O) peroxo-like dimers in high capacity layered Li-rich oxides by High Resolution Electron Microscopy, hence ending the long remaining controversies about the role of the anionic network. 2. Demonstrated the feasibility to trigger this novel anionic redox process in oxides having three dimensional (3D) rather than two dimensional (2D) crystal structures. Thus, by freeing the structural dimensionality constraint, he opens wide the rich crystal oxide chemistry for designing high energy density electrodes for the next generation of Li-ion batteries. 3. Designed and synthesized a novel Li_3IrO_4 phase that push the limit of the anionic redox activity to 3.7 e- per nd metals – a record among all the cathodes so far investigated. This work show that the O/M parameter delineates the boundary between the material's maximum capacity and its stability, hence providing valuable insights for further developing high capacity materials. 4. Isolated a Na-rich phase Na_2IrO_3 phase which can reversibly cycle 1.5 Na^+ per formula unit while not suffering from oxygen release nor cationic migrations.[318] This work turns out to be an impetus for the design of high energy Na-rich materials based on more sustainable elements than Ir as we are presently investigating. 5. Provided rationalization of the anionic redox process by showing that a strong M–(O2) covalence is an absolute condition to ensure high electrochemical reversion reversible and to prevent O_2 gas release from the structure at high states of charge, which is crucial application-wise. 6. Demonstrated enhanced OER activity in La_2LiIrO_6 when compared to the state-of-the-art IrO_2 catalysts in acidic environment. This large OER activity is triggered by an activation step in acidic media corresponding to the de-lithiation/oxidation of the surface. The mechanistic of the process was deduced by combined DFT calculations and HRTEM measurements. This work established for the first time the correlation existing between the OER activity stability for perovskites when triggering the surface oxygen redox 7. We unravel the poor kinetics of anionic-driven poor kinetics which keeps deteriorating further with cycling and we also find that voltage fades faster if oxygen is kept oxidized for longer.

Grant amount (round up € million)	2.25
Duration of the project (years; start-end dates)	5; 01/10/2015-30/09/2020
Number of scientific publications	18
Participation in conferences	4
Number of patents	NA

Table 25. ATMCinsituNMR project.

Project name	**ATMCinsituNMR**
Target application	Basic research focused on analytical technique and electrode materials development for Na-ion and Li-ion cell chemistries.
Work plan	Cathode material Anode material Development of ATMC in situ NMR and application it to Na-ion and Li-ion battery materials Other experimental methods – structural, spectroscopic and electrochemical analyses
Main goals	1. Overcome experimental challenges of in situ NMR on LIB/NIBs, by designing a new NMR probe system and a highly shielded in situ cell attachment setup. 2. Perform ATMC in situ NMR on lithium iron phosphate (LFP) cathodes as well as their Na-ion based "counterpart", sodium iron phosphate (NFP). Comparing the underlying chemistries based on the in situ NMR experiment should facilitate the development of cheaper NIBs as an accessible alternative to LIBs in the near future. 3. Apply the ATMC in situ NMR hardware to other (so-called) "beyond-Li" battery materials, including tin and Na-metal anodes for NIBs, as well as hard carbon electrodes. In addition, the new approach should be enhanced to study promising (but highly complex) sodium vanadium phosphate fluoride (NVPOF) cathodes for NIBs.
Achievements	1. We have established a huge range of new NMR equipment (ATMC in situ NMR, eATM ROBOT, PCC) to enable in situ NMR investigations with an outstanding flexibility. 2. ATMC in situ NMR on LFP, NFP, and NVPOF cathodes offered insights into structural changes of these materials during cycling. 3. Furthermore, in situ NMR on Na-metal anodes helped to monitor the formation of different Na-metal species, and to quantify the electrolyte consumption during the electrochemical experiment. 4. In addition, ATMC in situ NMR in combination with other experimental techniques provided insights into the structure of hard carbon anodes in NIBs. 5. The group has also explained the mechanism of intercalation reaction of alluaudite sodium iron sulfate $Na_{2+2x}Fe_{2-x}(SO_4)_3$
Grant amount (round up € million)	0.18
Duration of the project (years; start-end dates)	2; 01/03/2015-28/02/2017
Number of scientific publications	8
Participation in conferences	19 (13 oral, 6 posters)
Number of patents	NA

Table 26. B-PhosphoChem project.

Project name	**B-PhosphoChem**
Target application	Basic science - characterisation of properties of black phosphorus and its derivatives. Impact on Na-ion, Li-ion and K-ion chemistries
Work plan	Potential anode material Anode material Na-ion cells Development of BP and its intercalates chemistry and synthesis routes Development of PB properties tuning by control of the thickness of BP flakes – down to monolayer thickness layers First BP intercalation material based Li-ion and Na-ion batteries will be characterised by means of ”time and frequency dependent capacities” Characterisation of developed batteries performance
Main goals	We propose the development of the chemistry of black phosphorus (BP) in five areas: Five work packages will be addressed: 1. Production of Thin Layer BP, 2. Supramolecular Chemistry of BP, 3. Intercalation Compounds of BP, 4. Covalent Chemistry of BP, and 5. BP-Based Materials and Devices. And detailed targets relevant for batteries development: 1. Development of BP intercalates synthesis routes 2. PoC batteries development 3. Characterisation of batteries performance
Achievements	1. Successful alkali metal intercalation of black phosphorus 2. Proof of concept for the covalent functionalization of black phosphorus based on intercalated/activated BP starting materials 3. Access to monolayer black phosphorus by sequential wet-chemical surface oxidation 4. Catalytic activity of few-layer black phosphorus in alkylation of soft nucleophiles with esters 5. Catalytic activity of alkali metal black phosphorus intercalation compounds in radical transformations to alkenes.
Grant amount (round up € million)	2.49
Duration of the project (years; start-end dates)	5; 01/08/2017-31/07/2022
Number of scientific publications	8
Participation in conferences	NA
Number of patents	NA

Annex 2

Patent Landscape Analysis

February 2020

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ABOUT KNOWMADE

Knowmade is a Technology Intelligence and IP Strategy consulting company specialized in analysis of patents and scientific information. The company helps innovative companies and R&D organizations to understand their competitive landscape, follow technology trends, and find out opportunities and threats in terms of technology and patents.

Knowmade’s analysts combine their strong technology expertise and in-depth knowledge of patents with powerful analytics tools and methodologies to turn patents and scientific information into business-oriented report for decision makers working in R&D, Innovation Strategy, Intellectual Property, and Marketing. Our experts provide prior art search, patent landscape analysis, scientific literature analysis, patent valuation, IP due diligence and freedom-to-operate analysis. In parallel the company proposes litigation/licensing support, technology scouting and IP/technology watch service.

Knowmade has a solid expertise in Compound Semiconductors, Power Electronics, Batteries, RF Technologies & Wireless Communications, Solid-State Lighting & Display, Photonics, Memories, MEMS & Solid-State Sensors/Actuators, Semiconductor Manufacturing, Packaging & Assembly, Medical Devices, Medical Imaging, Microfluidics, Biotechnology, Pharmaceutics, and Agri-Food.

INTRODUCTION

CONTEXT AND OBJECTIVES

JRC seeks to acquire a **patent landscape** study covering the following post Li-ion battery technologies:

- **Li-Sulfur batteries**
- **Na-ion batteries**
- **RedOx flow batteries with organic shuttles/electrolytes**

The study shall provide information on the following aspects:

Main patent applicants for the above-mentioned battery technologies worldwide, including name of the applicant, number of assigned patents and their geographic coverage. Applicants shall include companies, universities, non-profit organizations such as e.g. research institutions, but not physical persons.

Patent categorization per type: active materials composition for anode, cathode, electrolyte, separator/membrane; electrode and cell manufacturing technology; recycling.

EU applicants and relative position/strength of EU applicants in the global context for the above-mentioned battery technologies evaluated based on the number of patents, relevance and strength of the documents.

The study shall cover the **time frame from the year 2000 onwards**, unless a valid reason for considering a shorter time period is identified and this is agreed with the technical contact at JRC Petten.

Data source, **search strategy** (e.g. search phrase and/or search codes), **definition** of patent families and **methodology** details explaining by which criteria patents are defined as relevant shall be explained in the study. **Codes** and the **keywords** for the queries shall be delivered.

For the **number of patents counting** the following approach shall be used: if a patent has a broad application across different codes/ keywords, or is filed jointly with several companies, it shall count as a fraction of a patent, and not as a full patent, for all the applicants to avoid double counting.

The study shall be delivered in an **electronic format as a Microsoft Word text file**. The underlying data, such as for example list of identified patents and year of application/award, shall be delivered in an electronic format as an Excel spreadsheet.

Half-term review via tele/web-conference shall take place to monitor the progress of the study. This meeting is meant for the contractor to present the work performed to the date and for the JRC to provide its feedback.

The report covers the following battery technologies: **Lithium-Sulfur batteries (Li-S), Sodium-ion batteries (Na-ion)** and **redox flow batteries with organic shuttles (organic redox-flow)**. Patents have been categorized by supply chain segments: electrode active materials (anode, cathode), electrolytes, separators, electrode (anode, cathode, manufacturing methods), battery cell (anode, cathode, manufacturing methods).

	Patents included in the study	Patents not included in the study
Na-ion batteries	• Rechargeable Na-ion batteries mentioned as sole technology in Title, Abstract or Claims (patents focused on Active materials, Electrode, electrolyte, separator, battery cell, recycling) • Rechargeable Na-ion batteries mentioned in a list of technologies in Title, Abstract or Claims (patents focused on Active materials, electrode, electrolyte, separator, battery cell, recycling) • Rechargeable Na-ion batteries with aqueous electrolytes (Title/Abstract/Claims)	• Na-ion battery pack, module, systems or BMS • Na-ion supercapacitors • Sodium solid electrolytes or molten salts operating at high temperature (>100°C) Example: Beta-alumina, $NaAlCl_4$ • Devices for testing Na-ion batteries • Na-S battery • Sodium battery with liquid electrode • Sodium solid electrolytes or molten salts (ionic liquid) operating at relatively low temperature (<100°C) • Non-rechargeable Na-ion batteries
Li-S batteries	• Rechargeable Li-S batteries mentioned as sole technology in Title, Abstract or Claims (patents focused on active materials, Electrodes, electrolyte, separator, battery cell, recycling) • Rechargeable Li-S batteries mentioned in a list of technologies in Title, Abstract or Claims (patents focused on active materials, Electrodes, electrolyte, separator, battery cell, recycling)	• Li-S battery pack/module/systems/BMS • Devices for testing Li-S batteries • Lithium/Metal sulfide battery, ie. Li-MS or Li-MS2 battery (With M= Fe, Ni, Mo, etc.) without reference to Li-S battery in Title/Abstract/Claims • Redox-flow Li-S batteries in Title, Abstract or Claims • Li-S battery with liquid electrodes • Non-rechargeable Li-S Batteries
Organic redox-flow batteries	• Rechargeable Redox-flow battery with organic molecules as sole redox shuttles mentioned in title/abstract/claims (patents focused on active materials, electrode, electrolyte, separator, battery cell, recycling) • Rechargeable Redox-flow battery with organic molecules among a list of redox shuttles (including also inorganic molecules) mentioned in title/abstract/claims (patents focused on active materials, electrode, electrolyte, separator, battery cell, recycling) • Rechargeable Hybrid organic/inorganic redox-flow battery (Examples: Cadmium acid/ Benzoquinone; Anthraquinone/Br2) • Rechargeable Organic redox-flow batteries with aqueous or organic electrolytes • Rechargeable Organic redox shuttles include: Polymers, coordinated metal complex, i.e. metal ion + organic ligands: metallocene (ex: ferrocene), other (ex: ferrocyanide, bipyridine ruthenium) and Metal-free molecules (Ex: quinone-based, etc.)	• Redox-flow battery pack, module, systems and BMS • Redox-flow battery without specification of the electrolyte material in the title/abstract/claims • Redox-flow battery without organic redox shuttles (vanadium, Titanium, Manganese, Bromine, Zinc, lead, etc.) • Non-rechargeable organic redox-flow batteries

Table 1: Patents included or excluded from the scope of the study during manual patent selection

METHODOLOGY

The data were extracted from the **FamPat worldwide patent database** (Questel-ORBIT) which provides 100+ million patent documents from 100 patent offices (USA, Europe, Japan, China, Taiwan, Korea, Hong Kong, Singapore, etc.).

The patents are grouped in **patent families**. A patent family is a set of patents filed in multiple countries to protect a single invention by a common inventor(s). A first application is made in one country – the priority country – and is then extended to other countries.

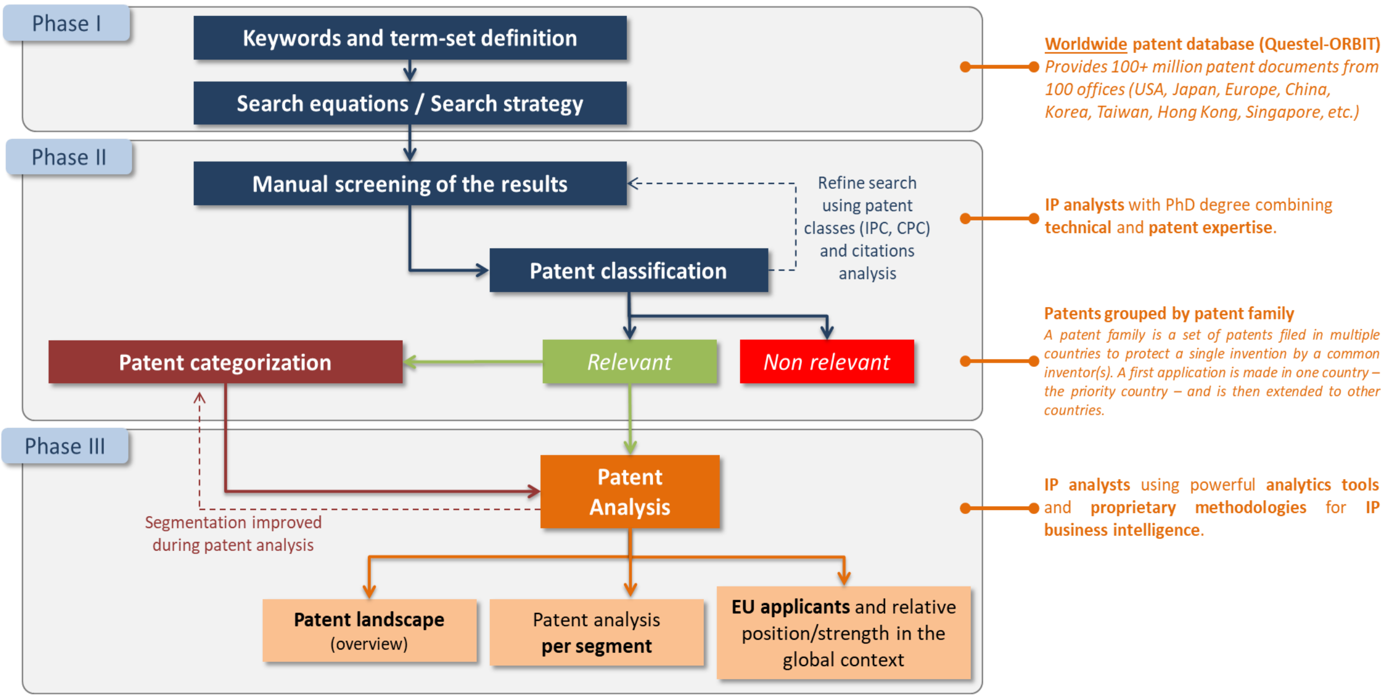

Figure 1: Methodology for patent search and selection

PHASE I (Figure 1**):** The search for patents was completed in **January 2020**, hence patents published after this date are not available in this report. Our search strategy combines searches based on keywords and patent classes (IPC, CPC) with expert review of the patents.

PHASE II (Figure 1**):** The **selection** of relevant patents according to the scope of the study (Table 1) and their **categorization** in technical segments (i.e. categories) are **manually** performed using **keywords analysis** of patent title, abstract and claims, combined with **patent classes** (IPC, CPC), in conjunction with **expert review** of the subject-matter of inventions. Patent search and selection are performed by patent families because a patent family corresponds to a single invention. Thus, if one patent in the patent family is in the scope of the study, all patents in the patent family will also be in the scope of the study. Some patents held by different entities are grouped considering the M&A history: If a company has acquired or merged with another company, their patents are gathered under the same patent assignee name. Examples: Bosch acquired SEEO in 2015 and thus their patents are gathered under the name Bosch/SEEO. Panasonic acquired Sanyo Electric in 2009 and thus their patents are gathered under the name Panasonic/Sanyo. Similarly, subsidiaries of a same mother company are gathered under the same patent assignee name. For instance, patents held by Global Graphene and Nanotek Instruments are gathered under the name Global Graphene. Gathering of main patent assignees are indicated in the comments of the ranking of main IP players.

PHASE III (Figure 1**): Data analysis** is performed using the **Questel Orbit IP Business Intelligence analytics platform** combined with **Excel-based data processing** and will be supplemented by **expert analysis**.

Li-S Batteries

Topic	Step	Search equations	Results (patent families)
Technologies not included in the scope of the report related to Li-S batteries	#1	(((fuel 0d (cell? or accumulator? or batter+)) or ((solar or photovoltaic?) 0d (batter+ or cell? or device?)))/ti or (h01m-008+)/ipc/cpc)	213037
	#2	(((batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 2d (sodium_sul??ur or na-s or na_sul??ur or metal_selenium or sodium_selenium or na_i or sodium_iodi?e or na_iodine or na_br or na_bromine or sodium_bromine or na_ni or sodium_nickel+ or sodium_metal_halide? or sodium_surfur or sodium_halogen?))/ti) not (li-s or lithium+ or li or lithium_sul??ur)/ti	1458
	#3	((sodium+ or na_ion) s (+batter+ or cell?))/ti not (li or lithium+ or li-s or li_ion or lithium_ion)/bi/clms	3155
	#4	(((nickel_metal_hydride or ni_mh or magnesium_ion or zinc_ion or fluoride_ion or potassium_ion or calcium_ion or metal_air or lithium_air or lead_acid or nickel_iron or manganese_dry or zinc_alkaline) s (+batter+ or cell?))/ti) not (li-s or sul??ur or sul??ide or lithium_sul??ur)/ti	16986
	#5	#1 or #2 or #3 or #4	232565
Li-S batteries	#6	((batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 3d (lithium_sul??ur or li-s or lithium_sul??ide? or ((li or lithium) 2d sul??ur)))/bi/clms/obj	3981
	#7	((batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 3d (metal+_sul??ur or metal_sul??ide? or ((metal) 2d sul??ur)))/bi/clms/obj	578
	#8	((batter+ or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 2d (lithium_sul??ur or li-s or lithium_sul??ide? or ((li or lithium) 2d sul??ur))/bi/clms/obj/desc	7649
Electrodes, separators or electrolytes for Li-S Batteries	#9	((+sul??ur or +sul??ide?) 3d (electrode? or anode? or cathode? or electrolyte? or separator?))/bi/clms and h01m+/ipc/cpc	8076
	#10	(lithium 2d (electrode? or anode? or ((metal+ or alloy?) 0d (electrode? or anode?)) or (negative 0d electrode?)))/bi/clms	52348
	#11	(((protect+ or passivat+ or stabiliz+ or stabilis+) 2d (anode? or ((lithium or negative) 2d (electrode?)))) and lithium+)/bi/clms and ((protect+ or passivat+ or stabiliz+ or stabilis+) s ((lithium or li) 0d (metal+ or alloy?)))/bi/clms	274
Li-S batteries (All)	#12	(#6 or ((#7 or #9 or #10 or #11) and #8)) not #5	5169
Citations	#13	cited and citing patents from manual selection of #12	
	#14	((batter+ or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 2d (lithium_sul??ur or li-s or lithium_sul??ide? or ((li or lithium) 2d sul??ur)))/bi/clms/obj/desc or ((batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) s (lithium_sul??ur or li-s or sul??ur or ((li or lithium) s sul??ur)))/ti	
	#15	(#13 and #14) not #5	
Manually screened patents	#16	#12 or #15	10917
Patents on Li-S battery manually selected according to criteria in Table 1	#17	Manual selection of #16	4317

- + Truncation replacing any number of characters
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- _ Truncation for word that may have a space
- OR Finds references containing at least one of the words
- AND Finds references containing all words

- /TI/OTI Search in Title
- /BI Search in Title and Abstract
- /CLMS Search in Claims
- /DESC/ODES Search in Description
- /PA.FLD Search in Patent Assignees
- /IPC Search in International Patent Classification (IPC)

- S Finds references containing the terms in the same sentence
- nD Finds references containing adjacent terms, regardless of the order, and may be separated by a maximum of n words
- ( ) Parentheses are necessary to combine different operators
- EPD>=YYYY-MM-DD search new patent families published since YYYY-MM-DD

Table 2: Search Equations used for the query of patents related to Li-S Battery

Na-ion Batteries

Topic	Step	Search equations	Results (patent families)
Technologies not included in the scope of the report related to Na-ion batteries	#1	(((fuel 0d (cell? or accumulator? or batter+)) or ((solar or photovoltaic?) 0d (batter+ or cell? or device?)))/ti or (h01m-008+)/ipc/cpc)	213037
	#2	((batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 2d (sodium_sul??ur or na-s or na_sul??ur or metal_sul??ur or metal_selenium or sodium_selenium or na_i or sodium_iodi?e or na_iodine or na_br or na_bromine or sodium_bromine or na_ni or sodium_nickel+ or sodium_metal_halide? or sodium_surfur or sodium_halogen?))/ti	1576
	#3	((lithium+ or li_ion) s (+batter+ or cell?))/ti not (na or sodium or na_ion or sodium_ion)/bi/clms	78796
	#4	((nickel_metal_hydride or ni_mh or magnesium+ or metal_air or lithium_air or lithium_sul??ur or lead_acid or nickel_iron or manganese_ dry or zinc_alkaline) s (+batter+ or cell?))/ti	19660
	#5	#1 or #2 or #3 or #4	309624
Na-ion batteries	#6	((batter+ or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 3d (sodium_ion or na_ion or (sodium 0d (secondary or rechargeable))))/bi/clms/obj	3109
	#7	((cell?) 3d (sodium_ion or na_ion or na or sodium))/bi/clms/obj and h01m+/ipc/cpc	1508
	#8	((+batter+ or cell? or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) s (sodium or na or na_ion or sodium_ion))/ti and h01m+/ipc/cpc	3256
Electrodes, separators or electrolytes for Na-ion Batteries	#9	((sodium or na or sodium_ion or na_ion) 3d (electrode? or anode? or cathode? or electrolyte? or separator?))/bi/clms and h01m+/ipc/cpc	6136
Na-ion batteries and its components and active materials	#10	(#6 or #7 or #8 or #9) not #5	5707
Citations	#11	cited and citing patents from manual selection of #10	
	#12	(((batter+ or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))) 2d (sodium_ion or na_ion or (sodium 0d (secondary or rechargeable))))/bi/clms/obj/desc or ((sodium or na) s (electrode? or anode? or cathode? or electrolyte? or separator? or +batter+ or accumulator+ or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?))))/ti)	
	#13	(#11 and #12) not #5	
Manually screened patents	#14	#10 or #13	9878
Patents on Na-ion battery manually selected according to criteria in Table 1	#15	Manual selection of #14	3615

- \+ Truncation replacing any number of characters
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- EPD>=YYYY-MM-DD search new patent families published since YYYY-MM-DD

Table 3: Search Equations used for the query of patents related to Na-ion Battery

Organic Redox-Flow Batteries

Topic	Step	Search equations	Results (patent families)
Technologies not included in the scope of the report related to Organic redox-flow battery	#1	((solar or photovoltaic?) 0d (batter+ or cell? or device?)))/ti	84488
Redox-Flow Battery	#2	((batter+ or accumulator+) 2d (flow or flowing or redow_flow))/bi/clms/obj	21904
	#3	((cell?) 2d ((redox 0d flow) or redox_flow or (liquid 0d fuel)))/bi/clms/obj	2437
	#4	(h01m-008/18+ or h01m-008/20+)/ipc/cpc	6564
	#5	(#2 or #3 or #4) not #1	26637
Organic redox shuttle list	#6	(+alloxazin+ or +acetylacetonat+ or +phenanthrolin+ or +thiol+ or +ferrocen+ or +cobaltocen+ or +viologen+ or +benzophenon+ or +quinon+ or +quinoxalin+ or +ferrocyanid+ or +piperidin+ or +indigo or +pherazin+ or +pyridin+ or +catechol+ or +eneimin+ or +acethylacetone?ethylen?diamin+ or +pht?alimid+ or +tempo or (+hydroxy?benzene+ 1d acid?) or +oxy?benzen+ or (+benzene?sulfonic 0d acid) or +carbonyl+ or +nitroxid+ or +nitroxyl+ or +quinoxalin+ or +pyrrid+ or +benzothiadiazol+ or +phenothiazin+ or +ferr?cyanid+ or +propenium+ or +pyrromethen+ or ethylenediaminetetraacetate or +edta+ or +phenanthrolin+ or +triethanolamin+ or dtpa or +methane?sulfonate? or +morpholin+ or +pyrrolidin+ or +piperid+ or +naphthalen+ or +thiaz+ or +thiophen+ or +fluorenon+ or +pyrromethen+ or +imidazol+ or +anthrac+ or +pyrrol+ or +phenylenediamin+ or +cn+ or fe2+ or fe3+)/bi/clms	2035352
	#7	(organo_metal+ or metallocen+ or ((metal_ligand or (metal 0d ligand)) 0d (coordinat+ or complex+)) or (ligand 0d complex+) or (complex+ 0d (agent? or compound? or molecule? or substance? or (redox 0d system?)))/bi/clms	111521
	#8	(organic+ or non_aqueous)/bi/clms	1844307
	#9	(complex+ or +ligand? or +coordinat+)/bi/clms	1936715
	#10	(#6 or #7 or #8 or #9)	5085562
Organic Redox-flow Battery	#11	#5 and #10	3504
Citations	#12	Cited and citing patents from manual selection of #11	
	#13	((batter+ or accumulator+) 2d (flow or redow_flow))/bi/clms/obj/desc or ((cell?) 2d ((redox 0d flow) or redox_flow or (liquid 0d fuel)))/bi/clms/obj/desc	
	#14	#12 and #13 and #10	
Manually screened patents	#15	#14 or #11	3491
Patents on Organic Redox-flow battery manually selected according to criteria in Table 1	#16	Manual selection of #15	459

- \+ Truncation replacing any number of characters
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- ( ) Parentheses are necessary to combine different operators
- EPD>=YYYY-MM-DD search new patent families published since YYYY-MM-DD

Table 4: Search Equations used for the query of patents related to Organic Redox-flow Battery

Segmentation by Supply Chain

Supply Chain Segment	Step	Search Equations
Separator	S1	(separator? or diaphragm?)/ti or ((membrane?/ti and h01m-002+/ipc/cpc) not (electrolyt+ 0w membrane?)/ti)
Active materials	EM1	(+material? or +substance? or grain? or +granule? or +composite? or +particle? or rod? or nano_rod? or micro_rod? or +wire? or nano+ or +powder+ or +particulate? or +compound? or precursor? or complex+)/ti
	EM2	(electrolyte/ti and h01m-004+/ipc/cpc) not (h01m-010/056+ or h01m-006/04+ or h01m-006/06+ or h01m-006/14+ or h01m-006/16+ or h01m-006/18+ or h01m-006/22+ or h01m-006/24+ or h01m-010/08+ or h01m-010/10+ or h01m-010/22+ or h01m-010/26+)/ipc/cpc
	EM3	EM1 not EM2
	Anode	(anode? or (negative 0d (electrode? or pole_piece? or pole_plate? or (active 1d +material?) or +material?)))/bi/iclm/obj or (lithium 0d metal+)/ti
	Cathode	(cathode? or (positive 0d (electrode? or pole_piece? or pole_plate? or (active 1d +material?) or +material?)))/bi/iclm/obj
Electrolyte	EL1	((electrolyte? or electrolytic) 0d (with or for or "and" or solution? or (composed 0d of) or film? or layer+))/ti or (ion+ 0d conduct+)/ti or ((electrolyte? or electrolytic) s (salt? or solvent? or additive?))/ti
	EL2	(h01m-010/056+ or h01m-006/04+ or h01m-006/06+ or h01m-006/14+ or h01m-006/16+ or h01m-006/18+ or h01m-006/22+ or h01m-006/24+ or h01m-010/08+ or h01m-010/10+ or h01m-010/22+ or h01m-010/26+)/ipc/cpc
	EL3	(electrode? or anode? or cathode? or separator? or diaphragm?)/ti
	EL4	(electrolyt+ or salt? or solvent? or additive? or ionic_liquid?)/ti
	EL5	(EL1 or (EL2 and EL4)) not EL3
Electrode	ED1	(+electrode? or anode? or cathode? or binder? or pole_piece? or (current 0w collector?) or ((positive or negative) 1d (plate? or pole_piece? or pole_plate?)))/ti and h01m-004+/ipc/cpc
	ED2	(+material? or +substance? or grain? or +granule? or +composite? or +particle? or rod? or nano_rod? or micro_rod? or +wire? or nano+ or +powder+ or +particulate? or +compound? or precursor? or complex+) /ti
	ED3	ED1 not ED2
	Anode	(anode? or (negative 0d (electrode? or pole_piece? or pole_plate?)))/ti
	Cathode	(cathode? or (positive 0d (electrode? or pole_piece? or pole_plate?)))/ti
Battery cell	BC1	(batter+ or accumulator+ or cell? or ((electrochemic+ or ((energy or power) 0d storage) or energy) 0d (device? or cell? or system?)))/ti
	BC2	((h01m-006+ or h01m-010+) not (h01m-006/4+ or h01m-006/5+ or h01m-006/6+ or h01m-010/4+ or h01m-010/5+ or h01m-010/60 or h01m-010/61+ or h01m-010/62+ or h01m-010/63+ or h01m-010/65+ or h01m-010/66+))/ipc/cpc
	BC3	BC1 and BC2
Manufacturing	Man1	(+manufact+ or +synthesi+ or +fabricat+ or +deposit+ or +process+ or +proceed+ or +production or +producing or +preparat+ or laminat+ or anneal+ or making)/Bi/clms
Recycling	R1	(recycl+ or recover+)/ti or (+batter+ s (waste? or scrap+))/bi
	R2	(h01m-010/54)/ipc/cpc
	R3	R1 and R2

- \+ Truncation replacing any number of characters
- ? Truncation replacing zero or one character
- # Truncation replacing one character
- _ Truncation for word that may have a space
- OR Finds references containing at least one of the words
- AND Finds references containing all words

- /TI/OTI Search in Title
- /BI Search in Title and Abstract
- /CLMS Search in Claims
- /DESC/ODES Search in Description
- /PA.FLD Search in Patent Assignees
- /IPC Search in International Patent Classification (IPC)

- S Finds references containing the terms in the same sentence
- nD Finds references containing adjacent terms, regardless of the order, and may be separated by a maximum of n words
- ( ) Parentheses are necessary to combine different operators
- EPD>=YYYY-MM-DD search new patent families published since YYYY-MM-DD

Table 5: Search Equations used for the query of patents related to each Supply Chain Segments

TERMINOLOGY

Patent Applicant, Patent Assignee

An applicant is a person or organization (e.g. company, university, etc.) who/which has filed a patent application. An assignee is a person or organization (e.g. company, university, etc.) who/which holds patent rights. There may be more than one applicant/assignee per patent application.

Patent Family

A patent family is a set of patents filed in multiple countries to protect a single invention by a common inventor(s). A first application is made in one country – the priority country – and is then extended to other countries.

Priority Date

The priority date is the date on which the first patent application in a patent family was filed. At this date the patent document is not made available to the public.

Priority Number

The priority number is the number of the application with respect to which priority is claimed, i.e. it is the same as the application number of the claimed priority document. The priority number is made up of a country code (two letters), the year of filing (four digits) and a serial number (variable, maximum seven digits).

Publication Date/Year

The publication date of a patent is the date on which the patent application was first published. It is the date on which the patent document is made available to the public, thereby becoming part of the state of the art.

Earliest Publication Date/Year

The earliest publication date of a patent family is the date on which the first patent application in the patent family was first published. It is the date on which the first patent document in a patent family is made available to the public, thereby becoming part of the state of the art.

Average age of a patent portfolio

The average age of a patent portfolio is calculated thanks to the following formula:

$$Average\ age\ of\ patent\ portfolio = \frac{\sum_{First\ publication\ date}^{2020} Number\ of\ patent\ families\ for\ the\ year\ x\ \times (2020 - x)}{Number\ of\ patent\ families}$$

Publication Number

The publication number is the number assigned to a patent application on publication. Publication numbers are generally made up of a country code (two letters) and a serial number (variable, one to twelve digits) (e.g. DE202004009768).

Citations

In the context of patents, a citation is a reference to a previous work (prior art) that is considered relevant to the considered patent application. Citations may be made by the Inventor or by the Examiner during patent examination.

WO and EP Patent Applications (patents)

International (WO) and European (EP) Patent Applications are made through the World Intellectual Property Organization (WIPO) and the European Patent Office (EPO), respectively. WO applications designate signatory states or regions to the Patent Cooperation Treaty (PCT) and will have the same effect as national or regional patent applications in each designated state or region, leading to a granted patent in each state or region. EP applications are regional patent applications designating signatory state to the European Patent Convention (EPC) and leading to granted patents having the same effect as a bundle of national patents for the designated states. Europe includes all countries members of European Patent Office (Albania, Austria, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Liechtenstein, Lithuania, Luxembourg, Latvia, Monaco, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Roumania, Serbia, Sweden, Slovenia, Slovakia, San Marino, Turkey).

Legal Status of the Patent

- Pending: Patent applications in a pre-grant/pre-final-rejection stage in the patent office.
- Granted: Patents in a "post-decision" or "post-grant" stage in the patent office.
- Abandoned (Lapsed): Patents or published applications that are not in force before the end of the normal term right because of applicant action or in-action. Normally this status refers to post-grant patents where the applicant has not paid the necessary renewal fees. However, "Lapsed" can include pre-grant published applications that are deemed likely abandoned because there has been no known activity in the office for a significant period of time. Typical office status for Lapsed could be "abandoned", "lapsed", "withdrawn", "surrendered", etc.
- Expired: Granted patents that have expired due to normal life of the patent cycle.
- Rejected (Revoked): Patents or published applications that are not in force before the end of the normal term right because of office action. Normally, this status refers to post-grant patents subject to opposition events. However, "Revoked" can include final rejection notices when we have that information from the office. Typical office status for "Revoked" could be "suspension", "interrupted", "cancelled", "revoked", "refused", etc.
- Dead: It gathers patents abandoned (lapsed), expired and/or rejected (revoked).

Seminal / Key patents

A seminal patent has a strong **technology impact** and significantly contributes to **prior art**. It has the **capability to limit the patenting activity of the other firms** (limit the scope of claimed inventions). The identification of seminal patents is based on the number of **citations received by the patents** (forward citations). A seminal patent has a high number of forward citations compared to the other patents published the same year, or it received a high number of citations per years since its publication.

"Pure Play" Company

A **"Pure Play" Company** is a company operating in the field of only one battery technology.

A key IP player is a patent assignee who has a large patent portfolio with numerous granted patents and/or pending patent applications and/or the capability to limit the patenting activity and/or the freedom-to-operate of other firms.

The identification of **key IP players** relies on the following metrics:

- **Number of patent families** (patent portfolio size)
- **IP leadership** (enforceability and current patenting activity)
- **IP blocking potential** (capability to limit the IP activity and/or the **freedom-to-operate** of other players)
- **Prior-art blocking potential** (capability to limit the IP activity of other players)
- **FTO blocking potential** (capability to limit the **freedom-to-operate** of other players)

The **IP leadership** of a company is assessed by analyzing the graphical representation of the number of granted patents (reflects the enforceability of the IP portfolio) versus the number of pending patent applications (reflects the current patenting activity). The more the company combines a high number of granted patents with a high number of pending patent applications, the greater its IP leadership is.

The **IP blocking potential** of the patent portfolio of a company A is assessed by analyzing the graphical representation of the number of different patent applicants citing the patent portfolio of this company A (number of different patent applicants holding patent families in which patent families held by the company A are cited) versus the number of forward citations received by the patent portfolio excluding self-citations (number of patent families in which patent families held by a company A are cited). The number of different patent applicants citing the patent portfolio reflects how many different companies consider the patent portfolio relevant. The number of forward citations reflects how many different patent families depend on the patent portfolio. The higher the number of forward citations from different patent applicants is, the stronger its blocking potential is.

For the **Prior-art blocking potential** of patent portfolio, i.e. capability to limit the patenting activity of other players (Figure 2), the capability of a patent assignee to limit the **patenting activity of other firms** is evaluated by analyzing the **prior art contribution** of its patent portfolio (number of forward citations received by the patent portfolio, excluding self-citations) and the **technological impact of its patent families** (average number of forward citations received per patent families of the portfolio, excluding self-citations), whatever the current legal status of patents (granted, pending, dead). The higher the **prior-art blocking potential**, the stronger its capability to **limit the patenting activity** of other firms. The more a patent family (invention) receives forward citations (technology impact), the higher its prior-art blocking potential is. The average number of forward citations per patent families of a company A is calculated by dividing the number of forward citations received by the patent portfolio of the company A by the number of patent families held by the company A. This metric can also be named technological impact (factor).

For the **FTO blocking potential** of patent portfolio, i.e. capability to limit the freedom-to-operate of other players (Figure 3), the capability of a patent assignee to limit the **freedom-to-operate of other firms** is evaluated by analyzing the **enforceability** of its patent portfolio (number of patent families with at least one granted patent), the **technological impact of its enforceable patent families** (average number of forward citations received per granted patent family), and the **geographical coverage of its enforceable patent portfolio** (average number of filing countries for granted patents). The higher the FTO blocking potential is, the stronger its capability to limit the freedom-to-operate of other firms is. The more a patent family (invention) comprises granted patents (enforceability) in multiple countries (geographic coverage) and receives forward citations (technology impact), the higher its FTO blocking potential is. A patent can be used to limit the freedom-to-operate of other companies only if it is granted. If a company does not have granted patents and only have pending patent applications or dead patents, its patent portfolio cannot be used to limit the freedom-to-operate of other companies and its FTO blocking potential will be equal to zero.

The FTO blocking potential of granted patent portfolio of a company is calculated according the following formula:

$$FTO\ Blocking\ potential(Company\ A) = \\ Technological\ Impact\ Factor\ of\ patent\ families\ with\ granted\ patents\ (Company\ A) \times \\ Average\ Geographic\ Coverage\ of\ patent\ families\ with\ granted\ patents\ (Company\ A) \times \\ Number\ of\ patent\ families\ with\ granted\ patents\ (Company\ A)$$

With

$$Technological\ Impact\ Factor\ of\ patent\ families\ with\ granted\ patents\ (Company\ A) = \frac{Number\ of\ forward\ citations\ of\ patent\ families\ with\ granted\ patents\ (Company\ A)}{Number\ of\ patent\ families\ with\ granted\ patents}$$

and

$$Average\ Geographic\ Coverage\ of\ patent\ families\ with\ granted\ patents\ (Company\ A) = \frac{Sum\ (Geographic\ coverage\ for\ all\ patent\ families\ with\ granted\ patents\ (Company\ A))}{Number\ of\ patent\ families\ with\ granted\ patents\ (Company\ A)}$$

With Geographic Coverage of a patent family A with granted patents = Number of publication countries of granted patents in the patent family A with granted patents.

For the geographic coverage, Europe counts as one and includes all countries members of European Patent Office (Albania, Austria, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Liechtenstein, Lithuania, Luxembourg, Latvia, Monaco, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Roumania, Serbia, Sweden, Slovenia, Slovakia, San Marino, Turkey).

The **average FTO blocking potential per granted patent families** of a company is calculated by dividing the FTO blocking potential of granted patent portfolio of a company by the number of patent families with granted patents held by the company A.

Each of these metrics brings **valuable information** about a company's IP portfolio, but has its limitation:

- A high number of patents in the portfolio is often a good indication of the level of activity of a company in a given technology and possibly, how critical it is to its product roadmap or strategy. However, it doesn't provide any information regarding the strength and relevance of its portfolio.
- The blocking potential can be affected in both direction by various factors. For example, a company with a very recent IP portfolio will likely have fewer forward citations which will lower its blocking potential. On the other hand, a company with a single but much holder patent is likely to receive more citations which leads to a high blocking potential.

These metrics are useful tools to identify the **companies that appear to be the strongest and most relevant** in the field, and single out a few **patent families that seem particularly relevant**. But ultimately, only a careful examination of every single patent by legal and technical experts could provide a more accurate assessment of a company's patent portfolio and the relevance to the field of a given family of applications.

Examples

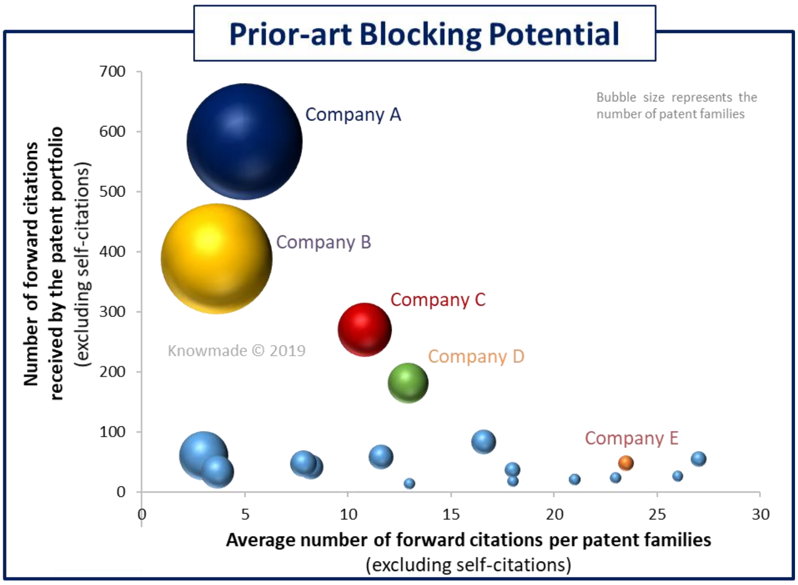


Figure 2: Example of Prior-art Blocking Potential Graph

Interpretation of Figure 2:

- **Company A**, **Company B** and **Company C** have a **high prior-art contribution** and thus they have the **capability to limit the patenting activity of other companies**. Indeed, they have a lot of patent families (inventions) and their patent portfolio receive a lot of forward citations.
- **Company E** holds **seminal key patents** with a prior-art contribution limited to specific technologies/applications. Indeed, it has few patent families (inventions) but they receive a lot of citations.

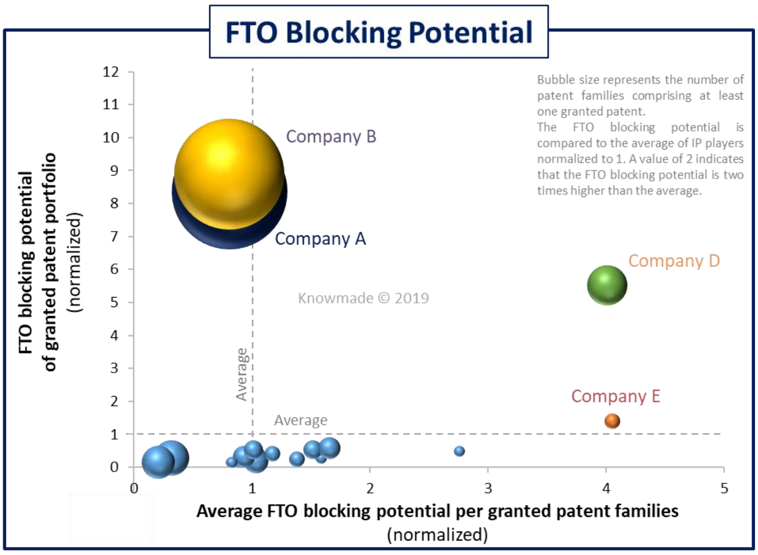


Figure 3: Example of FTO Blocking Potential Graph

Interpretation of Figure 3:

- **Company A** and **Company B** have the **capability to limit the freedom-to-operate (FTO) of other companies**. Indeed, their patent portfolio combines a high number of **granted patents** and a large **geographical coverage** with a high number of **forward citations** from numerous patent applicants (cf. formula of FTO blocking potential). **Company E** may impact the FTO of other companies only for **specific technologies/applications**.
- Contrary to companies A, B, D and E, the **Company C does not have granted patents**, thus the size of the bubble representing Company C is equal to 0 and does not appear on the FTO blocking potential graph (Figure 3). It means that Company C does not impact the FTO of other companies.

Evaluation of IP position of European IP players

IP Position of European IP players has been evaluated according to the following criteria:

- The size of a company patent portfolio, i.e. the number of patent families in its patent portfolio related to the topic of the study.
- The size of a company granted patent portfolio, i.e. the number of granted patents in its patent portfolio related to the topic of the study.
- The size of a company pending patent portfolio, i.e. the number of pending patent applications in its patent portfolio related to the topic of the study.
- Prior Art Blocking Potential of a company (cf. definition in the previous paragraph)
- FTO Blocking potential of a company (cf. definition the previous paragraph)

Patent portfolio of European IP players has been evaluated compared to the patent portfolio of other companies in the patent landscape.

For each criterion, companies have been ranked by descending order.

- Patent portfolio of a company having the highest value for one criterion is annotated “Very high”.
- Patent portfolio of a company having a value among the Top5/10 (depending of the difference of values between companies) for one criterion is annotated “High”. If values between company N°2 and company N°10 is close, all companies in the Top10 have been annotated “High”. If values between company N°2 and company N°10 is high, only companies in the Top5 have been annotated “High”.
- Patent portfolio of a company having a value around the average value for one criterion is annotated “Medium”.
- Patent portfolio of a company having a value much lower than the average value but not close to 0 for one criterion is annotated “Low”.
- Patent portfolio of a company for which the criterion is close to 0 is annotated “Very low”.
- Patent portfolio of a company for which the criterion is equal to 0 is annotated “Null”.

PATENT LANDSCAPE OVERVIEW

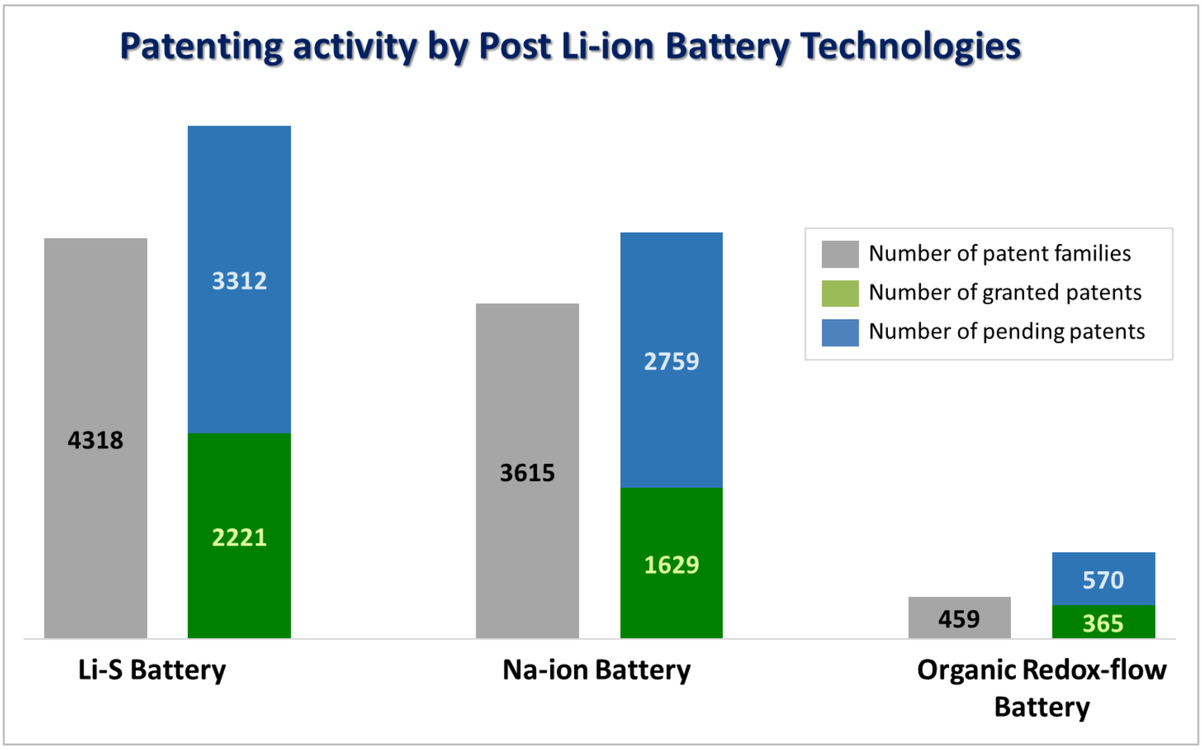


Figure 4: Patenting activity by Post Li-ion Battery Tech. from the beginning of patenting activity for each battery technology (i.e. 1970 for Li-S Battery, 1986 for Na-ion Battery, 1960 for Organic Redox-flow Battery)

There are a much higher number of patent families, granted patents and pending patent applications related to Li-S battery and Na-ion battery than organic redox-flow batteries (Figure 4). In fact, patenting activity on organic redox-flow battery emerged later than the one on Li-S battery and Na-ion battery (Figure 5). Moreover, patenting activities on Li-S batteries and Na-ion batteries are strongly increasing since 2013 mainly due to the emergence and high patenting activity of Chinese IP players (Figure 13, Figure 28). For organic redox-flow batteries, high patenting activity in China only begins in 2019 (Figure 43).

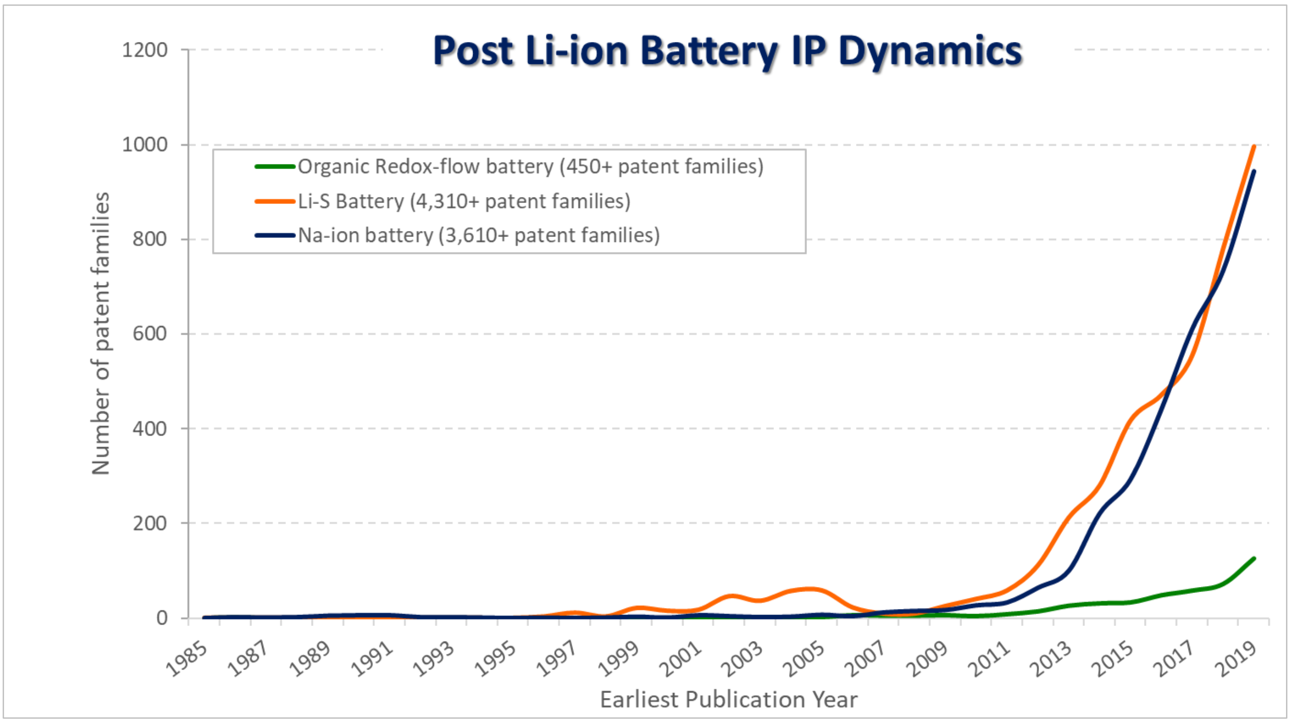


Figure 5: IP Dynamics (Number of patent families annually published by earliest publication year) for each Post Li-ion Battery Technology

MAIN IP PLAYERS BY TECHNOLOGIES

IP positions	Li-S Battery	Na-Ion Battery	Organic Redox-flow Battery
Main IP players *(Highest number of patent families)*	LG Chem, Samsung, Sion Power, Global Graphene Group, Poly Plus, Central South University, Dalian Institute of Chemical Physics	Shaanxi University of Science and Technology, Sumitomo Chemical, Central South University, Toyota, Wuhan University, CATL, Global Graphene Group	Jiangxi University of Science and Technology, Lockheed Martin, Panasonic Sanyo, Samsung, Chinasalt Jintan
Main EU IP player *(Highest number of patent families)*	Bosch, Seeo, Oxis Energy (Next Generation Battery Technology), BASF (The Chemical Company), Daimler, Solvay, cea	Faradion (Advanced Energy Storage Solutions), cnrs, Université de Picardie Jules Verne, cea, Collège de France, CIC energiGUNE — Exclusive license to Tiamat	acal energy, Jena Batteries, University of Chester, Friedrich-Schiller-Universität Jena, CMBlu

Figure 6: Main European and Non-European IP Players by Post Li-ion Battery Technologies according to their number of patent families on the corresponding battery technologies

More details on the number of patent families by patent assignees for each post Li-ion battery technology are detailed in the part dedicated to each post Li-ion battery technologies (Figure 14 and Figure 24 for Li-S Battery, Figure 29 and Figure 39 for Na-ion Battery, Figure 44 and Figure 54 for Organic Redox-flow Battery).

Some companies among main IP players are pure play companies operating only on a post Li-ion battery or have been founded relatively recently:

- **Oxis Energy** is a British Pure Play company spin-out from **Culham Science Center in Oxfordshire** in 2000 as **Intellikraft** and specialized in Li-S Battery
- **Faradion** is a British company founded in 2011 and specialized in Na-ion battery.
- **Tiamat** is a French start-up founded in 2017 on the basis of R&D results obtained at **CEA and CNRS**. It develops rechargeable Na-ion batteries. It is worth to note that **Tiamat** does not have published patents on Na-ion batterie but has an exclusive license on CNRS/CEA patents related to Na-ion battery.
- **Acal Energy** is a British company founded in 2004. It develops systems and components for redox fuel cells.
- **Jena Batteries** is a German pure play company specialized in organic redox flow battery founded in 2013 on the basis of R&D results obtained at **Universitat Jena**.
- **CMBLU** is a German pure play company specialized in organic redox flow battery founded in 2014.
- **Sion Power** is an American Pure Play company spin-out from **Brookhaven National Laboratory** in 1989 as **Moltech** and specialized in Lithium metal anode protection and Li-S Battery
- **PolyPlus Battery** is an American Pure Play company spin-out from **Berkeley University** in 1991 and specialized in Lithium metal anode protection.
- **Global Graphene** is an American company founded in 2007. It develops new materials for battery applications.

KEY IP PLAYERS BY TECHNOLOGIES

IP positions	Li-S Battery	Na-Ion Battery	Organic Redox-flow Battery
Most enforced IP players (*Highest number of granted patents*)	Sion Power, OXIS Energy, LG Chem, Bosch, SEEO, Samsung, GM, Hyundai, BASF, Dalian Institute of Chemical Physics	Shaanxi University of Science and Technology, Sharp, Sumitomo Chemical, AGC, Toyota, Central South University, Faradion	Lockheed Martin, UT-Battelle, Samsung, Jena Batteries, University of Chester, acal energy, University of Jena, MIT
Main active IP players (*Highest number of pending patent applications*)	Sion Power, Global Graphene Group, OXIS Energy, LG Chem, Bosch, SEEO, BASF, GM, Arkema, Solvay	Shaanxi University of Science and Technology, Global Graphene Group, Faradion, CATL, AGC, Sumitomo Chemical, Nippon Electric Glass, Toyota, Central South University	Lockheed Martin, UT-Battelle, CMBlu, Panasonic Sanyo, Harvard University, Jena Batteries, Chinasalt Jintan, acal energy, University of Jena
Strong IP Players (*Highest Prior Art blocking potential*)	Sion Power, Samsung, OXIS Energy, PolyPlus, BASF, Optodot, KH Chemicals, Bosch, SEEO, Sila	LithiumWerks, Carnegie Mellon University, Faradion, Sumitomo Chemical, Aquion Energy, CEA, Université de Picardie Jules Verne, CNRS, Panasonic Sanyo, The University of Tokyo	24M, Samsung, Lockheed Martin, The University of Chicago, UT-Battelle, acal energy, University of Chester, Sharp, MIT
Strong IP Players (*Highest FTO blocking potential*)	Sion Power, Samsung, OXIS Energy, PolyPlus, Cornell University, BASF, Fargo, Bosch, SEEO	Sumitomo Chemical, The University of Tokyo, Aquion Energy, Carnegie Mellon University, Mitsubishi Motors, Panasonic Sanyo, Faradion, U.Porto, CEA, Université de Picardie Jules Verne, CNRS, Arkema	24M, MIT, Samsung, UT-Battelle, acal energy, University of Chester, Lockheed Martin, Murata, Harvard University

European IP players

Figure 7: Key IP Players by Post Li-ion Battery Technologies

Li-S Battery: European IP players (**Oxis Energy, Bosch/SEEO, BASF)** and **Sion Power** combine a high number of granted patents and pending patent applications with a strong patent portfolio. This means that they have the capability to limit both patenting activity and freedom-to-operate of other companies. **Bosch/SEEO** mainly files patents on cathode material and battery cell. **Oxis Energy** mainly files patents on battery cell, separator and electrodes. **BASF** has a strong partnership with **Sion Power**. **BASF** mainly files patents on cathode materials, electrode manufacturing, electrolyte, anode and battery cell. **Sion Power** mainly files patents on electrolyte, electrode and battery cell. **Global Graphene** and **LG Chem** hold a high number of pending patent applications but still have a weak IP position because most of their patents have been filed after 2015. They could reach a better IP position within next years. **LG Chem** mainly files patents on cathode materials, cathode and electrode manufacturing. It also has a notable number of patent families on other supply chain segments, except anode materials. **Global Graphene** mainly files patents on anode materials, electrode manufacturing and battery cell. Despite its lower number of alive patents, **PolyPlus Battery** has a strong IP position due to numerous key patents on Lithium metal anode. **Samsung** combines a high number of granted patents and a strong patent portfolio. **Samsung** mainly files patents on cathode materials, electrolyte, electrode manufacturing, cathode and battery cell. It also has some patents on other supply chain segments.

Na-ion Battery: **Faradion** (Europe) and **Sumitomo Chemical** combine a high number of granted patents and pending patent applications with a strong patent portfolio. This means that they have the capability to limit both patenting activity and freedom-to-operate of other companies. **Faradion** mainly files patents on cathode materials. **Sumitomo Chemical** mainly files patents on battery cell, anode and cathode materials. **Global Graphene** and **CATL** hold a high number of pending patent applications but still have a weak IP position because most of their patents have been filed after 2015. They could reach a better IP position within next years. **Global Graphene** mainly files patents on anode materials and battery cell. **CATL** mainly files patents on electrolyte and electrode. Despite its lower number of alive patents, **CNRS, CEA, Univ. Of Picardie, Aquion Energy** and **Arkema** have a strong IP position. **Aquion Energy** mainly files patents on aqueous Na-ion battery. **Aquion Energy** has been acquired by **Juline Titans** in 2017 after having filed for bankruptcy. **CNRS, Arkema** and **Université de Picardie** mainly file on cathode materials. **CNRS** and **Arkema** also have a notable number if patents related to electrolyte. **CEA** mainly files patents on anode materials, cathode materials and battery cell.

<u>**Organic Redox-Flow Battery**</u>: European IP players (**Acal Energy, Univ. Of Chester**) and **Lockheed Martin / UT Battelle** combine a high number of granted patents and pending patent applications with a strong patent portfolio. This means that they have the capability to limit both patenting activity and freedom-to-operate of other companies. **Acal Energy** and **Univ. Of Chester** only file patents on battery cell. **Lockheed Martin / UT Battelle** file patents on all supply chain segments, except recycling. **CMBLU, Panasonic/Sanyo, Jena Batteries, University of Jena** and **Harvard University** hold a high number of pending patent applications but still have a weak/medium IP position because most of their patents have been filed after 2015. They could reach a better IP position within next years. **CMBLU** files patents on electrolytes and redox shuttles materials. **Panasonic/Sanyo, University of Jena and Jena Batteries** only file patents on battery cells. **Harvard University** files patents on redox shuttle materials, electrolyte and battery cell. Despite their small patent portfolio, **MIT, University of Chicago and 24M Technologies** have a strong IP position due to numerous key patents granted in numerous countries. **MIT and 24M** only file patents on battery cells. **University of Chicago** files patents on battery cells and redox shuttle materials. **Samsung** combines a high number of granted patents and a strong patent portfolio. **Samsung** files patents on battery cell and electrolyte.

PATENTING ACTIVITY BY TECHNOLOGIES IN EUROPE

Europe includes all countries members of European Patent Office (Albania, Austria, Belgium, Bulgaria, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Iceland, Italy, Liechtenstein, Lithuania, Luxembourg, Latvia, Monaco, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Roumania, Serbia, Sweden, Slovenia, Slovakia, San Marino, Turkey).

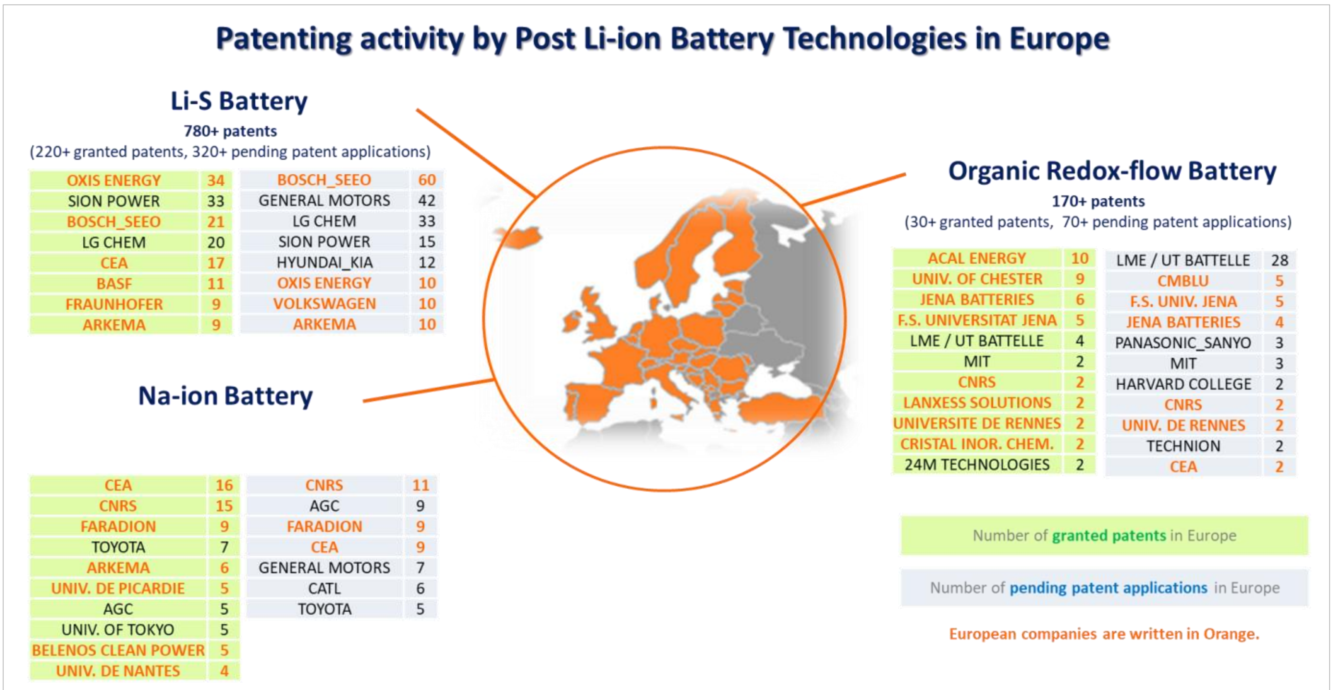


Figure 8: Patenting activity and main IP Players protecting their IP rights in Europe (independently from their originating countries) by Post Li-ion Battery Technologies

Patents on Post Li-ion battery in Europe are not only filed by European IP players but also foreign IP players from Japan, US, China and Korea.

PATENTING ACTIVITY BY TECHNOLOGIES AND SUPPLY CHAIN SEGMENTS

Technology	Supply Chain Segment						
	All supply chain segments	Active material	Electrolyte	Separator	Electrode	Battery cell	Recycling
Li-S Battery	4318	2059	445	311	805	741	4
Na-ion Battery	3615	2485	375	47	334	440	8
Organic Redox-flow battery	459	57	97	10	26	300	

Table 6: Number of patent families by Technologies and Supply Chain Segments

Patenting activity by supply chain segments is correlated to main development axes envisioned to improve post Li-ion battery performances and safety, i.e. electrode and electrolyte materials and battery cell for Li-S battery, electrode and electrolyte materials for Na-ion battery and battery cell, electrolyte and redox shuttle materials for organic redox flow battery.

MAIN IP PLAYERS BY TECHNOLOGIES AND SUPPLY CHAIN SEGMENTS

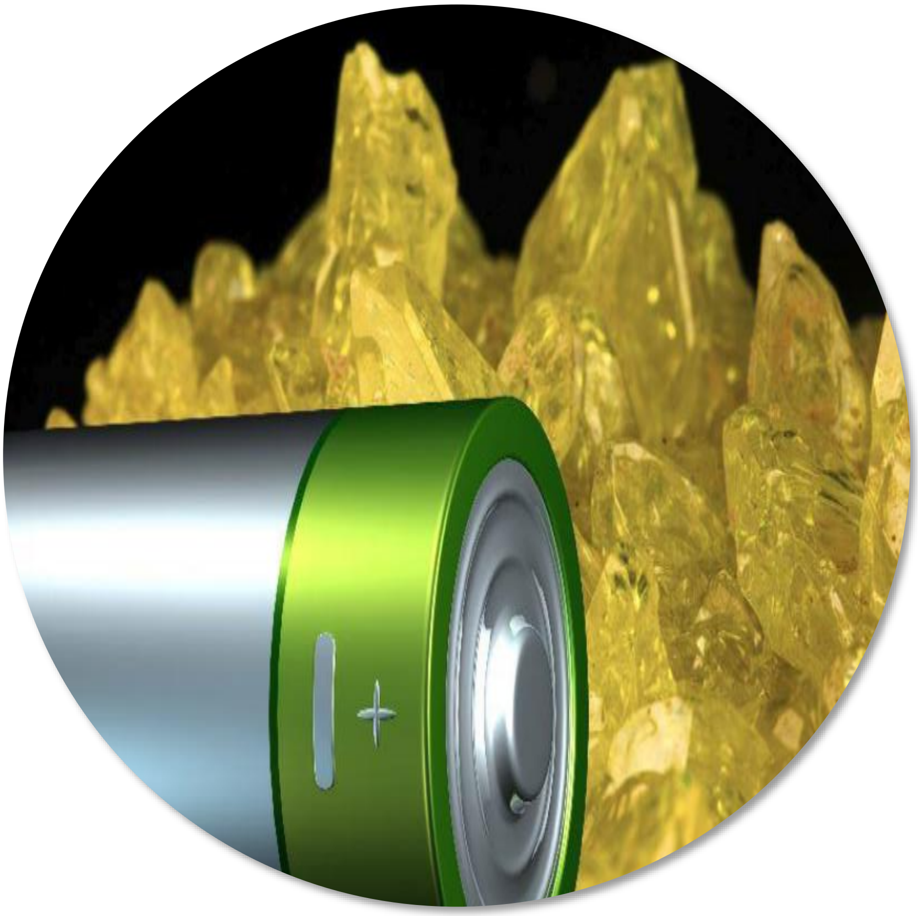
Techno.	Active materials	Electrolyte	Separator	Battery cells	Recycling
Li-S Battery	LG Chem; BOSCH; SEEO; Central South University; Zhaoqing University; SAMSUNG	LG Chem; BASF The Chemical Company; SAMSUNG; GM; Zhejiang University; Sion Power	GM; LG Chem; Zhejiang University; Central South University; Tsinghua University; Shenzhen Peicheng Technology Co., Ltd.	OXIS energy; Sion Power; LG Chem; SAMSUNG; TOYOTA; Global Graphene Group	Central South University
Na-Ion Battery	Central South University; Shaanxi Univ. of Science & Tech.; Wuhan University; Zhejiang University; Pekin University	CATL; AGC; SUMITOMO CHEMICAL; Institute of Physics CAS; TOYOTA; Pekin University	Zhejiang University; TOYOTA; SHARP	SUMITOMO CHEMICAL; SUMITOMO ELECTRIC; TOYOTA; Global Graphene Group	Kunming Univ. of Science & Tech.
Organic Redox flow Battery	CMBlu; Lockheed Martin; University of Kentucky; The University of Chicago; Chinasalt Jintan	Jiangxi Univ. of Science & Tech.; SAMSUNG; Seoul National University; Chinasalt Jintan; CMBlu; C-TRI	Dalian Inst. of Chemical Physics; Lockheed Martin; SAMSUNG	Jiangxi Univ. of Science & Tech.; Lockheed Martin; acal energy; Panasonic SANYO; SAMSUNG; Chinasalt Jintan	No patents

Figure 9: Main IP Players by Technologies and Supply Chain Segments according to their number of patent families

Techno.	Active materials	Electrolyte	Separator	Battery cells	Recycling
Li-S Battery	BOSCH SEEO cea BASF The Chemical Company ARKEMA VW	SOLVAY BASF The Chemical Company Schott N.Y.C. BOSCH SEEO DAIMLER	BOSCH SEEO BASF The Chemical Company DAIMLER	BOSCH SEEO OXIS ENERGY Next Generation Battery Technology DAIMLER BASF The Chemical Company cnrs cea	No European IP Player
Na-Ion Battery	cnrs FARADION cea BELENOS Clean Power Holding Ltd Université de Picardie Jules Verne Collège de France 1530 LithiumWerks New Energy. New World.	cnrs SOLVAY JÜLICH Forschungszentrum Collège de France 1530	BASF The Chemical Company cnrs GORE Creative Technologies Worldwide Université de Picardie Jules Verne BlueSolutions Bolloré	FARADION cea BlueSolutions Bolloré	No European IP Player
Organic Redox flow Battery	CMBlu Organic Flow Batteries cnrs SOLVAY	CMBlu Organic Flow Batteries DAIMLER	No European IP Player	acal energy Clean affordable power JENA BATTERIES University of Chester University of Jena cnrs	No patents

Figure 10: Main European IP Players by Technologies and Supply Chain Segments according to their number of patent families

LITHIUM-SULFUR BATTERY



Principle

The Lithium-Sulfur (Li-S Battery) is a type of rechargeable battery comprising a Lithium anode and a cathode containing Sulfur (most of the time mixed with Carbon).

During the discharge: Lithium metal anode reacts to produce Li+ ion and an electron. Li+ ions migrate to the cathode where the Sulfur is reduced to Lithium polysulfides and Lithium Sulfides (Li2S).

During the charge: Li2S is reoxidized to Sulfur and produce Li+ ions. Li+ ions migrate to the anode where Lithium metal is electroplated.

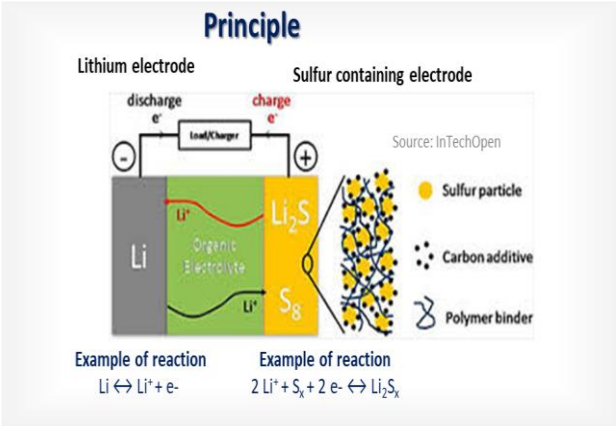


Figure 11: Principle of Li-S Battery

Advantages and Drawbacks

Advantages	Drawbacks
• High theoretical energy density (2,7 kWh/kg, 500Wh/kg expected in practical cells) • Use light materials, sulfur is cheap and abundant. • Operability at low temperature (-40°C) • Environmentally friendly • Full discharge capacity and tolerance to over-discharge • Long shelf-life	• Use of lithium metal (stability and safety concerns) • Expensive • Charging/discharging issues resulting in a huge drop in efficiency and an increased self-discharge mainly due to polysulfide shuttle effect that is responsible for the progressive leakage of active material from the cathode. • Low cycle life • Sulfur is a poor electronic conductor when used in positive electrode. • Li_2S formed during discharge is also an electrical insulator.

Table 7: Main advantages and drawbacks of Li-S Battery

Challenges and Envisioned Solutions

- **Increase battery life duration (reduce efficiency drop and self-discharge increase)**
  - Improve Lithium electrode protection
  - Reduce undesired reactions within the electrolyte (main polysulfides are soluble in the electrolyte inducing an irreversible loss of sulfur and increase of electrolyte viscosity.)
  - Reduce the presence of polysulfides within the electrolyte
  - Increase sulfur electrode conductivity and resistance to mechanical stress (Li_2S and sulfur have a low electric conductivity)
- **Improve safety**
  - Improve Lithium electrode protection (avoid electrode plating and ignition risks)
  - Improve its Battery Management System
  - Develop solid electrolytes for Li-S batteries

Main Market Players

Oxis Energy, Nohms, Amprius, Samsung SDI, GS Yuasa, Sony, Varta, Ficosa, Daramic, Idneo, Solvionic, Arkema, BASF, Covestro, FMC, Asahi Kasei, Toray Industry, 3M, Sumitomo Chemical, Solvay, Bayer, Bosch, Lithium Balance etc.

Lithium electrode protection: PolyPlus Battery, Sion Power, Rockwood Lithium

Envisioned Applications for Li-S Battery

Aeronautic applications, Space applications, Automotive applications

IP Dynamics

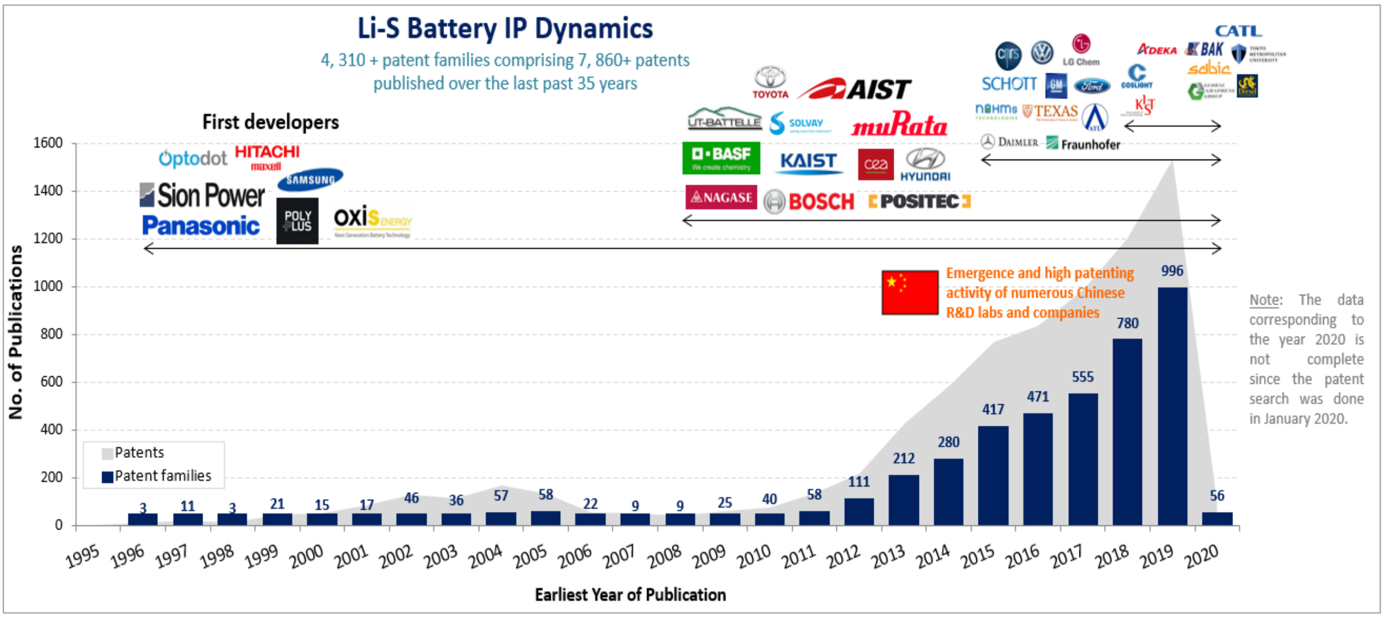


Figure 12: IP Dynamics for Li-S Battery (Number of patent families and patents annually published by earliest publication year)

Pioneer patents on Li-S battery have been published in the 1970's by **Aerojet Rocketdyne, Nifco, Rockwood lithium** and **Varta**. There were related to battery cell, manufacturing of Lithium sulfide compounds, Sulfur positive electrode and Lithium metal electrodes. Patenting activity on Li-S battery emerged in the mid 1990's thanks to the high patenting activity of Japanese and Korean battery manufacturers (**Panasonic, Hitachi Maxell, Samsung**) and American and British pure play companies (**PolyPlus Battery, Sion Power, Oxis Energy, Optodot**). After the economic crisis in the late 2000's, the renewal of automotive industry leads to a reinforcement of researches on post Li-ion batteries enabling the removal of technological barriers and opening new doors to Li-S technology. In fact, at this period, automotive manufacturers start to show a growing interest for the development of electric vehicles and thus batteries. This growing demand for more performant and safe batteries leads to growing R&D efforts from companies and R&D labs on Li-ion batteries but also alternative battery technologies with theoretical better performances than Li-ion batteries. Since 2010, patenting activity on Li-S battery is booming (+75% CAGR between 2006 and 2019) mainly due to the emergence and the high patenting activity of numerous Chinese R&D Labs and companies. At the same time, numerous material manufacturers (**BASF, Solvay, Nagase, Adeka, Schott, Global Graphene, etc.**), battery manufacturers (**LG Chem, Murata, BAK, CATL, ATL, Nohms Technology, etc.**), R&D labs (**AIST, KAIST, CEA, CNRS, Fraunhofer, KIST, UT Battelle, University of Texas, etc.**) and end-users (**Toyota, Hyundai, Positec, Bosch, Volkswagen, GM, Ford, Daimler, etc.**) have entered the patent landscape. The second wave of patent filings combined with an increase in patent extensions worldwide is an indication of the technology growing maturity and market interest for Li-S batteries.

IP Dynamics by Countries

- Since 2011, numerous Chinese R&D labs and industrial companies are entering Li-S battery patent landscape, leading to a booming patenting activity in China. It is worth to note that since 2014 patenting activity in China strongly increases while patent activity in other countries is stable or slightly increasing.

- Numerous European car manufacturers are entering Li-ion battery patent landscape, indicating a growing interest of company active in battery field for Europe. This interest in Europe could also be seen within next years if Li-S battery reaches a higher market share. Thus, patenting activity on Li-S battery in Europe could also increase within next years.

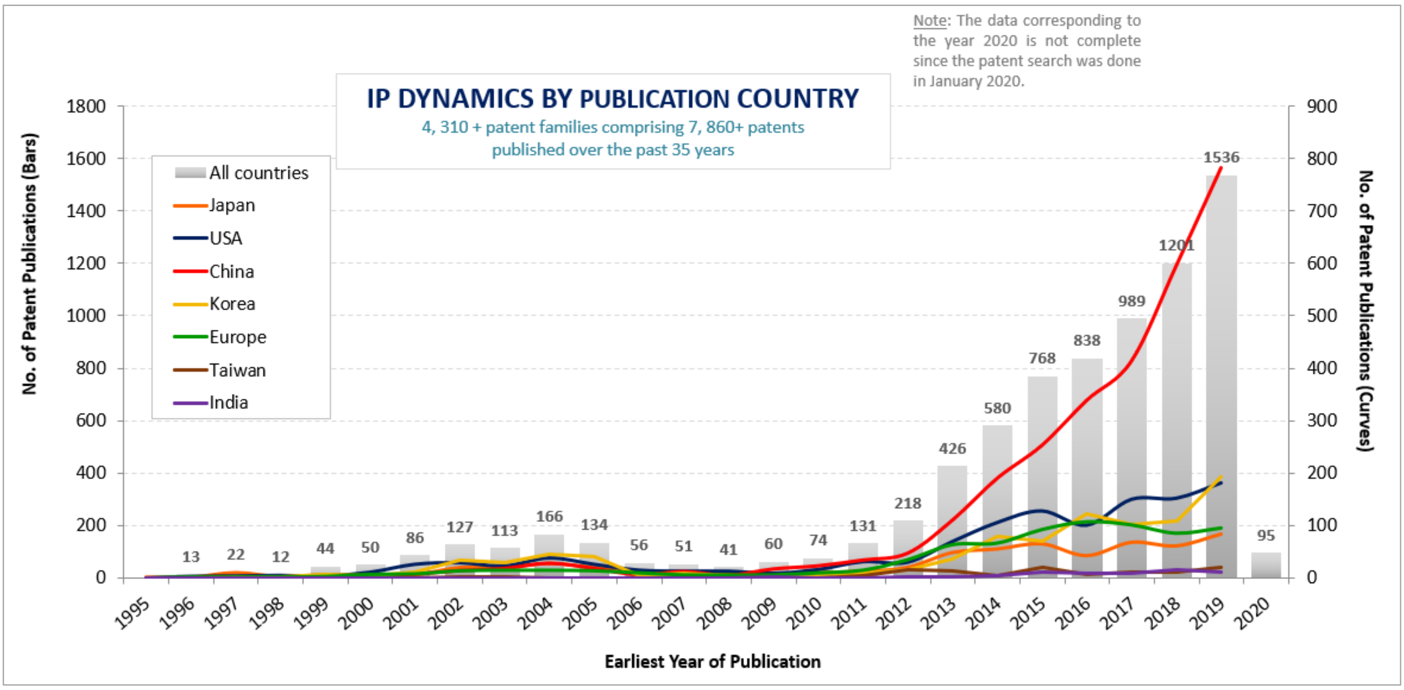


Figure 13: IP Dynamics by Publication Countries for Li-S Battery (Number of patents annually published by earliest publication year and by countries)

Main IP Players

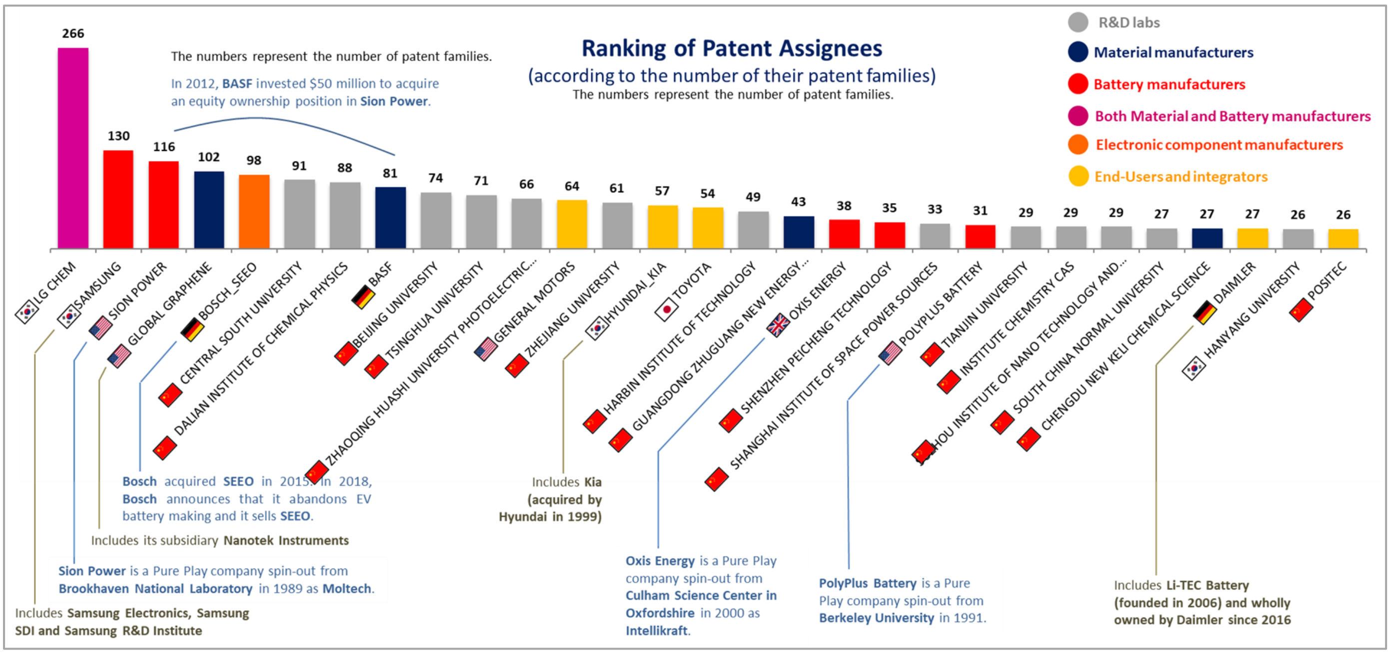


Figure 14: Ranking of Patent Assignees according to the number of their patent families related to Li-S Battery

- More than **810 organizations** have filed patents related to Li-S battery. 47% of patent assignees holds only one patent family. **The top 10 and top 5** patent applicants hold respectively **26%** and **16%** of the patent families.

• Main patent assignees are mainly Chinese R&D labs. However, there are also numerous industrial companies from the whole supply chain confirming their strong interest for this trendy technology. There is no recycler among main patent assignees. There is no European R&D lab among main patent assignees according their number of patent families.

• Well-known Korean battery manufacturers (**LG Chem** and **Samsung**) dominate the patent landscape. Several non-Asian pure-play companies are among the main IP players (**Sion Power, Global Graphene, PolyPlus Battery, Oxis Energy**). There are only few European companies among the main IP Players (**Bosch, BASF, Oxis Energy, Daimler**). Several car manufacturers are among the main IP players (**Toyota, General Motors, Hyundai/Kia, Daimler**) highlighting the fact that this technology could be used in EVs/HEVs. There are no Japanese companies (except **Toyota**) among main IP Players.

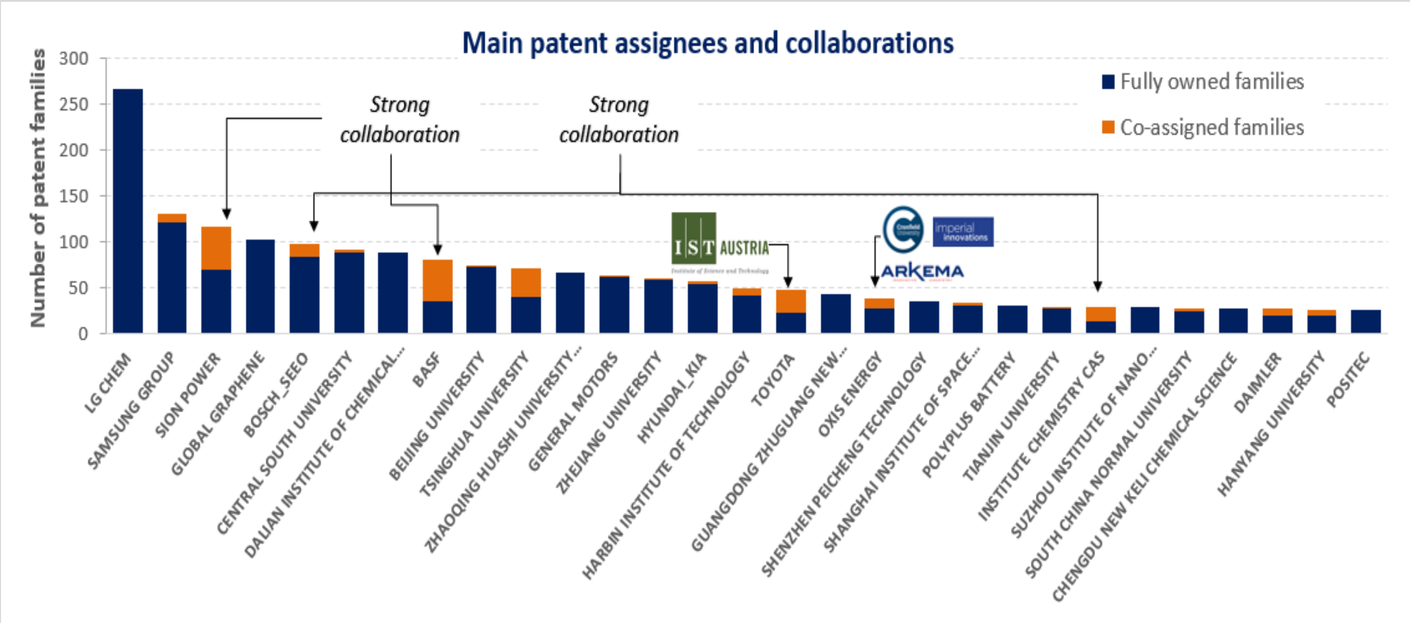


Figure 15: Number of co-assigned patent families by main patent assignees in Li-S Battery patent landscape

Main IP Players by Type of Companies

Material Manufacturers

GLOBAL GRAPHENE	102
BASF	81
G.Z. NEW ENERGY TECH.	43
CHENGDU NEW KELI CHEM. SCI.	27
SOLVAY	25
DUPONT	14
SABIC GLOBAL TECHNOLOGIES	12
NAGASE	12
ARKEMA	10
ALBEMARLE	10
CHINA ENERGY LITHIUM	9
NOHMS TECHNOLOGIES	9
HAITAI NANO MATERIAL	8
POSCO	8
SHANDONG YUHUANG CHEMICAL	8
Q.N. NEW ENERGY TECH.	7
SCHOTT	6
OPTODOT	6
LYTEN	5
SUMITOMO RUBBER INDUSTRIES	5
HERAEUS	5
TORAY INDUSTRIES	5
KURARAY	4
SJ MATERIALS	4
MITSUBISHI CHEMICALS	4

Battery Manufacturers

LG CHEM	266
SAMSUNG	130
SION POWER	116
OXIS ENERGY	38
POLYPLUS BATTERY	31
HEFEI GUOXUAN HTPE	22
SOUNDON NEW ENERGY TECH.	16
PANASONIC_SANYO	15
COSLIGHT	14
MURATA / SONY	13
SICHUAN HUAKUN ENERGY	10
NEWTURN ENERGY	10
LISHEN	8
FOREVER NEW ENERGY	7
ABRI	7
AMPEREX TECHNOLOGY	6
BAK BATTERY	5
MCNAIR TECHNOLOGY	5
YINLONG ENERGY	5
DONGGUAN MAIKE NEW ENERGY	4
GS YUASA	4
Z.Z. NEW ENERGY TECHNOLOGY	4
SHENZHEN OPTIMUM BATTERY	4
BLUE SOLUTIONS_BOLLORE	4
SHENZHEN HYB BATTERY	4
E-SQUARE TECHNOLOGIES	4

Electronic Component Manufacturers

BOSCH_SEEO	98
FOXCONN	19
CHINA ELECTRONIC TECH.	17
SUMITOMO ELECTRIC IND.	7
II VI	3
INTERGRATED POWER TECH.	3
RICOH	3
DENSO	2
INTEL	1
NAMLAB	1
IRICO	1

End-Users and Integrators

GENERAL MOTORS	64
HYUNDAI_KIA	57
TOYOTA	54
DAIMLER	27
POSITEC	26
CHERY AUTOMOBILE	11
VOLKSWAGEN	11
GUIZHOU MEILING POWER SUPPLY	6
HUAWEI	6
DAIHATSU MOTOR	6
HYDRO QUEBEC	5
BMW	5
NISSAN	5

R&D Labs

CENTRAL SOUTH UNIV.	91
DALIAN INST. OF CHEMICAL PHYSICS	88
BEIJING UNIV.	74
TSINGHUA UNIV.	71
Z.H. UNIV. PHOTOELECT. IND. RES. INST.	66
ZHEJIANG UNIV.	61
HARBIN INST. OF TECH.	49
SHANGHAI INST. OF SPACE POWER SCES	33
TIANJIN UNIV.	29
INSTITUTE CHEMISTRY CAS	29
SUZHOU INST. OF NANO TECH.	29
SOUTH CHINA NORMAL UNIV.	27
HANYANG UNIV.	26
SHANGHAI JIAO TONG UNIV.	25
WUHAN UNIV.	25
GYEONGSANG NAT. UNIV.	25
UNIV. OF XIAMEN	24
AIST	24
DALIAN UNIVERSITY OF TECHNOLOGY	23
XI AN UNIVERSITY OF TECHNOLOGY	23
UNIST	22
SHAANXI UNIV. OF SCI. & TECHN.	22
UNIVERSITY OF CALIFORNIA	22

Table 8: Ranking of main Patent Assignees by Type of Companies according to their number of patent families related to Li-S Battery (Time period: 1970-2020, i.e. all patent families in the patent landscape). European companies are written in orange color. The numbers represent the number of patent families of the corresponding patent assignee in Li-S Battery patent landscape.

Pioneer IP Player with a decreasing patenting activity: POLYPLUS BATTERY
Pioneer IP players still active: SAMSUNG, SION POWER
Most active IP players in 2019: CENTRAL SOUTH UNIV., ZHEJIANG UNIV., LG CHEM, GLOBAL GRAPHENE, Z.H. UNIV. PHOTOEL. IND. RES. INST.

Earliest year of publication for each patent family

Patent assignee	Nb of patent families	Average age of the patent portfolio	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
POLYPLUS BATTERY	31	17		1	1	1	3	4	4	5	1	2	3	2	1						2				1			
SAMSUNG	130	14					1		1	20	12	41	33			1					1	1		3	10	1	5	
SION POWER	116	10		2	3		8	7	8	4	1	1	4	1	2	2	4	2	6	7	4	11	13	7	7	10	2	
OXIS ENERGY	38	8										1	4	7	2	2				1		5	8	2	2	3	1	
POSITEC	26	7																1	2	3	7	8	4	1				
BOSCH_SEEO	98	6																8	3	10	20	10	18	18	9	2		
BASF	81	6																	4	17	12	7	16	8	9	6	2	
HYUNDAI_KIA	57	6																	1	4	9	12	18	12	1			
TOYOTA	54	6											1	1			3	4	2	7	10	3		2	6	9	8	
DAIMLER	27	5																	2			2	10	7	3	2	1	
DALIAN INST. OF CHEM. PHYS.	88	4																			4	12	10	17	17	14	13	1
BEIJING UNIV.	74	4															3	8	1		4	4	9	11	8	14	12	
TSINGHUA UNIV.	71	4												1			2			1	7	3	11	8	15	12	12	1
GENERAL MOTORS	64	4																		1	1	4	20	13	6	5	14	
G.Z. NEW ENERGY TECH.	43	4																					24	16	3			
SHANGHAI INST. OF SPACE POWER SCES	33	4																		3	1	1	5	10	7	1	5	
INSTITUTE CHEMISTRY CAS	29	4																		2	4	2	7	4	5	3	2	
SUZHOU INST. OF NANOTECH.	29	4																			6	1	2	6	9	2	3	
HANYANG UNIV.	26	4																1		4	2	4	1	3	3	1	7	
CENTRAL SOUTH UNIV.	91	3															1		2	4	6	6	7	9	17	14	27	
ZHEJIANG UNIV.	61	3																			9	5	12	5	9	11	22	2
HARBIN INST. OF TECH.	49	3																				3	6	3	12	19	6	
SHENZHEN PEICHENG TECH.	35	3																						1	20	14		
SOUTH CHINA NORMAL UNIV.	27	3																	2			2	5	1	2	7	8	
LG CHEM	266	2					1											2			1	3	14	35	38	59	103	10
GLOBAL GRAPHENE	102	2																	1		2	4	5	4	10	32	43	1
TIANJIN UNIV.	29	2																	2		1			1	3	12	11	
Z.H. UNIV. PHOTOEL. IND. RES. INST.	66	1																								17	48	1
CHENGDU NEW KELI CHEM. SCI.	27	1																							1	7	19	

Table 9: Time Evolution of Patent Publications by main Patent Assignees and by earliest year of publication for each patent family in Li-S Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignee). European companies are written in orange color. In each cell referring to a publication year, the numbers represent the number of patent families.

- **PolyPlus Battery** is an American company spin-out from **Berkeley University** in 1991. The company has invented and patented a Lithium anode (PLE) which can be used in Li-S, Li-Air and Lithium-Water Battery.
- **Sion Power** is an American company spin-out from **Brookhaven National Laboratory** in 1989 as **Moltech**. The company has also invented and patented a Lithium metal anode (Licerion®) which can be used in Li-S and Lithium metal batteries. In 2012, **BASF** invested $50 million to acquire an equity ownership position in **Sion Power**. Contrary to **PolyPlus Battery** who has strongly decreased its patenting activity since 2008, **Sion Power** still files several new patents per years. This may indicate that **Sion Power** has a higher R&D activity than **PolyPlus Battery**.
- **Oxis Energy** is a British Pure play company focused on Li-S battery and spin-out from **Culham Science Center** in Oxfordshire in 2000 as **Intellikraft. Oxis Energy** restarts its patenting activity in the mid 2010's after several year without new patent publication.
- **Global Graphene** is an American group founded in 2007. It develops, sells and licenses advanced graphene raw materials and nanocomposites for next-generation products such as phones, tires, paints and batteries.
- Two major Korean battery manufacturers (**Samsung** and **LG Chem**) have different IP strategies. **Samsung** was among the first Li-S battery developers and has a high patenting activity on this topic until 2005. It re-increases its patenting activity on this topic recently in 2016-2017. On the contrary, **LG Chem** starts its patenting activity on Li-S battery in 2010 and has strongly increased it since 2015.

Newcomers in the patent landscape

- Newcomers are companies who started their patenting activity in 2017. There are more than 390+ newcomers in the Li-S battery patent landscape.
- New comers are mainly Chinese R&D labs (*Institute Of Coal Chemistry, Shenzhen University, Dongguan University of Technology, University of Jinan, Shaanxi University of Science and Technology, Donghua University, Anhui Normal University, Zhaoqing Huashi University Photoelectric Industry Research Institute, Harbin University of Science and Technology, etc.*) and Companies (*Lishen, Chengdu New Keli Chemical Science, Haitai Nano Materials, Shenzhen Qichen New Energy Technology, BAK Battery, Soudon New Energy Technology, Coslight, Sichuan Huakun Energy, Yinlong Energy, Sinochem, CATL, AVIC, SAIC Motor, NIO NextEV, BTR New Energy Materials, Tianmu Anode Material, Dynabat, etc*.).
- Among newcomers, there are also notable American IP players (*Cabot, Ford, Intel, Navitas Systems, University of Michigan, Drexel University, Johns Hopkins University, Monolith Materials, Hexcel, Columbia University*, etc.) , European IP Players (*Covestro, Cidetec, TU. Darmstadt, Uni. Picardie, Repsol, Ubatt, Graphene Batteries, SAFT/Total, AIT, Forschungszentrum Juelich, Max Planck institute, Iontech Systems, Université de Grenoble, Shell, Grabat Energy,* etc.), Japanese IP Players (*TEPCO, Tokyo Metropolitan University, Kuraray, Abri, Adeka,* etc.) and Korean IP Players (Ubatt, etc.).
    - **Monolith Materials** is an American start-up founded in 2012. It produces and markets carbon materials, especially carbon black.
    - **Covestro** is a German Chemical company spin-out from **Bayer** in 2015 and formerly called Bayer Material Science. It manufactures polymers and high-performance plastics.
    - **Cidetec** is a Spanish private organization for applied research founded in 1997. It is comprised of three international technological reference institutes in energy storage, surface engineering and nanomedicine.
    - **Repsol** is a Spanish company which produces crude oil, natural gas, petroleum, hydrocarbon products. Recently, it enters renewable energies market.
    - **Ubatt** is a Korean start-up founded in 2016 on the basis of R&D developments of UNIST. Ubatt's core technologies include solution-processable/non-flammable solid-state electrolytes, scalable printing/impregnation processes, Lithium-based batteries and customized cell design/configuration.
    - **Graphene Batteries** is a Norwegian start-up founded in 2012. It is engaged in the development of Li-S battery technology enhanced with Graphene derivatives (supplied by its sister company **Abalonyx**).
    - **Iontech Systems** is a Swiss company founded in 2016. It develops and manufactures equipment, materials and accessories for the battery market.
    - **Grabat Energy** is a Spanish battery manufacturer founded in 2012 (subsidiary of **GrapheneNano**). It manufactures graphene polymer cells for different types of batteries. It works with the University of Cordoba and has a strategic agreement with the CHINT Group.
    - **Abri** is a Japanese joint venture established in 2017 between **Furukawa Battery** and **Tokyo Metropolitan University**. It develops higher performance Li-ion and post Li-ion batteries and materials used therein.

Current Legal Status of Patents

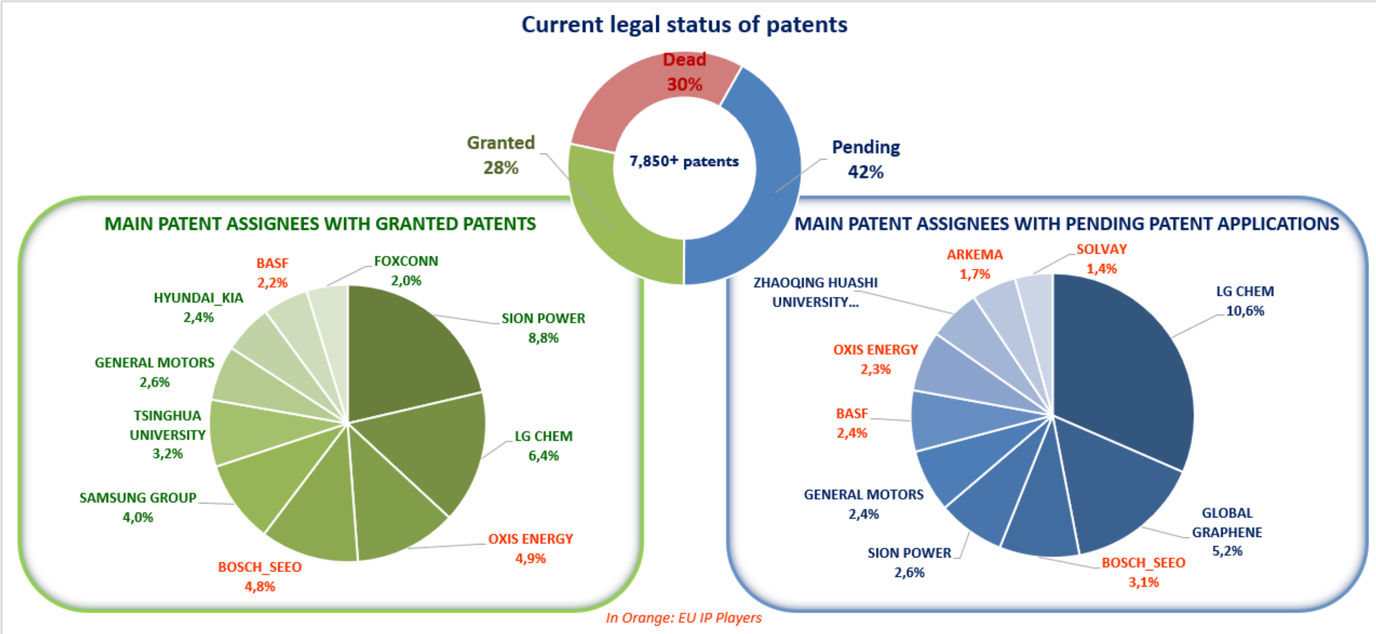


Figure 16: Current legal status and main patent assignees with granted patents and pending patent applications for Li-S Battery. European companies are written in orange color.

More than 70% of the patents in Li-S battery patent landscape are currently pending or granted. This reflects that many R&D developments are still on-going to solve current technical issues related to Li-S battery. **Sion Power, LG Chem, Oxis Energy, Bosch/SEEO** and **Samsung** hold the highest number of granted patents. **LG Chem, Global Graphene, Bosch/SEEO, Sion Power** and **General Motors** hold the highest number of pending patent applications. European IP players show great patenting activities. Indeed, **BASF, BOSCH** and **OXIS Energy** are among the only 4 IP players (with LG Chem) to be in the top 10 of established and active IP players, i.e. IP players with the highest number of granted patents and pending patent applications

Legal Status by Countries

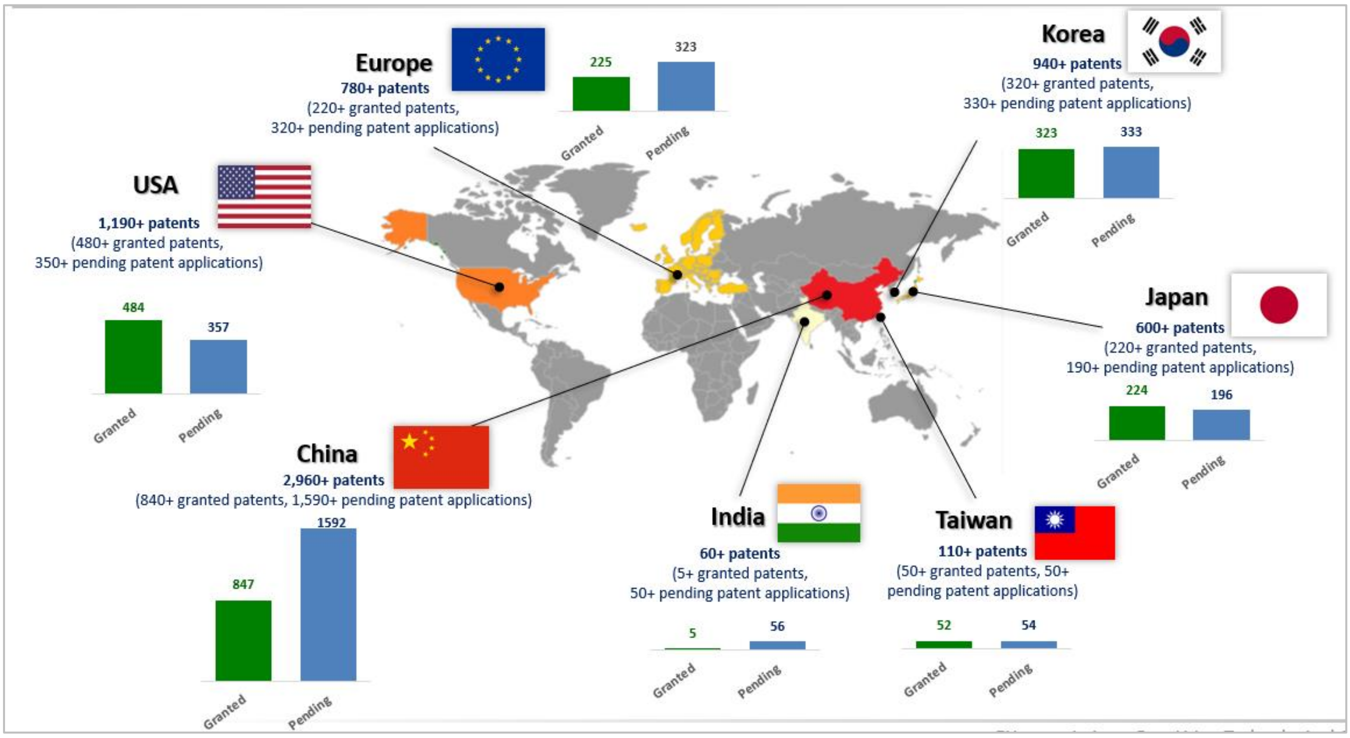


Figure 17: Mapping of Legal Status by Countries for Li-S Battery

Pending patent applications are mainly filed in China. In fact, there are numerous Chinese IP Players with a high patenting activity in the patent landscape. Most of them focus their patenting activity in China. The strong activity in China is not surprising as a lot of batteries (Li-ion and others) are produced in China. It is worth to note that more than 10% of pending applications have been filed in Europe.

Most Active IP Players by Countries

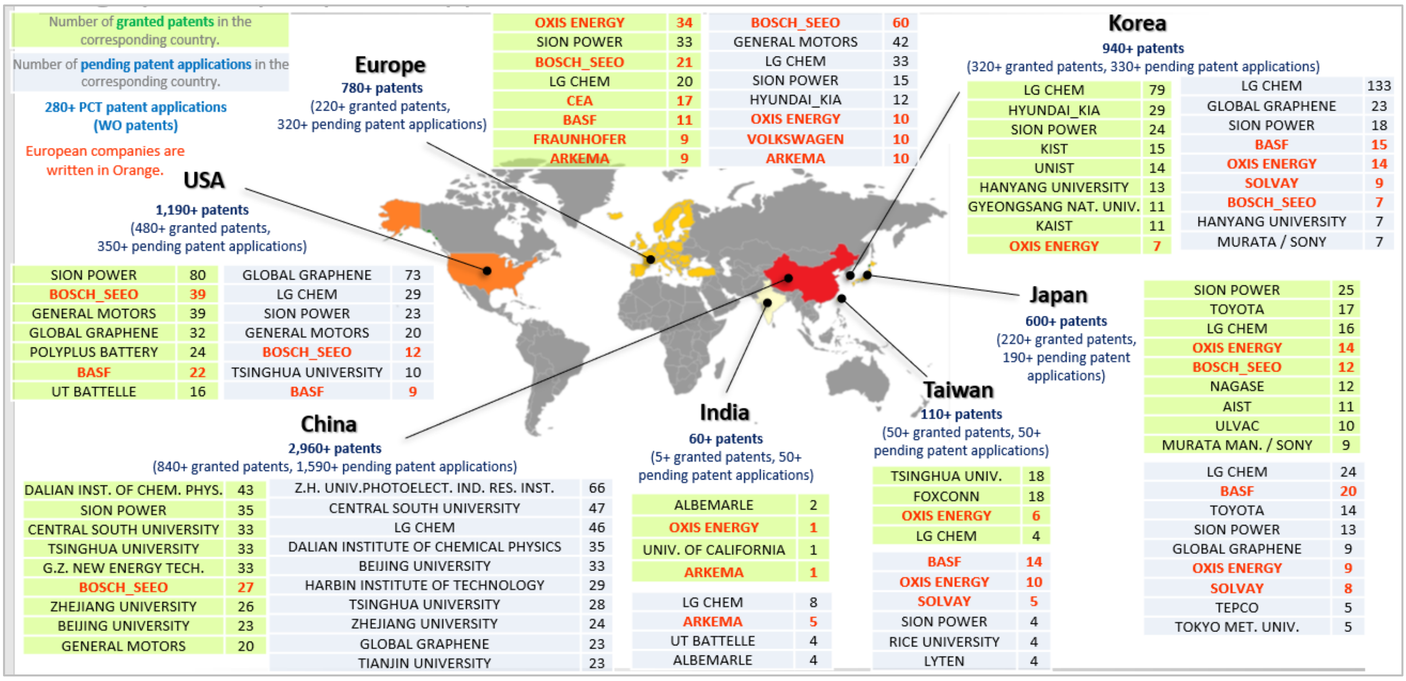


Figure 18: Main current patent assignees by countries for Li-S Battery

Patents in Europe are not only filed by European IP Players but also by foreign companies (**Sion Power, LG Chem, General Motors, Hyundai/Kia,** etc.). It is worth to note that **Sion Power** has a strong partnership with **BASF**, explaining its high patenting activity in Europe. Li-S battery R&D developments are driven by automotive applications. Europe represents an important market for car manufacturers. Thus, patenting activity in Europe should increase within next years.

Patenting Activity of IP Leading Companies

Most of main Chinese IP players only file patents in China, except **Tsinghua University, Zhejiang University, Shenzhen Peicheng Technology, Shanghai Institute of Space Power Sciences, South China Normal University** and **Positec** who file WO patents or extend their patents in other countries (Table 10). **Tsinghua University** has several patents co-assigned with **MIT** or **Foxconn** who has an international market strategy.

Main IP players originating from other countries than China, including European companies, have a worldwide IP strategy. Thanks to their global IP strategies, **BASF, Oxis Energy and Bosch** can and will continue to hamper the freedom to operate of their competitor all around the word (Table 10).

Only few companies **(Albemarle, Oxis Energy, Arkema, University of California**) have granted patents in India (Table 10). However, it is worth to note that several major companies in battery field (**LG Chem, Sion Power, BASF, Toyota, etc.**) have pending patent applications in India (Table 10). In fact, India becomes an attractive market for battery manufacturers due to Indian government policies to push the conversion towards EVs/HEVs. Thus, European IP leaders in the field of Li-S batteries are already competing against the Asian giant in this promising country.

Assignee	Number of Patent families		Patent Legal status			Number of granted patents							Number of pending patent applications							
	All	Alive	Granted	Pending	Dead	USA	Europe	Japan	China	Korea	Taiwan	India	USA	Europe	Japan	China	Korea	Taiwan	India	PCT applications (WO patents)
LG CHEM	266	249	143	353	54	13	20	16	11	79	4		29	33	24	46	133		8	80
SAMSUNG	130	41	89	33	221	26	8	19	18	18			6	3	6	4	13			1
SION POWER	116	81	197	86	287	80	33	25	35	24			23	15	13	7	18	4	1	5
GLOBAL GRAPHENE	102	102	32	173	7	32							73		9	23	23			45
BOSCH_SEEO	98	86	106	102	118	39	21	12	27	6			12	60	4	18	7			1
CENTRAL SOUTH UNIVERSITY	91	80	33	47	11				33							47				
DALIAN INST. OF CHEM. PHYSICS	88	78	43	35	10				43							35				
BASF	81	53	49	78	145	22	11	5	9	2			9	9	20	6	15	14	1	4
BEIJING UNIVERSITY	74	56	23	33	18				23							33				
TSINGHUA UNIVERSITY	71	63	72	44	23	14		7	33		18		10			28		1		5
Z.H. UNIV. PHOTOEL. IND. RES. INST.	66	66		66												66				
GENERAL MOTORS	64	59	59	80	25	39			20				20	42		18				
ZHEJIANG UNIVERSITY	61	50	26	29	11				26				1	1	2	24				1
HYUNDAI_KIA	57	40	53	28	46	12		6	6	29			1	12	2	8	5			
TOYOTA	54	42	35	40	35	10	3	18		3			6	3	17	7	2	1	1	2
HARBIN INSTITUTE OF TECHNOLOGY	49	44	15	29	5				15							29				
G.Z. NEW ENERGY TECHNOLOGY	43	33	33		10				33											
OXIS ENERGY	38	37	110	77	59	14	34	14	13	7	6	1	8	10	9	8	14	10	1	4
SHENZHEN PEICHENG TECHNOLOGY	35	29	9	20	6				9							6				14
SHANGHAI INST. OF SPACE POWER SCES	33	26	15	12	7				15							11				1
POLYPLUS BATTERY	31	9	42	2	135	24	1	3	3	2					1					
TIANJIN UNIVERSITY	29	27	4	23	2				4							23				
INSTITUTE CHEMISTRY CAS	29	26	25	23	18	7	2	1	15				4	4	3	7	3			1
SUZHOU INST. OF NANOTECH.	29	26	20	6	4				20							6				
SOUTH CHINA NORMAL UNIVERSITY	27	23	8	16	4				8							15				1
CHENGDU NEW KELI CHEMICAL SCIENCE	27	22	1	21	5				1							21				
DAIMLER	27	8	8	8	38	1	2	2	3					8						
POSITEC	26	18	17	8	13	1	1		15				2	1	1	3	1			
HANYANG UNIVERSITY	26	22	23	15	16	5	2	1	2	13			1	1		2	7			4

Table 10: Legal status of patents by countries for main patent assignees in Li-S Battery patent landscape. European companies are written in orange color.

IP Leadership

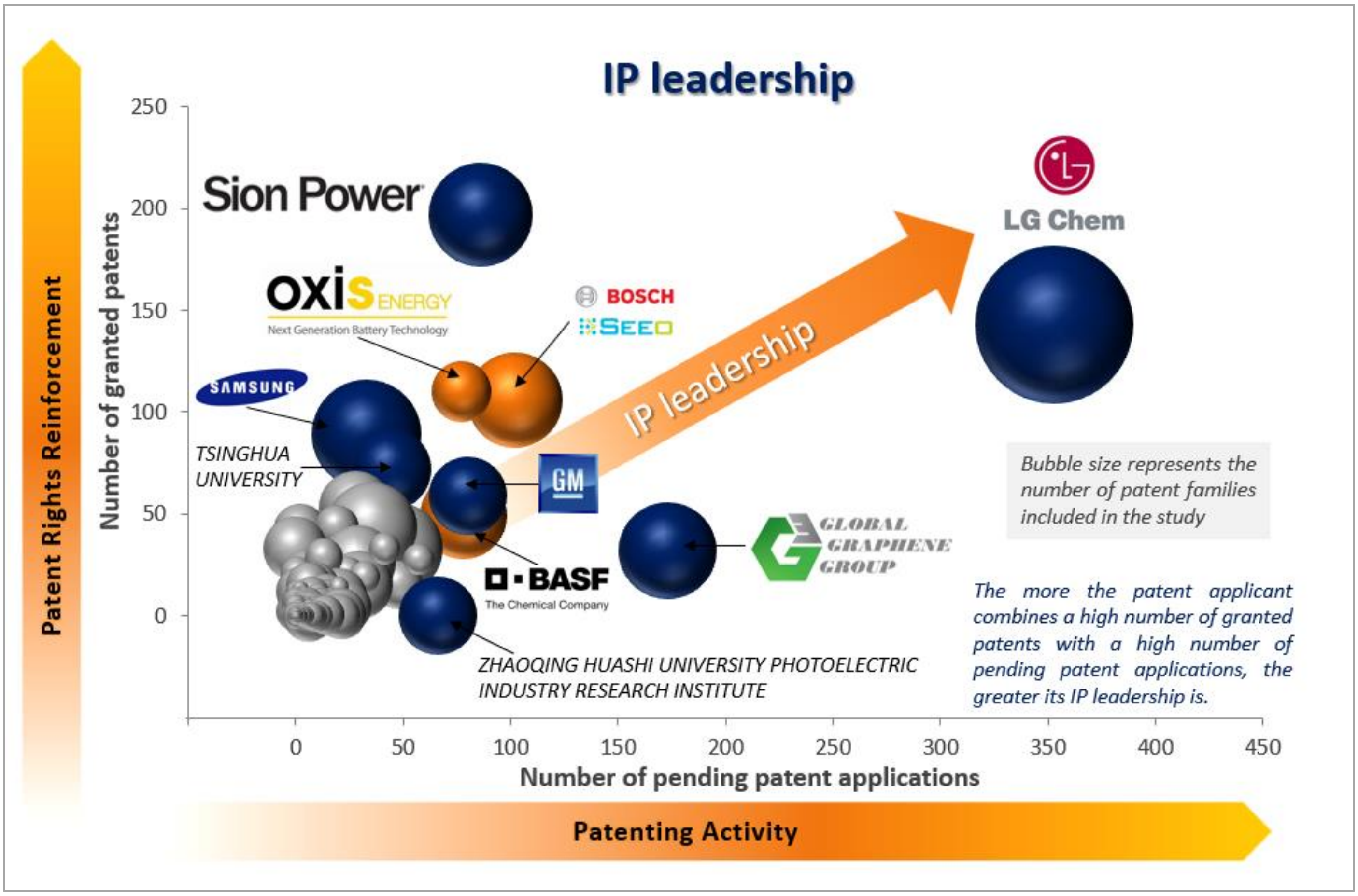


Figure 19: IP Leadership of Patent Assignees for Li-S Battery. Orange bubbles indicate European companies with a notable IP leadership. Blue bubbles indicate Non-European companies with a notable IP leadership. Grey bubbles indicate companies without a notable IP leadership.

- In Figure 19, Only companies with a notable IP leadership (Orange and blue bubbles) have been annotated. Companies with a low IP leadership have grey bubbles and have not been annotated for more clarity on the graph. Thus, if a company having patent families related to Li-S battery is not annotated in the graph, it means that it has a low IP leadership compared to other IP Players.
- **LG Chem** leads Li-S battery patent landscape. It holds the highest number of patent families, granted patents and pending patent applications worldwide. It is worth to note that **LG Chem** has strongly increased its patenting activity on Li-S battery since 2015.
- **Global Graphene** is an IP challenger with the second highest number of pending patent applications worldwide. **Global Graphene** starts its patenting activity on Li-S battery at the same period than **LG Chem** but it has a lower patenting activity each year.
- **Sion Power, Oxis Energy, Bosch/SEEO and Samsung** are established IP players, with a high number of granted patents and numerous pending patent applications worldwide. **Sion Power** is a pioneer IP player still active. **Bosch/SEEO** has decreased its patenting activity on Li-S battery since 2017. **Oxis Energy** has a stable patenting activity. **Samsung** was among the first Li-S battery developers and has a high patenting activity on this topic until 2005. It re-increases its patenting activity on this topic recently in 2016-2017.
- **Tsinghua University, General Motors, BASF and Zhaoqing Huashi University Photoelectric Industry Research Institute** also have a notable number of alive patents. It is worth to note that **BASF** has a strong partnership with **Sion Power** and has several patents co-filed with them.

- Despite a high number of patent families, Chinese IP Players have a relatively low IP leadership because most of them focus their patenting activity in China, i.e. there is only one patent (filed in China) by patent family
- Despite its high number of patent families, **PolyPlus Battery** has a low IP leadership. In fact, it has almost stopped its patenting activity since 2008 and it focuses its patenting activity in the US
- Today the 3 main European IP players have a great IP leadership. Even if they are challenged by American companies (**GM, Global Graphene**), they all exhibit well-balanced patent portfolios (i.e. almost the same number of granted patents and pending patent applications) and will be able to maintain their IP positions in the coming years.

Key IP Players

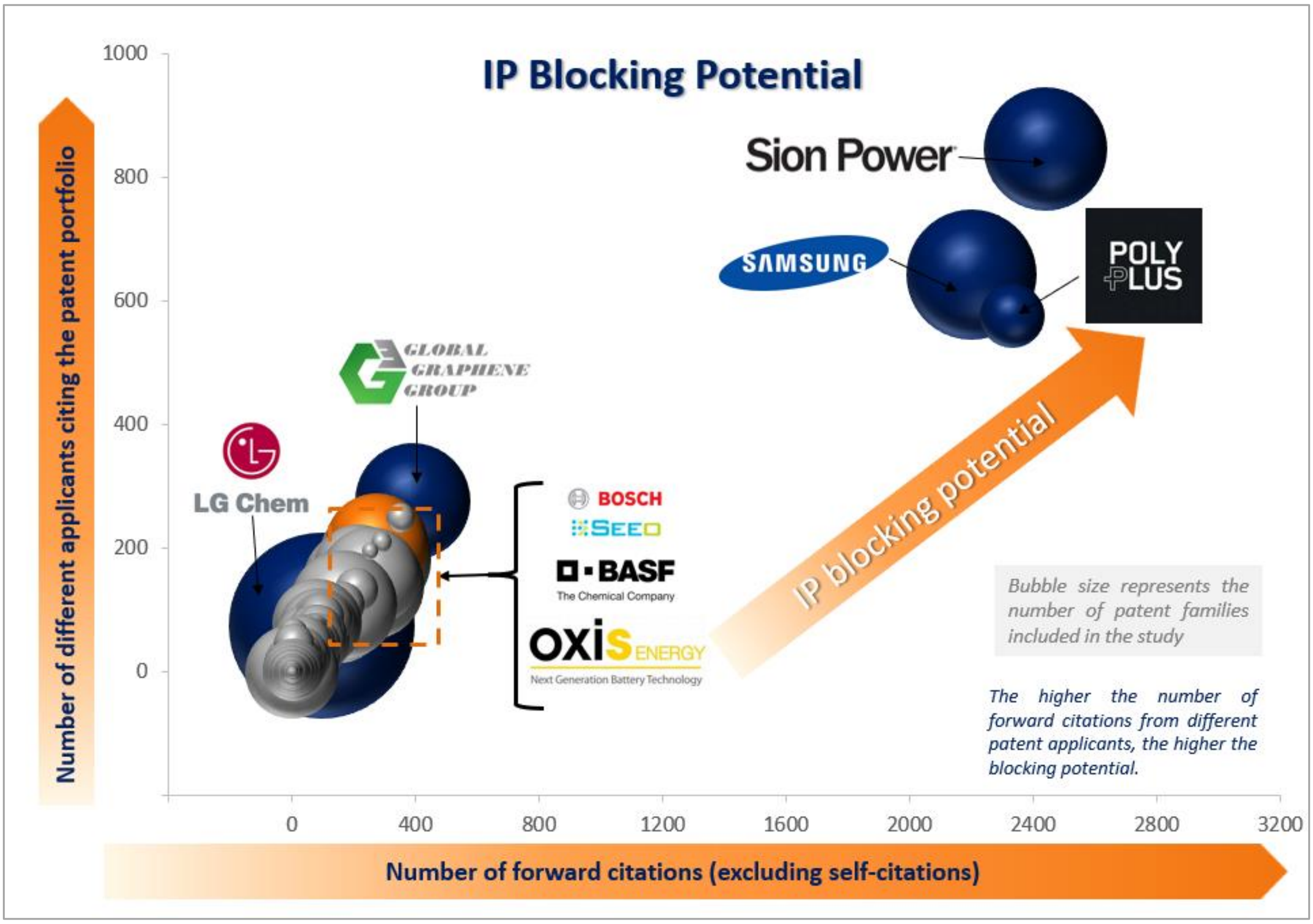


Figure 20: IP Blocking Potential of Patent Assignees for Li-S Battery. Orange bubbles indicate European companies with a notable IP Blocking Potential. Blue bubbles indicate Non-European companies with a notable IP Blocking Potential. Grey bubbles indicate companies without a notable IP Blocking Potential.

- **Sion Power** combines a large patent portfolio with the highest IP Blocking Potential. **Samsung** and **PolyPlus Battery** have the second highest IP Blocking potential far from the other IP Players. Their patents related to Li-S battery strongly contribute to the prior art and have received numerous forward citations from a lot of different patent applicants, meaning that their patent portfolios offer them the capability to block other firms involved in the field. It is worth to remind that **Sion Power**, **Samsung** and **PolyPlus Battery** are pioneer IP players in Li-S battery field that benefit from a strong prior art contribution. Contrary to **Sion Power** who is still among most active IP Players during the last decade, **PolyPlus Battery** has strongly decreased its patenting activity since 2008. **Samsung** had a strong patenting activity on Li-S battery in the early 2000's followed by a period of inactivity and restarted it in 2016.
- Despite their high IP leadership, **Global Graphene** and **LG Chem** have respectively a medium and small IP Blocking Potential. In fact, most of their patents have been filed after 2015 and thus receive only few forward citations. Their

IP blocking potential could be improved within next years. Even if **LG Chem** and **Global Graphene** started their patenting activity at the same period and **LG Chem** has a larger patent portfolio on Li-S battery, **Global Graphene** has a higher IP blocking potential. In fact, its patents receive more forward citations than those held by **LG Chem**.

- European IP Players **Bosch/SEEO, Oxis Energy** and **BASF** combines a notable IP leadership and IP Blocking potential induced by several key patents. In **Bosch/SEEO** patent portfolio, only 2 patent families on 98 patent families gathered under the name "Bosch/SEEO" are assigned only to **SEEO** thus Bosch IP position on Li-S battery should not change if **Bosch** sells **SEEO**.

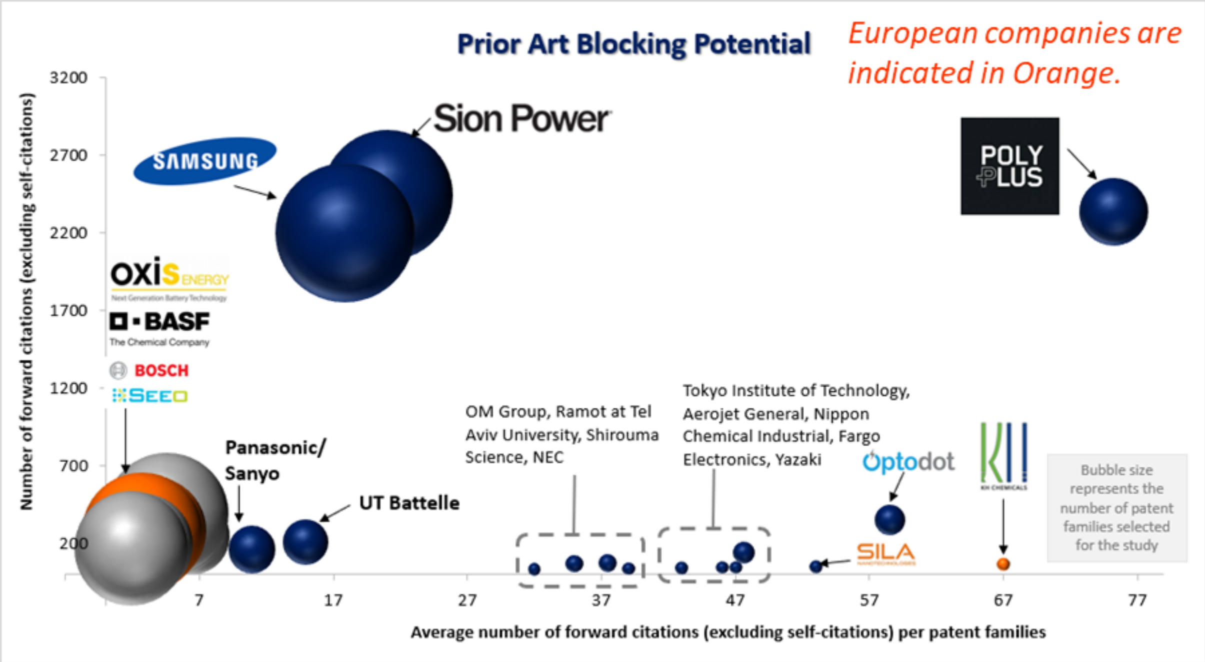


Figure 21: Prior Art Blocking Potential of Patent Assignees for Li-S Battery. Orange bubbles indicate European companies with a notable Prior Art Blocking Potential. Blue bubbles indicate Non-European companies with a notable Prior Art Blocking Potential. Grey bubbles indicate companies without a notable Prior Art Blocking Potential.

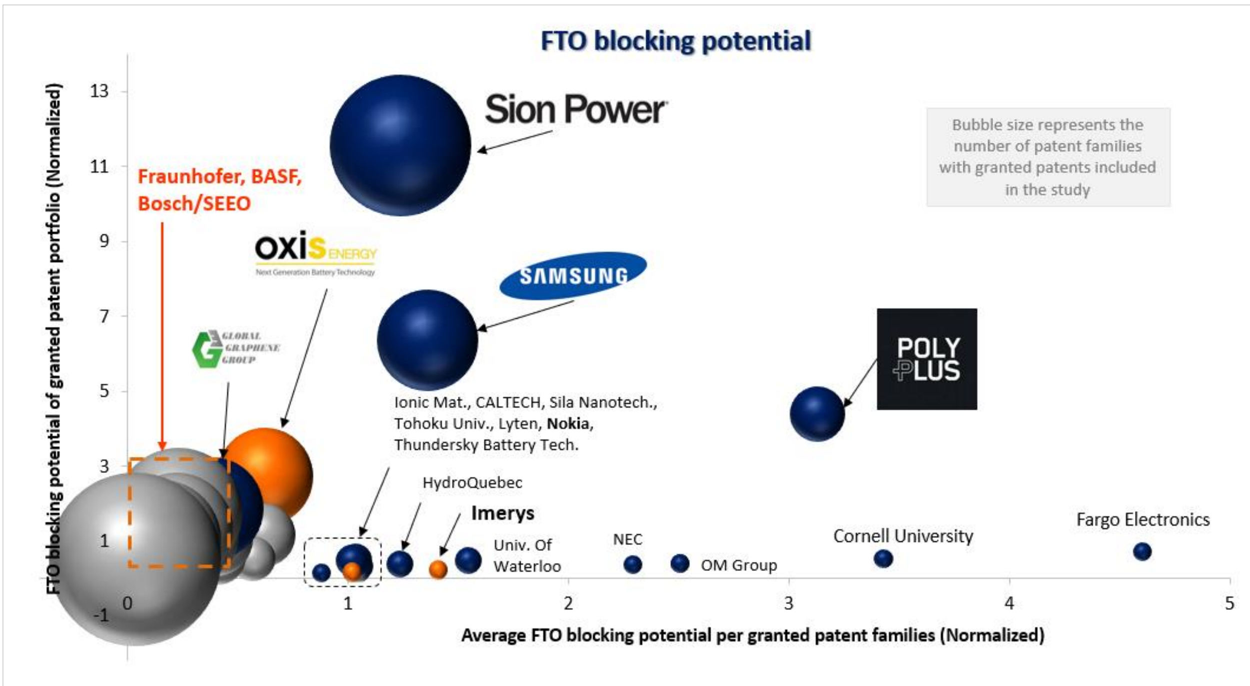


Figure 22: FTO Blocking Potential of Patent Assignees for Li-S Battery. Orange bubbles indicate European companies with a notable FTO Blocking Potential. Blue bubbles indicate Non-European companies with a notable FTO Blocking Potential. Grey bubbles indicate companies without a notable FTO Blocking Potential.

- **Sion Power, Samsung** and **PolyPlus** hold the highest Prior Art blocking potential and FTO blocking potential induced by a high number of patent families and highly cited patents. This indicates that they have a high capability to limit both patenting activity and freedom-to-operate of other companies. **PolyPlus** has a higher technological impact than **Sion Power** and **Samsung** because most of its patents are key patents with numerous forward citations. **Sion Power** and **Samsung** have a higher FTO blocking potential than **PolyPlus** due to their higher number of granted patents and their larger geographic coverage.
- Despite its high IP leadership, **LG Chem** has a low Prior art blocking potential and FTO blocking potential. In fact, most of its patents have been filed after 2015, are still pending and thus receive only few forward citations. Its IP position could be improved within next years
- Despite its high IP leadership, **Global Graphene** has a low Prior Art blocking potential and a medium FTO blocking potential induced by a high technological impact of its granted patents.
- Among European IP players, **KH Chemicals** has a notable technological impact factor. **Oxis Energy, Bosch/SEEO and BASF** have a notable Prior Art and FTO blocking potential induced by highly cited patents granted in numerous countries. It is worth to remind that **BASF** has a strong partnership with **Sion Power**.
- Despite their very small patent portfolio, **KH Chemicals, Optodot, Sila Nanotech., Tokyo Inst. of Tech., Aerojet General, NCI, Fargo Elec., Yazaki, OM Group, Tel Aviv Univ., Shiruma Science** and **NEC** have a high technological impact because they hold key patent families with numerous forward citations. It is worth to note that **KH Chem., Yazaki, NCI, Aerojet General, Tokyo Inst. of Tech.** and **Shiruma Science** have no more granted patents and thus they only have the capability to limit the patenting activity of other companies but don't have the capability to limit freedom-to-operate of other companies. **Sila Nanotech.** is an American start-up spin-out from **Georgia Tech** in 2011 and specialized in silicon-based anodes. **Optodot** is an American company founded in 2000 and specialized in nanoporous membranes. Optodot and LG Chem have signed a patent licensing agreement on Li-ion batteries in 2016 (Link).
- Similarly, despite its very small patent portfolio, **Fargo Elec., NEC, OM Group, Cornell Univ., Imerys, Univ. of Waterloo** and **HydroQuebec** have a high average FTO Blocking potential per patent families induced by highly cited patent families granted in numerous countries.

PATENT SEGMENTATION BY SUPPLY CHAIN SEGMENTS

Overview of Patenting Activity by Supply Chain Segments

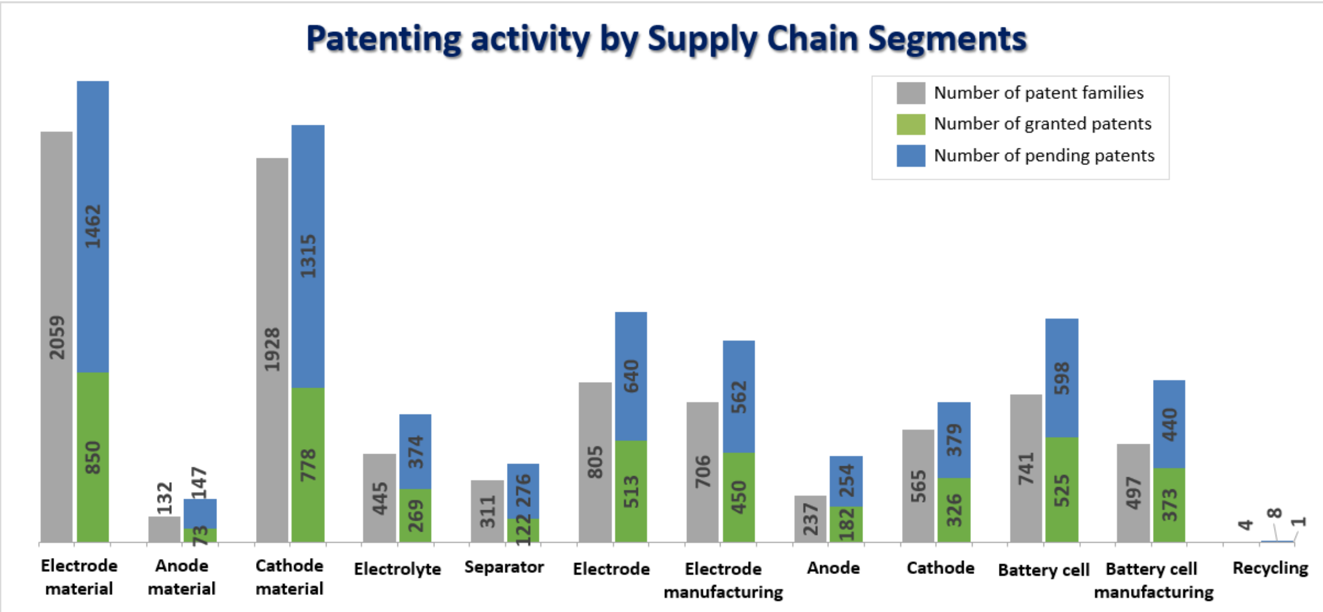


Figure 23: Patenting activity by Supply Chain Segments for Li-S Battery

- Patenting activity by supply chain segments is correlated to main development axes envisioned to improve Li-S battery performances and safety (electrode and electrolyte materials and battery cell).
- Patents on Li-S battery are mainly related to electrode materials, especially cathode materials.
- There are more patents related to the anode at the electrode level than the active material level because the main challenge for the anode in Li-S battery is the protection of the lithium metal electrode.
- There are very few patents on Li-S battery recycling. They are related to recycling method of waste Li-S battery, waste cathode materials and recovering Lithium from Li-S battery. Recycling of Li-S battery is not a topic of interest for the moment because there are no Li-S batteries on the market yet. Companies specialized on battery recycling prefer to focus on recycling of Li-ion battery for which the demand is strongly increasing.

IP Dynamics by Supply Chain Segments

The numbers represent the number of patent families.

Earliest publication year

Supply Chain Segment	Number of patent families	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Electrode material	2059		1	6	2	7	5	2	9	9	13	12	4	1	3	8	16	21	63	102	133	179	223	307	392	509	29
Anode material	132					1					2	4			1		1	2	1	2	6	11	19	17	19	43	3
Cathode material	1928		1	6	2	6	5	2	9	9	11	8	4	1	2	8	15	19	62	100	127	168	205	290	373	466	26
Electrolyte	445			1		3	1		5	6	16	15	6	2	1	3	7	5	10	16	31	39	50	58	74	93	3
Separator	311					1	1				1	1						1	1	9	12	30	30	42	76	100	6
Electrode	805		1	2		5	3	3	17	10	24	13	3	2		6	3	13	19	45	54	86	101	72	143	167	11
Electrode manufacturing	706		1	2		3	3	3	14	7	17	9	3	2		6	2	11	17	41	45	77	95	61	128	146	11
Anode	237			1		2		1	6	2	6	9	1	1				2	5	6	9	22	23	27	52	58	4
Cathode	565		1	1		3	3	2	11	8	18	4	2	1		6	3	11	13	39	45	65	77	45	89	109	7
Battery cell	741		1	3	1	6	5	11	14	10	10	19	10	4	5	8	15	18	19	45	53	92	68	80	101	132	7
Battery cell manufacturing	497		1	2	1	4	3	10	6	6	5	10	3	3	3	5	4	13	11	29	37	68	51	55	73	88	6
Recycling	4																						1	1		1	1

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Table 11: Time Evolution of patent families by supply chain segments and earliest publication year in Li-S Battery patent landscape (Number of patent families annually published by earliest publication year and by supply chain segments)

First patents on Li-S battery were related to cathode materials, anode, cathode and battery cells. Patenting activity on cathode materials, electrode manufacturing and battery cell has strongly increased within last 10 years. Patenting activity on the electrolyte emerged in the early 2000's. Patenting activity on anode materials and separators emerged more recently respectively in 2015 and 2013 and has continuously increased since these dates. Patenting activity on recycling started in 2016 but it is still anecdotic.

Main IP players by Supply Chain segments

IP positions	Electrode material	Anode material	Cathode material	Electrolyte	Separator
Main IP players *(Highest number of patent families)*	LG CHEM, CENTRAL SOUTH UNIVERSITY, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, BEIJING UNIVERSITY, ZHEJIANG UNIVERSITY, BOSCH_SEEO, HARBIN INSTITUTE OF TECHNOLOGY, TSINGHUA UNIVERSITY, GLOBAL GRAPHENE	GLOBAL GRAPHENE, GENERAL MOTORS, SAMSUNG GROUP, ZHEJIANG UNIVERSITY, INSTITUTE OF PHYSICS CAS, CENTRAL SOUTH UNIVERSITY, HUAWEI, GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY, JIANGXI ZICHEN SCIENCE AND TECHNOLOGY, SHANGHAI PUTAILAI NEW ENERGY TECHNOLOGY	LG CHEM, CENTRAL SOUTH UNIVERSITY, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, BEIJING UNIVERSITY, HARBIN INSTITUTE OF TECHNOLOGY, BOSCH_SEEO, ZHEJIANG UNIVERSITY, TSINGHUA UNIVERSITY, DALIAN INSTITUTE OF CHEMICAL PHYSICS, BASF	LG CHEM, SAMSUNG GROUP, SOLVAY, SION POWER, BASF, CENTRAL SOUTH UNIVERSITY, GENERAL MOTORS, ZHEJIANG UNIVERSITY, DALIAN INSTITUTE OF CHEMICAL PHYSICS, BEIJING UNIVERSITY	LG CHEM, SHENZHEN PEICHENG TECHNOLOGY, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, CENTRAL SOUTH UNIVERSITY, GENERAL MOTORS, TSINGHUA UNIVERSITY, DALIAN INSTITUTE OF CHEMICAL PHYSICS, DONGHUA UNIVERSITY, CHANGSHA RESEARCH INSTITUTE OF MINING & METALLURGY, FOXCONN
Most enforced IP players *(Highest number of granted patents)*	TSINGHUA UNIVERSITY, BOSCH_SEEO, ALBEMARLE, LG CHEM, AIST, INSTITUTE CHEMISTRY CAS, GENERAL MOTORS, FOXCONN, NAGASE, CENTRAL SOUTH UNIVERSITY, TOYOTA	GENERAL MOTORS, ULVAC, AGC, SAMSUNG GROUP, ALBEMARLE , GLOBAL GRAPHENE, UNIVERSITAET MUENSTER, MSMH, QUICKHATCH	TSINGHUA UNIVERSITY, BOSCH_SEEO, LG CHEM, ALBEMARLE, AIST, INSTITUTE CHEMISTRY CAS, FOXCONN, NAGASE, TOYOTA, CENTRAL SOUTH UNIVERSITY	SION POWER, SAMSUNG GROUP, LG CHEM, BASF, OXIS ENERGY, SOLVAY, GENERAL MOTORS, SCHOTT, BOSCH_SEEO, ZHEJIANG UNIVERSITY	TSINGHUA UNIVERSITY, FOXCONN, GENERAL MOTORS, LG CHEM, BOSCH_SEEO, CENTRAL SOUTH UNIVERSITY, DALIAN INSTITUTE OF CHEMICAL PHYSICS, SAMSUNG GROUP, UNIST, CHINA ELECTRONIC TECHNOLOGY
Main active IP players *(Highest number of pending patent applications)*	LG CHEM, GLOBAL GRAPHENE, BOSCH_SEEO, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, ALBEMARLE, ARKEMA, CENTRAL SOUTH UNIVERSITY, BEIJING UNIVERSITY, ZHEJIANG UNIVERSITY	GLOBAL GRAPHENE, ALPHA EN CORPPORATION, CHINA ENERGY CAS TECHNOLOGY, ZHONGNENG ZHONGKE NEW ENERGY TECHNOLOGY, NGK, GENERAL MOTORS, SAMSUNG GROUP, UNIVERSITY OF NORTH TEXAS	LG CHEM, BOSCH_SEEO, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, ARKEMA, ALBEMARLE, CENTRAL SOUTH UNIVERSITY, BEIJING UNIVERSITY, SHAANXI UNIVERSITY OF SCIENCE AND TECHNOLOGY, HARBIN INSTITUTE OF TECHNOLOGY, GLOBAL GRAPHENE	LG CHEM, SOLVAY, BASF, SION POWER, GENERAL MOTORS, GLOBAL GRAPHENE, SCHOTT, CENTRAL SOUTH UNIVERSITY, NOHMS TECHNOLOGIES, UT BATTELLE	LG CHEM, GENERAL MOTORS, ZHAOQING HUASHI UNIVERSITY PHOTOELECTRIC INDUSTRY RESEARCH INSTITUTE, SHENZHEN PEICHENG TECHNOLOGY, BOSCH_SEEO, TSINGHUA UNIVERSITY, FOXCONN, DONGHUA UNIVERSITY, SAMSUNG GROUP, SOUTH CHINA NORMAL UNIVERSITY

Table 12: Main IP players by supply chain segments (electrode materials, electrolyte, separator) in Li-S Battery patent landscape

IP positions	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
Main IP players *(Highest number of patent families)*	LG CHEM, SION POWER, SAMSUNG GROUP, DALIAN INSTITUTE OF CHEMICAL PHYSICS, GLOBAL GRAPHENE, BASF, POLYPLUS BATTERY, GENERAL MOTORS, HYUNDAI_KIA, BOSCH_SEEO	LG CHEM, SION POWER, DALIAN INSTITUTE OF CHEMICAL PHYSICS, SAMSUNG GROUP, GLOBAL GRAPHENE, POLYPLUS BATTERY, GENERAL MOTORS, BASF, HYUNDAI_KIA, GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY	LG CHEM, SION POWER, BASF, SAMSUNG GROUP, GENERAL MOTORS, POLYPLUS BATTERY, GLOBAL GRAPHENE, KIST, CHINA ENERGY LITHIUM, TSINGHUA UNIVERSITY	LG CHEM, SAMSUNG GROUP, DALIAN INSTITUTE OF CHEMICAL PHYSICS, HYUNDAI_KIA, SION POWER, BOSCH_SEEO, GYEONGSANG NATIONAL UNIVERSITY, DUPONT, GLOBAL GRAPHENE, TOYOTA, CEA	SION POWER, GLOBAL GRAPHENE, LG CHEM, BOSCH_SEEO, SAMSUNG GROUP, OXIS ENERGY, TOYOTA, GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY, BASF, HYUNDAI_KIA	SION POWER, GLOBAL GRAPHENE, LG CHEM, BOSCH_SEEO, GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY, SAMSUNG GROUP, OXIS ENERGY, BASF, DALIAN INSTITUTE OF CHEMICAL PHYSICS, BEIJING UNIVERSITY	SHANGHAI INSTITUTE OF TECHNOLOGY, CENTRAL SOUTH UNIVERSITY, SICHUAN UNIVERSITY, ALBEMARLE
Most enforced IP players *(Highest number of granted patents)*	SION POWER, LG CHEM, POLYPLUS BATTERY, HYUNDAI_KIA, BASF, OXIS ENERGY, SAMSUNG GROUP, CEA, DALIAN INSTITUTE OF CHEMICAL PHYSICS, GENERAL MOTORS	SION POWER, LG CHEM, POLYPLUS BATTERY, HYUNDAI_KIA, BASF, CEA, SAMSUNG GROUP, DALIAN INSTITUTE OF CHEMICAL PHYSICS, GENERAL MOTORS	SION POWER, POLYPLUS BATTERY, BASF, LG CHEM, OXIS ENERGY, SAMSUNG GROUP, HANYANG UNIVERSITY, NATIONAL RESEARCH COUNCIL OF CANADA, KIST, GENERAL MOTORS	LG CHEM, SION POWER, HYUNDAI_KIA, CEA, DALIAN INSTITUTE OF CHEMICAL PHYSICS, SAMSUNG GROUP, OXIS ENERGY, GENERAL MOTORS, ULVAC	SION POWER, OXIS ENERGY, BOSCH_SEEO, POLYPLUS BATTERY, LG CHEM, ARKEMA, BASF, CNRS, BLUE SOLUTIONS_BOLLORE, UNIVERSITE DE NANTES	SION POWER, OXIS ENERGY, POLYPLUS BATTERY, BOSCH_SEEO, CNRS, BLUE SOLUTIONS_BOLLORE, UNIVERSITE DE NANTES, UNIVERSITE PIERRE AND MARIE CURIE, GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY, BASF	CENTRAL SOUTH UNIVERSITY
Main active IP players *(Highest number of pending patent applications)*	LG CHEM, GLOBAL GRAPHENE, SION POWER, GENERAL MOTORS, BASF, OXIS ENERGY, TOYOTA, CEA, HYUNDAI_KIA, CORNELL UNIVERSITY	LG CHEM, GLOBAL GRAPHENE, GENERAL MOTORS, SION POWER, OXIS ENERGY, BASF, TOYOTA, CEA, HYUNDAI_KIA, CORNELL UNIVERSITY	LG CHEM, SION POWER, GLOBAL GRAPHENE, GENERAL MOTORS, BASF, OXIS ENERGY, COVESTRO, TSINGHUA UNIVERSITY, UNIVERSITY OF ILLINOIS, 3M	LG CHEM, GLOBAL GRAPHENE, OXIS ENERGY, TOYOTA, CEA, HYUNDAI_KIA, CORNELL UNIVERSITY, BOSCH_SEEO, UNIVERSITY OF CALIFORNIA	GLOBAL GRAPHENE, OXIS ENERGY, LG CHEM, SION POWER, ARKEMA, CNRS, BLUE SOLUTIONS_BOLLORE, UNIVERSITE DE NANTES, UNIVERSITE PIERRE AND MARIE CURIE, BOSCH_SEEO	GLOBAL GRAPHENE, OXIS ENERGY, LG CHEM, SION POWER, ARKEMA, CNRS, BLUE SOLUTIONS_BOLLORE, UNIVERSITE DE NANTES, UNIVERSITE PIERRE AND MARIE CURIE, BOSCH_SEEO, HYDRO QUEBEC, BASF	ALBEMARLE , SHANGHAI INSTITUTE OF TECHNOLOGY, SICHUAN UNIVERSITY

Table 13: Main IP players by supply chain segments (electrode, battery cell, recycling) in Li-S Battery patent landscape

Patents on active materials, electrolyte and separator are not only filed by material manufacturers and R&D labs but also by battery manufacturers and end-users. In fact, most of battery manufacturers have R&D department dedicated to the development and evaluation of new battery materials. Some of them also collaborates with R&D labs or material manufacturers.

Patenting Activity of main IP Players by Supply Chain segments

Assignee	Number of patent families	Supply Chain Segments											
		Electrode material	Anode material	Cathode material	Electrolyte	Separator	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
LG CHEM	266	64		64	38	19	109	93	38	70	37	26	
SAMSUNG	130	60	14	46	65	6	75	48	27	48	57	33	
SION POWER	116	12	1	11	19	3	41	36	28	13	51	37	
GLOBAL GRAPHENE	102	34	24	10	7	2	23	22	11	10	42	27	
BOSCH_SEEO	98	40	2	38	8	6	14	13	1	13	31	18	
CENTRAL SOUTH UNIVERSITY	91	54	4	50	13	13	8	8	2	6	5	4	1
DALIAN INST. OF CHEM. PHYSICS	88	34	2	32	10	10	25	25	3	22	9	9	
BASF	81	34	2	32	14	5	20	18	15	5	14	10	
BEIJING UNIVERSITY	74	47	1	46	9	4	6	6	1	5	8	8	
TSINGHUA UNIVERSITY	71	36	1	35	3	12	13	9	6	7	9	3	
Z.H. UNIV. PHOTOELEC. IND. RES. INST.	66	47		47		13	1	1		1	5	5	
GENERAL MOTORS	64	16	10	6	13	12	18	18	13	6	6	4	
ZHEJIANG UNIVERSITY	61	42	6	36	12	4	12	11	4	8	5	5	
HYUNDAI_KIA	57	15		15	6	4	18	15	2	16	14	8	
TOYOTA	54	20	1	19	2		11	8	1	10	23	8	
HARBIN INST. OF TECHNOLOGY	49	38		38	2	2	1	1		1	6	6	
G.Z. NEW ENERGY TECHNOLOGY	43	11	3	8		1	14	14	4	10	18	18	
OXIS ENERGY	38	1		1	6		6	5	2	4	26	16	
SHENZHEN PEICHENG TECH.	35	21		21		14							
SHANGHAI INST. OF SPACE POWER SCES	33	14		14		1	11	11	2	9	7	7	
POLYPLUS BATTERY	31	1	1		3		20	19	12	8	10	7	
TIANJIN UNIVERSITY	29	18	1	17	1	2	8	8	3	5	1	1	
INSTITUTE CHEMISTRY CAS	29	20	2	18		2	3	2	3		4	4	
SUZHOU INST. OF NANO TECH.	29	22	2	20		1	3	2		3	3	3	
SOUTH CHINA NORMAL UNIV.	27	18	1	17	1	6	1	1	1		1	1	
CHENGDU NEW KELI CHEM. SCIENCE	27	17	2	15	5	2	1	1		1	2	2	
DAIMLER	27	4		4	7	3	2	2		2	11	5	
HANYANG UNIV.	26	10		10	4	3	4	4	3	1	5	3	
POSITEC	26	16	2	14	4						6	3	

Table 14: Number of patent families by main IP Players and by Supply Chain segments in Li-S Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments. European companies are written in orange color. Most of main IP players file patents on all supply chain segments except recycling. Mastering and controlling the whole supply chain are important for all these players. By doing so, they can control the whole supply chain and limit the risk and impact of the competitors specialized in other part of the supply chain.

- **LG Chem** mainly files patents on cathode materials, cathode and electrode manufacturing. It also has a notable number of patent families on other supply chain segments, except anode materials.
- **Samsung** mainly files patents on cathode materials, electrolyte, electrode manufacturing, cathode and battery cell. It also has some patents on other supply chain segments. **Sion Power** mainly files patents on electrode manufacturing, anode and battery cell. It also has some patents on cathode material, electrolyte and separator. **Global Graphene** mainly files patents on anode materials, electrode manufacturing and battery cell.

On the European side, the 3 main IP players have patents that cover the whole supply chain from material to battery cells. However, we can witness some specific IP strategies. Bosch/ SEEO addresses the whole supply chain as its patents are mainly related to cathode material and battery cell. **BASF and Oxis Energy** have more specialized portfolios. **BASF** mainly files patents on cathode materials. **Oxis Energy** mainly files patents on battery cells while separator and electrodes related patenting activities are secondary.

FOCUS ON EUROPEAN IP PLAYERS

Main European IP Players

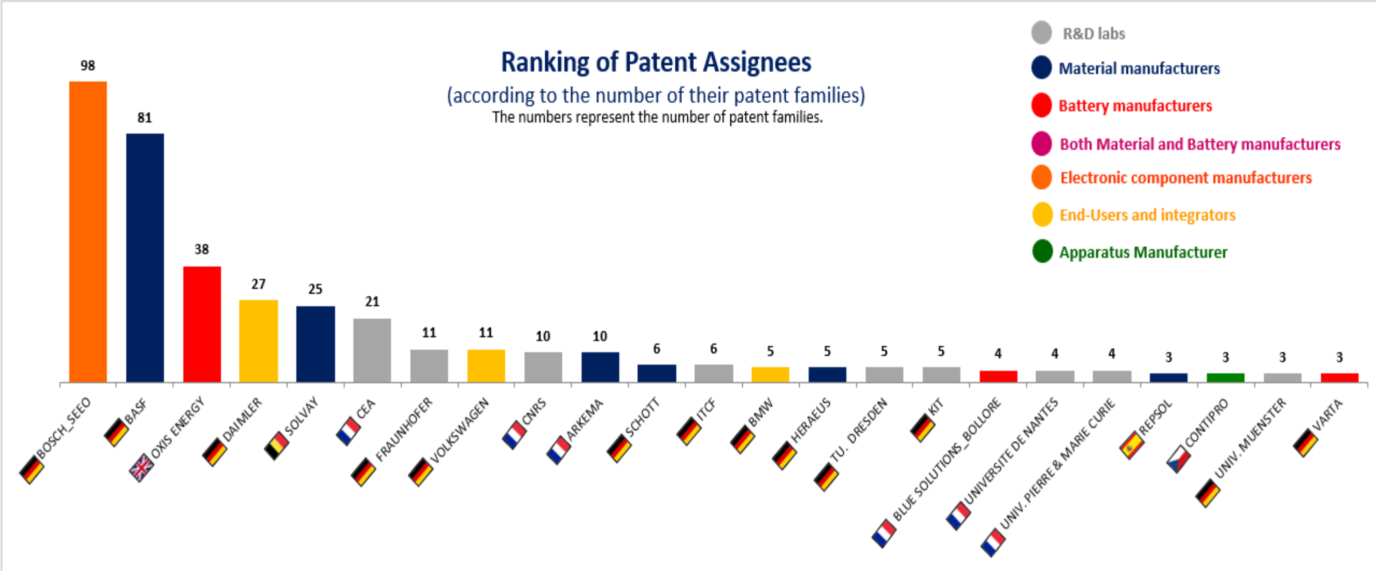


Figure 24: Ranking of main European Patent Assignees according to their number of patent families related to Li-S Battery

- More than **60 European organizations** have filed patents related to Li-S battery. European IP players are mainly originating from Germany and France and are mainly R&D labs and material manufacturers.
- In 2018, **Bosch** announces that it abandons EV battery making. **BASF** has a strong partnership with Li-S battery key IP player (**Sion Power)** and has numerous patents co-filed with them.
- **Oxis Energy** is a pure play company specialized in Li-S battery. They have already manufactured Li-S battery prototypes and announce a future commercialization within next years.
- European IP players co-file patents on Li-S battery with European and non-European companies (Samsung, Chinese universities, etc.

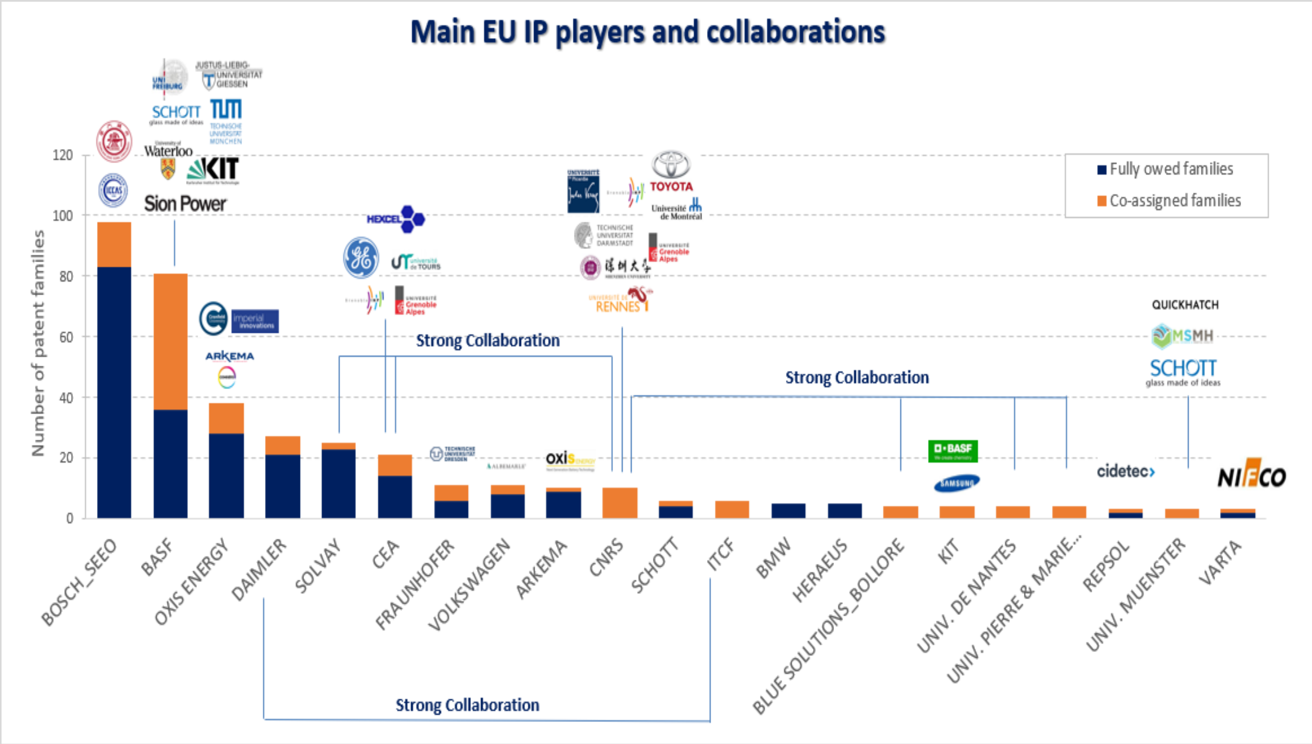


Figure 25: Number of co-assigned patent families by main European patent assignees in Li-S Battery patent landscape

Main European IP Players by Type of Companies

Material Manufacturers

BASF	81
SOLVAY	25
ARKEMA	10
SCHOTT	6
HERAEUS	5
REPSOL	3
SHELL	2
SGL CARBON	2
COVESTRO	1
ELPANI	1
PERPETUUS R&D	1
IMERYS	1
KH CHEMICALS	1

Electronic Component Manufacturers

BOSCH_SEEO	98
NAMLAB	1

Battery Manufacturers

OXIS ENERGY	38
BLUE SOLUTIONS_BOLLORE	4
VARTA	3
BLUE SKY	2
GRAPHENE BATTERIES	1
SAFT_TOTAL	1
GRABAT ENERGY	1

End-Users and Integrators

DAIMLER	27
VOLKSWAGEN	11
BMW	5
OAKS ENERGY	1
NOKIA	1

R&D Labs

CEA	21
FRAUNHOFER	11
CNRS	10
ITCF	6
TU. DRESDEN	5
UNIV. DE NANTES	4
UNIV. PIERRE & MARIE CURIE	4
UNIV. MUENSTER	3
UNIV. FREIBURG	2
UNIV. HAMBURG	2
AIT	1
FORSCHUNGSZENTRUM JUELICH	1
INPG	1
UNIV. GRENOBLE ALPES	1
CIDETEC	1
TU. DARMSTADT	1
UNIV. DE PICARDIE	1
UNIV. OF LIVERPOOL	1
LEIBNIZ INST. OF POLYMER RES.	1
CRANFIELD UNIV.	1
TU. MUENCHEN	1
UNIV. DE TOURS	1
KEMIJSKI INSTITUT	1
ZSWF	1
UNIV. GIESSEN	1
TNO	1

Table 15: Ranking of main European Patent Assignees by Type of Companies according to their number of patent families related to Li-S Battery. (Time period: 1970-2020, i.e. all patent families in the patent landscape). The numbers represent the number of patent families of the corresponding patent assignee in Li-S Battery patent landscape.

- **Heraeus** is a German technology group which focuses on precious and special metals, carbon additives for battery applications, medical technology, quartz glass, sensors and specialty light sources.
- **Repsol** is a Spanish fossil fuel company, operating in all areas of the oil and gas industry, from exploration and production to petrochemicals. It has started a shift towards cleaner and renewable energy. It invested in storage start-up **Ampere Energy** in 2019. **Repsol Technology Center** works on Electric Vehicles and Energy storage.
- **Shell** explores, produces and refines petroleum. It produces fuels, chemicals and lubricants. **Shell** bought German home energy-storage start-up **Sonnen** in 2019.
- **Covestro** is a German company spin-out from **Bayer** in 2015. It produces specialty chemicals for heat insulation foams and transparent polycarbonate plastics.
- **Elpani** is a Belgium company specialized in polymer technology established in 2007.
- **Perpetuus R&D** is a British advanced material manufacturer primarily founded in 2013 and focused on surface engineered carbon structures such as Graphene and Carbon Nanotubes.
- **Imerys** is a French multinational company which specializes in the production and processing of industrial minerals and graphite materials, notably for battery applications.
- **KH Chemicals** provides chemical products. **Total** fully acquired **SAFT** in 2016.
- **Blue Sky** is a German company founded in 2012 and specialized in battery for stationary applications.
- **Graphene Batteries** is a Norwegian company founded in 2012. It develops and manufactures Li-S battery.
- **Grabat Energy** is a Spanish battery manufacturer founded in 2012 (subsidiary of **GrapheneNano**). It manufactures graphene polymer cells for different types of batteries. It works with the **University of Cordoba** and has a strategic agreement with the **CHINT Group**.
- **Oaks Energy** is a British company established in 2007. It designs and installs commercial and domestic renewable energy systems.
- **Namlab** is a university-industry joint-venture of **TU. Dresden**, operating in microelectronic field.

IP Dynamics of main European IP Players

Earliest year of publication for each patent family

Group	Assignee	Nb of patent families	Average age of the patent portfolio	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	KH CHEMICALS	1	16										1																
	TNO	1	16										1																
	BLUE SKY	2	13						1														1						
	NOKIA	1	9																	1									
Most active IP players within last 10 years	OXIS ENERGY	38	8										1	4	7	2	2				1		5	8	2	2	3	1	
	IMERYS	1	7																			1							
Most active IP players within last 10 years	BOSCH_SEEO	98	6																8	3	10	20	10	18	18	9	2		
Most active IP players within last 10 years	BASF	81	6																	4	17	12	7	16	8	9	6	2	
	TU. DRESDEN	5	6																			1	3			1			
	UNIV. GIESSEN	1	6																				1						
	PERPETUUS R&D	1	6																				1						
	NAMLAB	1	6																				1						
Most active IP players within last 10 years	DAIMLER	27	5																	2			2	10	7	3	2	1	
Most active IP players within last 10 years	SOLVAY	25	5																	1	1	7	2	5	3	3	3		
	VOLKSWAGEN	11	5																		1	1	2	6		1			
	FRAUNHOFER	11	5																		2	1	3	1	1	2	1		
	HERAEUS	5	5																		1		1	1	1	1			
	CRANFIELD UNIV.	1	5																					1					
	IMPERIAL INNOVATIONS	1	5																					1					
	TU. MUENCHEN	1	5																					1					
	UNIVERSITE DE TOURS	1	5																					1					
	KEMIJSKI INSTITUT	1	5																					1					
	ZSWF	1	5																					1					
Most active IP players within last 10 years	CEA	21	4																1	1		3	4	3	2	2	4	4	
Most active IP players within last 10 years	CNRS	10	4												1									1	3	1	1	3	
	SCHOTT	6	4																			1		1	2	1		1	
	BLUE SOLUTIONS	4	4																					1	3				
	UNIV. DE NANTES	4	4																					1	3				
	UNIV. PIERRE & MARIE CURIE	4	4																					1	3				
	UNIV. MUENSTER	3	4																					2		1			
	UNIV. FREIBURG	2	4																					1			1		
	SGL CARBON	2	4																			1						1	
	LEIBNIZ INST. OF POLYMER RES.	1	4																						1				
Most active IP players within last 10 years	ARKEMA	10	3																			1	1	1	2		1	4	
Most active IP players within last 10 years	ITCF	6	3																						3	2	1		
	BMW	5	3																						2	2	1		
	KIT	5	3																					2		1		2	
New comers	CONTIPRO	3	3																							2	1		
New comers	GRABAT ENERGY	1	3																							1			
New comers	UNIVERSITY OF LIVERPOOL	1	3																							1			
New comers	ELPANI	1	3																							1			
New comers	REPSOL	3	2																								2	1	
New comers	UNIV. HAMBURG	2	2																							1	1		
New comers	COVESTRO	1	2																								1		
New comers	CIDETEC	1	2																								1		
New comers	TU. DARMSTADT	1	2																								1		
New comers	UNIVERSITE DE PICARDIE	1	2																								1		
New comers	OAKS ENERGY	1	2																								1		
New comers	SHELL	2	1																									1	1
New comers	GRAPHENE BATTERIES	1	1																									1	
New comers	SAFT_TOTAL	1	1																									1	
New comers	AIT	1	1																									1	
New comers	FORSCHUNGSZENTRUM JUELICH	1	1																									1	
New comers	IONTECH SYSTEMS	1	1																									1	
New comers	INPG	1	1																									1	
New comers	UNIVERSITE GRENOBLE ALPES	1	1																									1	

Table 16: Time Evolution of Patent Publications by main European Patent Assignees and by earliest year of publication for each patent family in Li-S Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignee). R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment manufacturers are written in Green. In each cell referring to a publication year, the numbers represent the number of patent families.

Patenting Activity of Main European IP Players

Most of European IP Players extend their patents in other countries. Some European IP players have no more alive patents.

IP players focused on Europe

IP players no more active

	Number of Patent families		Patent Legal status			Number of granted patents							Number of pending patent applications							
	All	Alive	Granted	Pending	Dead	USA	Europe	Japan	China	Korea	Taiwan	India	USA	Europe	Japan	China	Korea	Taiwan	India	PCT applications (WO patents)
BOSCH_SEEO	98	86	106	102	118	39	21	12	27	6			12	60	4	18	7			1
BASF	81	53	49	78	145	22	11	5	9	2			9	9	20	6	15	14	1	4
OXIS ENERGY	38	37	110	77	59	14	34	14	13	7	6	1	8	10	9	8	14	10	1	4
DAIMLER	27	8	8	8	38	1	2	2	3					8						
SOLVAY	25	18	15	48	46	4	5	4	2				6	6	8	8	9	5	2	2
CEA	21	21	39	23	24	12	22	3					5	12	1	3	1			1
FRAUNHOFER	11	11	21	24	20	3	9	3	2	3			2	8	1	1	2		1	1
VOLKSWAGEN	11	11	16	13	5	2	3	2	3	3	1			10		1			2	
CNRS	10	10	19	32	7	3	8	4	1				4	4	4	6	5			2
ARKEMA	10	10	28	57	9	4	9	3	1	4	3	1	3	10	4	10	3		5	6
SCHOTT	6	5	9	12	4	1	4	2	1	1			2	3	2	2	3			
ITCF	6	4		4	2									4						
BMW	5	5		10	2								2	5		2				1
HERAEUS	5	5	12	1	6	3	4	1	3		1		1							
TU. DRESDEN	5	5	13	3	11	2	4	2	2	2				2			1			
BLUE SOLUTIONS	4	4	14	20	4	2	7	1	1				2	1	3	3	4			
UNIVERSITE DE NANTES	4	4	14	20	4	2	7	1	1				2	1	3	3	4			
UNIV. PIERRE & MARIE CURIE	4	4	14	20	4	2	7	1	1				2	1	3	3	4			
REPSOL	3	3		8	1									1	1	2	2			2
CONTIPRO	3				3															
UNIV. MUENSTER	3	3	7	5	2	1		2		2			2	3						
VARTA	3				12															
SHELL	2	2		3														1		2
SGL CARBON	2	2	2	6	1	1		1						3		1	1			1
UNIVERSITAET FREIBURG	2	1		1	1															1
UNIVERSITAET HAMBURG	2	2		2	2									2						
BLUE SKY	2	2	2		4	2														
GRAPHENE BATTERIES	1	1		2										1						1
SAFT_TOTAL	1	1		2										1						1
AIT	1	1		2													1			1
FORSCHUNGSZENTRUM JUELICH	1	1		2										1						1
IONTECH SYSTEMS	1	1		2										1						1
INPG	1	1	1	3			1						1	1		1				
UNIVERSITE GRENOBLE ALPES	1	1	1	3			1						1	1		1				
COVESTRO	1	1		7									1	1	1	1	1	1		1
CIDETEC	1	1		4	1									1	1	1	1			
TU. DARMSTADT	1	1		1	1															1
UNIV. DE PICARDIE	1	1		1	1															1
OAKS ENERGY	1	1		8									1	1	1	1	1	1		1
UNIV. OF LIVERPOOL	1	1		1	1															1
ELPANI	1				1															
GRABAT ENERGY	1	1	1	13	3								1	2	1	1	1		1	
LEIBNIZ INST. OF POLYMER RES.	1	1		2	2								1	1						
CRANFIELD UNIVERSITY	1	1	2	6	1		1						1	1	1	1	1	1		
IMPERIAL INNOVATIONS	1	1	2	6	1		1						1	1	1	1	1	1		
TU. MUENCHEN	1				1															
UNIV. DE TOURS	1	1	4		1	1	2													
KEMIJSKI INSTITUT	1	1	2		1		1													
ZSWF	1				3															
UNIV. GIESSEN	1	1		2	4									1	1					
PERPETUUS R&D	1	1		4	5									1	1		1		1	
NAMLAB	1	1	1				1													
IMERYS	1	1	13	3	1	2	1	1	2	1									1	
NOKIA	1	1	4	1	1	1	1		1									1		
KH CHEMICALS	1				2															
TNO	1				6															

Table 17: Legal status of patents by countries for main European patent assignees in Li-S Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

Patenting Activity of Main European IP Players by Supply Chain Segments

Assignee	Number of patent families	Supply Chain segments											
		Electrode material	Anode material	Cathode material	Electrolyte	Separator	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
BOSCH_SEEO	98	40	2	38	8	6	14	13	1	13	31	18	
BASF	81	34	2	32	14	5	20	18	15	5	14	10	
OXIS ENERGY	38	1		1	6		6	5	2	4	26	16	
DAIMLER	27	4		4	7	3	2	2		2	11	5	
SOLVAY	25	1		1	20		3	3	1	2	1		
CEA	21	8		8	1		11	11	1	10	5	3	
FRAUNHOFER	11	2		2	2		4	4	1	2	4	2	
VOLKSWAGEN	11	5		5	3	1	1	1		1	1		
CNRS	10				3	1	1	1		1	5	4	
ARKEMA	10	6		6			1	1		1	3	2	
SCHOTT	6				6								
ITCF	6	2		2	3	1							
BMW	5					1					4	3	
HERAEUS	5	4		4			1	1		1			
TU. DRESDEN	5						2	2	1	1	3	1	
BLUE SOLUTIONS	4										4	4	
UNIVERSITE DE NANTES	4										4	4	
UNIV. PIERRE & MARIE CURIE	4										4	4	
REPSOL	3	1		1	1		1	1	1				
CONTIPRO	3	3		3									
UNIVERSITAET MUENSTER	3	2	1	1	1								
VARTA	3						2	2		2	1		
SHELL	2	1		1							1		
SGL CARBON	2	2		2									
UNIVERSITAET FREIBURG	2	1		1	1								
UNIVERSITAET HAMBURG	2										2	1	
BLUE SKY	2						2	2		2			
GRAPHENE BATTERIES	1						1	1		1			
SAFT_TOTAL	1										1		
AIT	1	1		1									
FORSCHUNGSZENTRUM JUELICH	1				1								
IONTECH SYSTEMS	1										1	1	
INPG	1						1	1		1			
UNIVERSITE GRENOBLE ALPES	1						1	1		1			
COVESTRO	1						1	1	1				
CIDETEC	1				1								
TU. DARMSTADT	1					1							
UNIVERSITE DE PICARDIE	1					1							
OAKS ENERGY	1						1	1		1			
UNIVERSITY OF LIVERPOOL	1	1		1									
ELPANI	1	1		1									
GRABAT ENERGY	1	1		1									
LEIBNIZ INST. OF POLYMER RES.	1						1	1		1			
CRANFIELD UNIVERSITY	1										1	1	
IMPERIAL INNOVATIONS	1										1	1	
TU. MUENCHEN	1				1								
UNIVERSITE DE TOURS	1				1								
KEMIJSKI INSTITUT	1										1		
ZSWF	1	1		1									
UNIVERSITAET GIESSEN	1					1							
PERPETUUS R&D	1	1		1									
NAMLAB	1										1		
IMERYS	1	1		1									
NOKIA	1										1	1	
KH CHEMICALS	1	1		1									
TNO	1										1	1	

Table 18: Number of patent families by main European IP Players and by Supply Chain segments in Li-S Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments.

- No European IP players file patents on Li-S battery recycling.
- **Bosch/ SEEO** mainly files on cathode material and battery cell. **BASF** mainly files patents on cathode materials, electrode manufacturing, electrolyte, anode and battery cell. **Oxis Energy** mainly files patents on battery cell, separator and electrodes. **Solvay and Schott** focus their patenting activity on Electrolyte.

IP Position of Main European IP Players

Relative size and strength of Li-S battery patent portfolio held by European IP players have been evaluated in comparison with patent portfolio of all IP players (cf. Identification of key IP players). **Bosch/SEEO, BASF** and **Oxis Energy** have a good IP position in Li-S battery patent landscape.

	Relative size of patent portfolio	Relative size of granted patent portfolio	Relative size of pending patent portfolio	Relative Prior Art Blocking Potential	Relative FTO Blocking Potential
BOSCH_SEEO	High	High	High	High	High
BASF	High	Medium	High	High	High
OXIS ENERGY	Medium	High	High	High	High
CEA	Medium	Medium	Medium	Medium	Medium
SOLVAY	Medium	Medium	Medium	Medium	Medium
DAIMLER	Medium	Low	Low	Low	Very low
FRAUNHOFER	Low	Medium	Medium	Medium	Medium
CNRS	Low	Medium	Medium	Low	Medium
ARKEMA	Low	Medium	Medium	Low	Medium
TU. DRESDEN	Low	Low	Very low	Low	Medium
VOLKSWAGEN	Low	Medium	Low	Low	Medium
HERAEUS	Low	Low	Very low	Low	Medium
BLUE SOLUTIONS	Low	Low	Medium	Very low	Medium
UNIVERSITE DE NANTES	Low	Low	Medium	Very low	Medium
UNIV. PIERRE & MARIE CURIE	Low	Low	Medium	Very low	Medium
SCHOTT	Low	Low	Low	Very low	Low
BMW	Low	Null	Low	Very low	Null
KIT	Low	Null	Very low	Very low	Null
ITCF	Low	Null	Very low	Very low	Null
IMERYS	Very low	Low	Very low	Low	Medium
NOKIA	Very low	Very low	Very low	Low	Medium
CRANFIELD UNIVERSITY	Very low	Very low	Low	Low	Medium
IMPERIAL INNOVATIONS	Very low	Very low	Low	Low	Medium
GRABAT ENERGY	Very low	Very low	Low	Very low	Medium
SGL CARBON	Very low	Very low	Low	Very low	Low
UNIV. MUENSTER	Very low	Low	Very low	Very low	Low
BLUE SKY	Very low	Very low	Null	Very low	Low
KEMIJSKI INSTITUT	Very low	Very low	Null	Low	Low
UNIVERSITE DE TOURS	Very low	Very low	Null	Very low	Very low
VARTA	Very low	Null	Null	High	Null
KH CHEMICALS	Very low	Null	Null	High	Null
TNO	Very low	Null	Null	Low	Null
PERPETUUS R&D	Very low	Null	Very low	Very low	Null
LEIBNIZ INST. OF POLYMER RES.	Very low	Null	Very low	Very low	Null
ELPANI	Very low	Null	Null	Very low	Null
TU. MUENCHEN	Very low	Null	Null	Very low	Null
ZSWF	Very low	Null	Null	Very low	Null
REPSOL	Very low	Null	Low	Null	Null
OAKS ENERGY	Very low	Null	Low	Null	Null
COVESTRO	Very low	Null	Low	Null	Null
CIDETEC	Very low	Null	Very low	Null	Null
INPG	Very low	Very low	Very low	Null	Null
UNIV. GRENOBLE ALPES	Very low	Very low	Very low	Null	Null
SHELL	Very low	Null	Very low	Null	Null
UBATT	Very low	Null	Very low	Null	Null
UNIV. HAMBURG	Very low	Null	Very low	Null	Null
GRAPHENE BATTERIES	Very low	Null	Very low	Null	Null
SAFT_TOTAL	Very low	Null	Very low	Null	Null
AIT	Very low	Null	Very low	Null	Null
FORSCHUNGSZENTRUM JUELICH	Very low	Null	Very low	Null	Null
IONTECH SYSTEMS	Very low	Null	Very low	Null	Null
UNIVERSITAET GIESSEN	Very low	Null	Very low	Null	Null
UNIVERSITAET FREIBURG	Very low	Null	Very low	Null	Null
TU. DARMSTADT	Very low	Null	Very low	Null	Null
UNIVERSITE DE PICARDIE	Very low	Null	Very low	Null	Null
UNIVERSITY OF LIVERPOOL	Very low	Null	Very low	Null	Null
NAMLAB	Very low	Very low	Null	Null	Null
CONTIPRO	Very low	Null	Null	Null	Null

Table 19: IP Position of main European IP Players in Li-S Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

SODIUM-ION BATTERY

Principle

The Sodium-ion Battery (Na-ion Battery) is a type of rechargeable battery analogous to the Li-ion battery but using sodium ions as charge carriers. The cathode material can be polyanionic compounds ($Na_3V_2(PO_4)_3$, $Na_4Co_3(PO_4)_2P_2O_7$, etc.), layered compounds ($Na_{0.6}CoO_2$, $Na_{0.66}Ni_{0.33}Mn_{0.66}O_2$, $Na_{0.66}Fe_{0.33}Mn_{0.66}O_2$, etc.), Prussian Blue analogues ($Na_4Fe_2(CN)_6$, etc.), etc.. The anode material can be carbon materials (hard carbon, graphene, etc.), Sodium alloys (NaxSb, NaxSn, etc.), Sodium/Lithium Titanates ($Na_2Ti_3O_7$, LTO), etc.

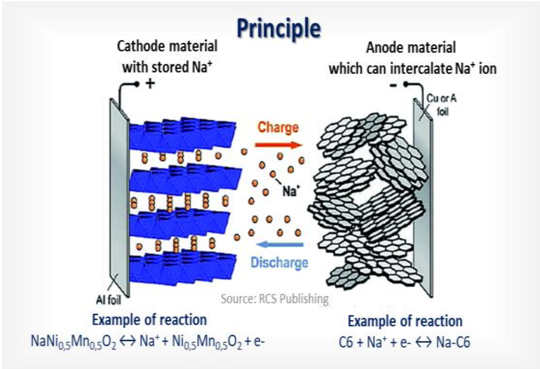


Figure 26: Principle of Na-ion Battery

During the discharge: Na^+ ions are extracted from the anode and re-inserted in the cathode.
During the charge: Na^+ ions are extracted from the cathode and re-inserted in the anode.

Advantages and Drawbacks

Advantages	Drawbacks
• Safer technology compared to Li-ion (not flammable, not corrosive), Operation at RT • Low cost, Na-ion materials can be processed similar to Li-ion materials at every step from active materials synthesis to electrode processing. Existing Li-ion manufacturing lines can be used to make Na-ion batteries • No heavy metals or toxic chemicals	• Lower cell voltage compared to Li-ion • Low energy density compared to Li-ion • Flammable electrolyte (for organic Na-ion battery) • Low cell voltage, Low power, High volume batteries (for aqueous Na-ion battery

Table 20: Main advantages and drawbacks of Na-ion Battery

Challenges and Envisioned Solutions

- Improve performances (energy density, power density, life duration and high temperature operation)
  - Develop new electrode materials (anodes with high capacity and low voltage, cathode with high capacity and high voltage)
  - Develop new electrolytes (High voltage electrolytes-new solvents, salts or additives, solid electrolytes with high ionic conductivity)
  - Develop cell designs and electrode balancing and improve the battery control by BMS
- Improve safety
  - Use solid/non-flammable electrolytes or with fire-retardant
  - Improve cells arrangements in battery packs to avoid fire propagation upon failure and resistance to exterior constraints
  - Develop new separators (High ionic conductivity, high resistance to solvents, high mechanical strength (do not cracks if dendrites are created), No electric conductivity
  - Improve thermal management in battery packs (BMS + cooling systems + fire retardant products)

Main Market Players

Faradion, Tiamat (spin-off of CEA/CNRS), Aquion Energy, Novasis Energies (Spin-off of the Univ. of Texas), HiNa Battery Technology (Spin-off Chinese Academy of Science), Natron Energy (Spin-off of Stanford Univ.), Altris AB (Spin-off of Uppsala Univ.), Solvay, Toyota, Haldor Topse, etc.

Main Applications Envisioned for Na-ion Battery

Transport applications, stationary applications (grid storage, home storage, etc.), Consumer electronics

IP Dynamics

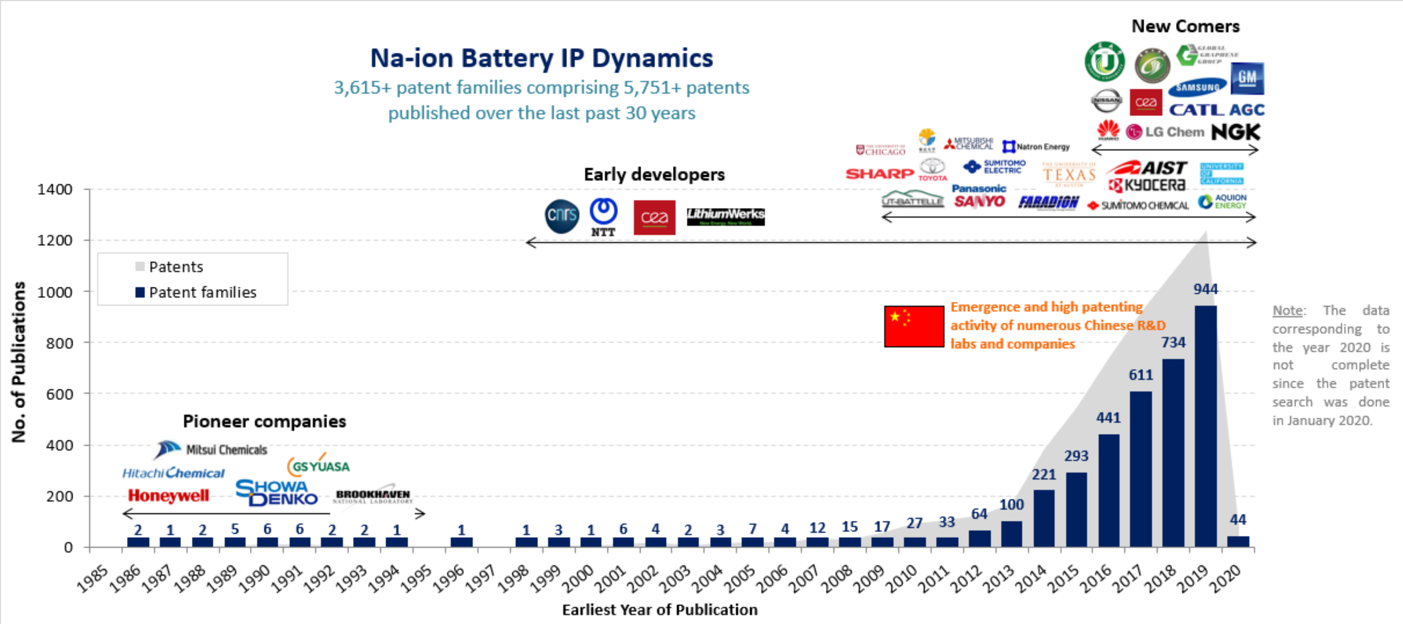


Figure 27: IP Dynamics for Na-ion Battery (Number of patent families and patents annually published by earliest publication year)

Pioneer patents on Na-ion battery have been published in the mid 1980's by **Honeywell** and **Japanese companies (Hitachi Chemical, Showa Denko, etc**.). They were related to anode materials (sodium alloys), cathode materials (sodium cobalt dioxide) and their use in rechargeable Na-ion batteries. Patenting activity on Na-ion battery emerged in the mid 2000's thanks to the entry of numerous companies and R&D labs in the patent landscape (**CEA, CNRS, NTT, Faradion, Panasonic, Sharp, University of Texas, Aquion Energy,** etc.). Since 2010, patenting activity on Na-ion battery is booming (+69% CAGR between 2006 and 2019) mainly due to the emergence and high patenting activity of numerous Chinese R&D Labs and companies. More recently, several major battery manufacturers (**LG Chem, Samsung, CATL**, etc.) and end-users (**Huawei, General Motors, Nissan,** etc.) have entered the patent landscape. The strong increase in patent filings, the entry of major companies in the patent landscape and the emergence of several American and European start-ups (**Tiamat, Altris, Natron Energy, Ubatt, Echion Technology, Nohms Technology,** etc.) confirm the growing maturity and strong market potential of Na-ion battery.

IP Dynamics by countries

- Since 2014, numerous Chinese R&D labs and industrial companies are entering Na-ion battery patent landscape, leading to a booming patenting activity in China. It is worth to note that since 2014 patenting activity in China strongly increases while patent activity in other countries is stable or slightly increasing.

- Numerous European car manufacturers are entering Li-ion battery patent landscape, indicating a growing interest of company active in battery field for Europe. This interest in Europe could also be seen within next years if Li-S battery reaches a higher market share. Thus, patenting activity on Na-ion Battery in Europe could also increase within next years.

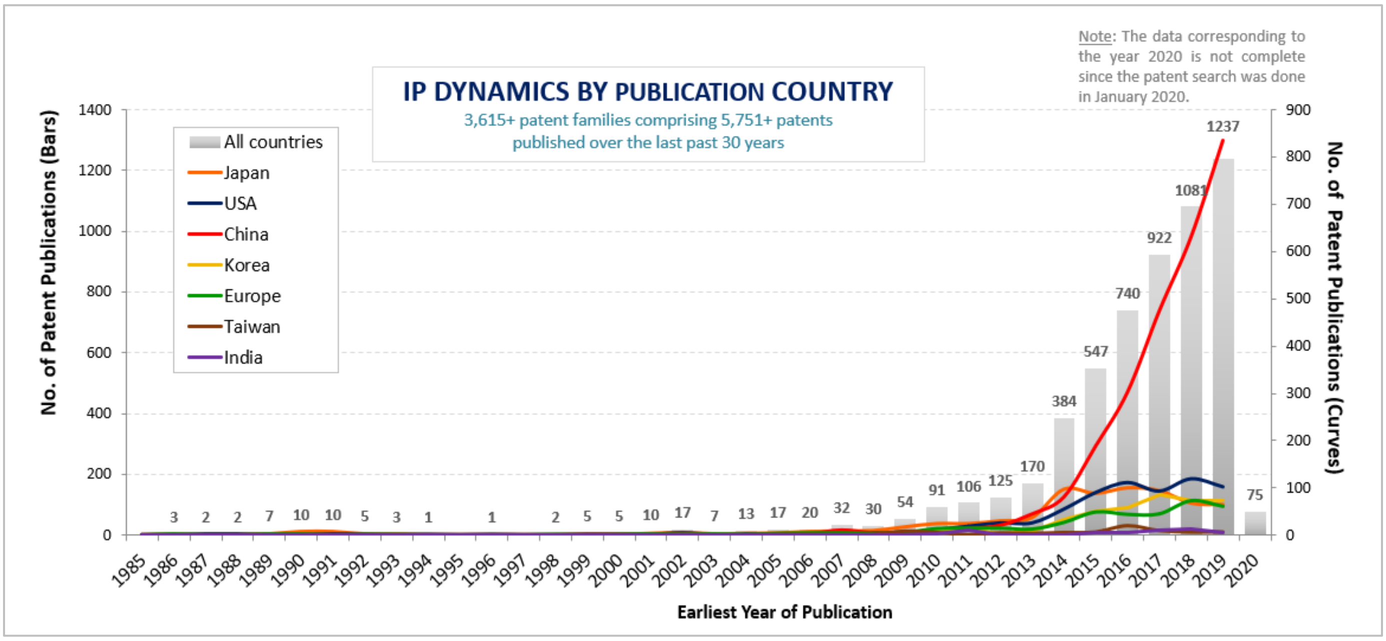


Figure 28: IP Dynamics by Publication Countries for Na-ion Battery (Number of patents annually published by earliest publication year and by countries)

Main IP Players

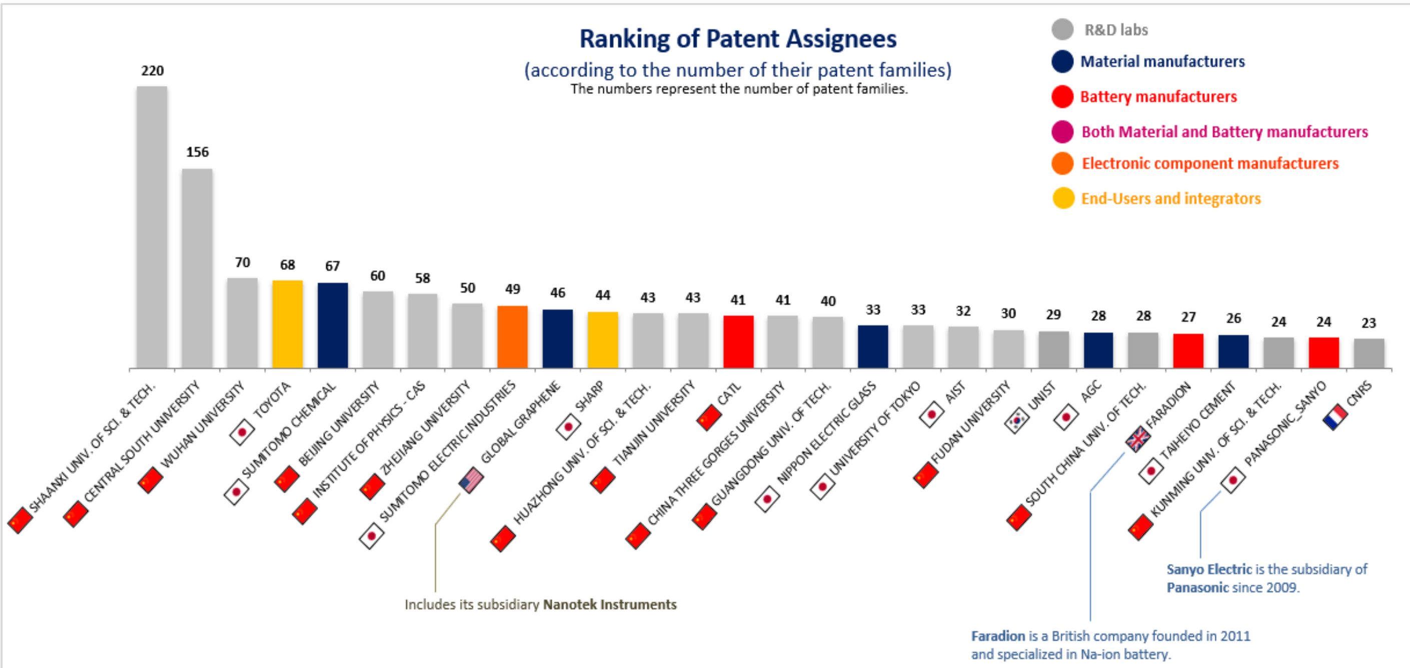


Figure 29: Ranking of Patent Assignees according to the number of their patent families related to Na-ion Battery

- More than **760 organizations** have filed patents related to Na-ion battery. 45% of patent assignees holds only one patent family. **The top 10 and top 5** patent applicants hold respectively **23%** and **16%** of the patent families.
- Main patent assignees are mainly Chinese R&D labs (**Shaanxi University of Science and Technology, Central South University, Wuhan University, etc.**). There are also few industrial companies (**Toyota, Sumitomo Chemical, Sumitomo Electric Industries, Global Graphene, Sharp, CATL, NEG, AGC, Faradion, Panasonic**) from the whole supply chain among main IP players confirming their interest for this trendy technology.

- There are only few European companies among the main IP Players (**Faradion, CNRS**). **Faradion** is a British company founded in 2011 and focused on Na-ion battery.
- **Global Graphene** is the sole American company among main IP Players. **Global Graphene** is an American group founded in 2007. It develops, sells and licenses advanced graphene raw materials and nanocomposites for next-generation products such as phones, tires, paints and batteries.

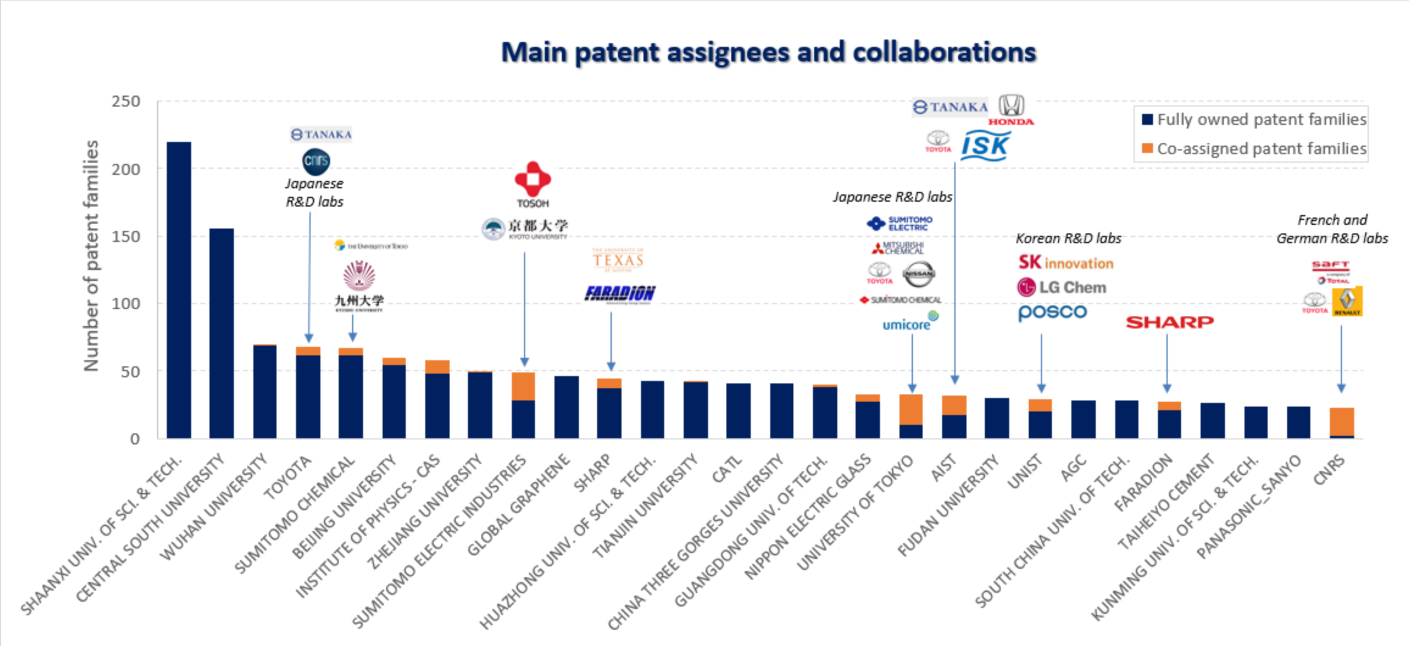


Figure 30: Number of co-assigned patent families by main patent assignees in Na-ion battery patent landscape

Main IP Players by Type of Companies

Material Manufacturers	
SUMITOMO CHEMICAL	67
GLOBAL GRAPHENE	46
NIPPON ELECTRIC GLASS	33
AGC	28
TAIHEIYO CEMENT	26
SHOWA DENKO	18
G.Z. NEW ENERGY TECHNOLOGY	15
HITACHI CHEMICAL	14
KYOCERA	14
MITSUBISHI CHEMICALS	11
PETROCHINA	11
N.J. NEW MATERIAL TECH.	10
POSCO	7
STELLA CHEMIFA	7
XIFENG 2D MATERIAL TECHNOLOGY	7
KANEKA	6
OSAKA GAS	6
TOSOH	6
3M	5
ASAHI KASEI	5
KURARAY	5
MONALISA	5
NOHMS TECHNOLOGIES	5

Battery Manufacturers	
CATL	41
FARADION	27
PANASONIC_SANYO	24
LG CHEM	18
SAMSUNG	15
DONGGUAN MAIKE NEW ENERGY	13
MCNAIR TECHNOLOGY	13
NATRON ENERGY	12
SINOPOLY BATTERY TECH.	10
AMPEREX TECHNOLOGY	9
AQUION ENERGY / JULINE TITANS	8
HEFEI GUOXUAN HTPE	7
SUNWODA ELECTRONICS	7
ENPOWER ENERGY TECH.	6
LIAONING STARRY SKY SODIUM BAT.	6
MURATA / SONY	6
BEIJING WEILAN NEW ENERGY TECH.	5
BELENOS CLEAN POWER	5
LITHIUM WERKS / VALENCE TECH.	5
SEL	5
TOSHIBA	5

Electronic Component Manufacturers	
SUMITOMO ELEC. IND.	49
SUZHOU S. ELECT. TECH.	10
CHINA ELECTRONIC TECHNOLOGY	5
RICOH	3
BOSCH_SEEO	2
DAINIPPON SCREEN MAN.	2

End-Users and Integrators	
TOYOTA	68
SHARP	44
NTT	19
NISSAN	15
EQUOS RESEARCH	11
SGCC	11
GENERAL MOTORS	8
HONEYWELL	6
HUAWEI	6
HYDRO QUEBEC	6
MITSUBISHI MOTORS	4
SPARKLE POWER	4
FORD	3
SUBARU	3

R&D Labs	
SHAANXI UNIV. OF SCI. & TECH.	220
CENTRAL SOUTH UNIVERSITY	156
WUHAN UNIVERSITY	70
BEIJING UNIVERSITY	60
INSTITUTE OF PHYSICS - CAS	58
ZHEJIANG UNIVERSITY	50
HUAZHONG UNIV. OF SCI. & TECH.	43
TIANJIN UNIVERSITY	43
CHINA THREE GORGES UNIVERSITY	41
GUANGDONG UNIV. OF TECH.	40
UNIVERSITY OF TOKYO	33
AIST	32
FUDAN UNIVERSITY	30
UNIST	29
SOUTH CHINA UNIV. OF TECH.	28
KUNMING UNIV. OF SCI. & TECH.	24
CNRS	23
DALIAN INST. OF CHEMICAL PHYSICS	23
FUJIAN NORMAL UNIVERSITY	22
INSTITUTE CHEMISTRY CAS	22
SOUTHWEST UNIVERSITY	22
KYUSHU UNIVERSITY	21
QILU UNIV. OF TECHNOLOGY	21
SHANGHAI UNIV. OF ELEC. POWER	21
TSINGHUA UNIVERSITY	21

Table 21: Ranking of main Patent Assignees by Type of Companies according their number of patent families related to Na-ion Battery. (Time period: 1986-2020, i.e. all patent families in the patent landscape). European companies are written in orange color. The numbers represent the number of patent families of the corresponding patent assignee in Na-ion Battery patent landscape.

IP Dynamics of Main IP Players

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Earliest year of publication for each patent family

		Nb of patent families	Average age of the patent portfolio	1985-1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Old IP Player with a decreasing patenting activity	PANASONIC_SANYO	24	10		1							2	6	4		2				6	3					
	SUMITOMO CHEMICAL	67	8								1	1			12	13	9	5	4	8	5	4	3	2		
	FARADION	27	6														1	6	3	6	5	1		2	3	
	TOYOTA	68	5									1				1	1	3	8	10	21	12	4	1	4	2
	SHARP	44	5																6	11	12	9	4	2		
	UNIVERSITY OF TOKYO	33	5													1		4	3	7	1	7	5	2	3	
	AIST	32	5											1				3	8	8	5	5	1	3	6	
Old IP player still active	CNRS	23	5				1									1	2	1	2	2		3	3	3	5	
	WUHAN UNIVERSITY	70	4															4	1	2	12	14	19	14	6	
	SUMITOMO ELECTRIC IND.	49	4															2	1	7	11	13	11	2	2	
	FUDAN UNIVERSITY	30	4										1	2					2		4	6	6	6	3	
	AGC	28	4							1						1			1	1		8	5	5	6	
Most active IP players since 2018	CENTRAL SOUTH UNIVERSITY	156	3															3			12	25	40	39	36	4
	INSTITUTE OF PHYSICS - CAS	58	3																7	2	14	5	5	5	20	
	ZHEJIANG UNIVERSITY	50	3																	8	2	8	8	11	18	
	HUAZHONG UNIV. OF SCI. & TECH.	43	3																	3	3	3	16	9	9	
	TIANJIN UNIVERSITY	43	3										1							1	2	11	8	11	15	
	NIPPON ELECTRIC GLASS	33	3																1	2	4	6	6	7	7	
	UNIST	29	3																3	1	1	7	4	8	5	
	SOUTH CHINA UNIV. OF TECH.	28	3																		1	10	8	5	3	1
	TAIHEIYO CEMENT	26	3																			4	14	6	2	
	SHAANXI UNIV. OF SCI. & TECH.	220	2																		11	39	46	46	78	
	BEIJING UNIVERSITY	60	2																2	2	3	6	6	20	21	
	GLOBAL GRAPHENE	46	2															1	1		1	6	9	15	13	
	CHINA THREE GORGES UNIV.	41	2																		1	8	14	5	13	
	KUNMING UNIV. OF SCI. & TECH.	24	2																			1	5	12	6	
	CATL	41	1																					16	23	2
	GUANGDONG UNIV. OF TECH.	40	1																				1	12	25	2
	DALIAN INST. OF CHEM. PHYSICS	23	1																				2	7	13	1

Table 22: Time Evolution of Patent Publications by main Patent Assignees and by earliest year of publication for each patent family in Na-ion Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignee). European companies are written in orange color. In each cell referring to a publication year, the numbers represent the number of patent families.

- **Panasonic/Sanyo** is an old IP player who has decreased its patenting activity since 2015. It still has alive patents worldwide. This indicates that it is still interested by Na-ion battery even if it may have decreased its R&D developments on this topic.
- Most active IP players since 2018 are mainly Chinese R&D labs, except **Global Graphene** (American material manufacturer) and **CATL** (Chinese battery manufacturer).

Newcomers in the Patent Landscape

- Newcomers are companies who started their patenting activity in 2017. There are more than 170 newcomers in the Na-ion battery patent landscape.
- They are mainly Chinese R&D labs (*Guandong University of Technology, Dalian Institute of Chemical Physics, Shenzhen Institute of Advanced Technology, China Electronic New Energy Research Institute, Henan Normal University, Qingdao University, Tonji University, Jiangsu University, etc.*) and Companies (*SGCC, Sunwoda Electronics, Xifend 2D Material Technology, CATL, Huawei, Petrochina, Monalisa, Soudon new energy technology, Pulead Technology Industry, CALB, Liaoning Starry Sky Sodium Battery, Coslight, Shanghai Zijian Chemical Technology, Yinlong Energy, Tianneng Battery, etc*.).
- Among newcomers, there are also notable American IP players (*Nohms Technologies, General motors, Cabot, Ford, Northwestern University, Farad Power, Drexel University, Purdue Research Foundation,* etc.) , European IP Players (*KIT, Haldor Topsoe, EDF, DSM, Morgan Advanced Material, Altris, Université de Liège, Stockholm University, SAFT/Total, Echion Technology, SGL Carbon, ENSICAEN/Université de Caen,* etc.), Japanese IP Players (*JSR, Tohoku University*, *Kuraray, Hokkaido University, Kureha, Asahi Kasei, Mitsubishi Materials,* etc.) and Korean IP Players (*Yonsei University, KRICT, Ubatt, etc*.).
  - **Nohms Technologies** is an American company founded in 2011. It develops non-flammable and high voltage electrolyte solutions for battery applications. Its NanoLyte Electrolyte solutions contain new functional ionic liquid materials that significantly improve performance and safety of next-generation lithium ion batteries.
  - **Farad Power** is an American company founded in 2012. It develops carbon materials for next-generation applications in energy storage.
  - **Ubatt** is a Korean start-up founded in 2016 on the basis of R&D developments of UNIST. Ubatt's core technologies include solution-processable/non-flammable solid-state electrolytes, scalable printing/impregnation processes, Lithium-based batteries and customized cell design/configuration.
  - **Haldor Topsoe** is Danish company founded din 1972. It develops and manufactures catalysts and battery materials for energy generation and storage.
  - **Morgan Advanced Material** is a British company founded in 1856. It manufactures specialty materials, such as carbon, advanced ceramics and composite for a broad range of markets.
  - **Altris** is a Swedish start-up founded in 2017 on the basis of R&D results obtained at **Uppsala University**. It develops and produce highly sustainable cathode materials for rechargeable sodium batteries.
  - **Echion Technology** is a British start-up founded in 2017 as a spin-off of Cambridge University. It develops unique materials for next-generation batteries, notably materials compatible with fast-charging.
  - **Tiamat** is a French start-up founded in 2017 on the basis of R&D results obtained at **CEA and CNRS**. It develops rechargeable Na-ion batteries. It is worth to note that **Tiamat** does not have published patents on Na-ion batterie but has an exclusive license on CNRS/CEA patents related to Na-ion battery.

Current Legal Status of Patents

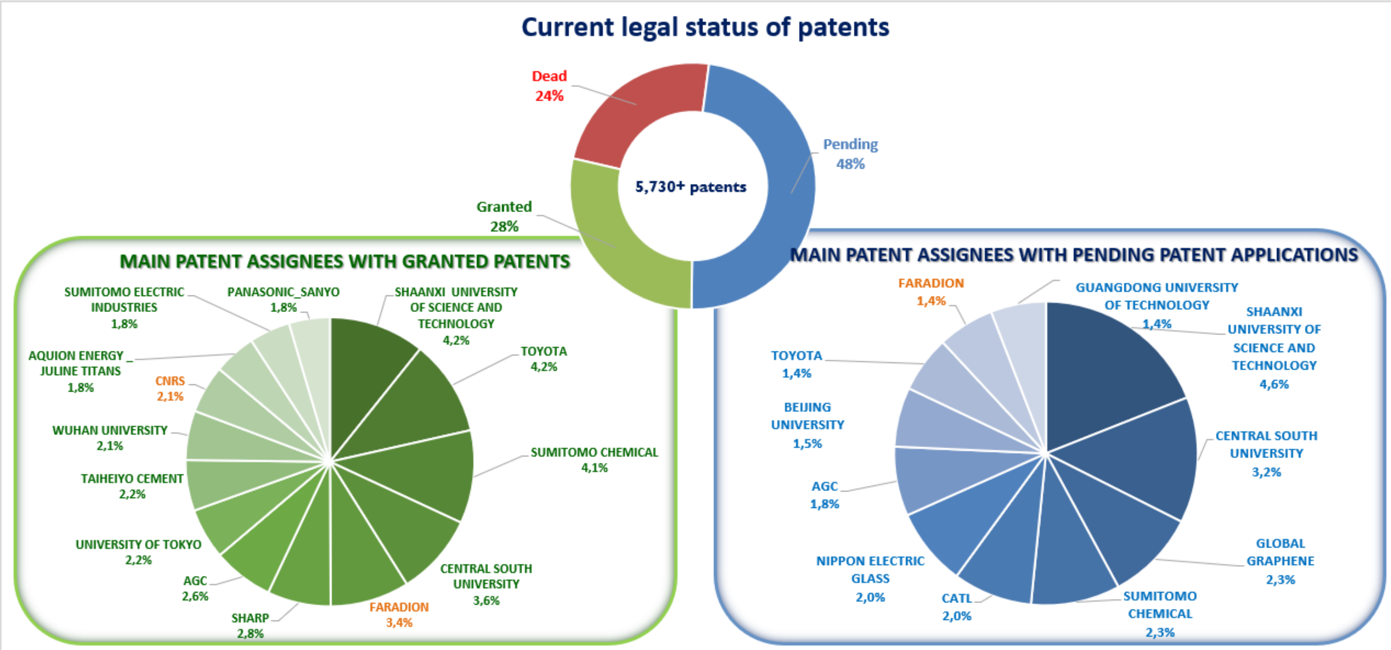


Figure 31: Current Legal Status and main patent assignees with granted patents and pending patent applications for Na-ion Battery. European companies are written in orange color.

More than 76% of the patents in Na-ion battery patent landscape are currently pending or granted. This reflects that many R&D developments are still on-going to solve current technical issues related to Na-ion battery. **Shaanxi University of Science and Technology, Toyota, Sumitomo Chemical, Central South University, Faradion and Sharp** hold the highest number of granted patents. **Shaanxi University of Science and Technology, Central South University, Global Graphene, Sumitomo Chemical, CATL and NEG** hold the highest number of pending patent applications.

Legal Status by Countries

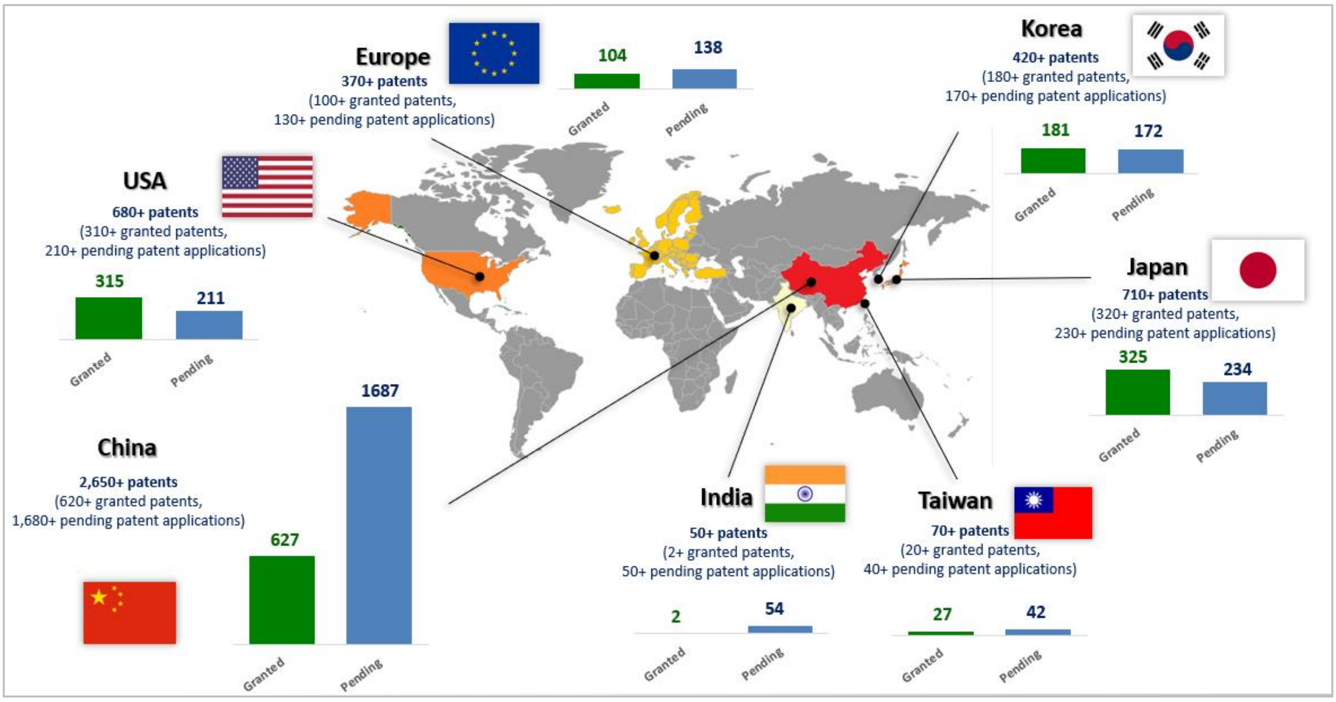


Figure 32: Mapping of Legal Status by Countries for Na-ion Battery

Pending patent applications are mainly filed in China. In fact, there are numerous highly active Chinese IP players in the patent landscape. Most of them focus their patenting activity in China. It is worth to note that more than 5% of pending applications have been filed in Europe.

Most Active IP Players by Countries

Patents in Europe are not only filed by European IP Players but also by foreign companies (**Toyota, AGC, University of Tokyo,** etc.). It is worth to note that **Toyota and University of Tokyo** have co-filed patents with European IP Players, explaining their high patenting activity in Europe. Li-ion battery R&D development are driven by automotive applications. Europe represent an important market for car manufacturers. Thus, patenting activity in Europe should increase within next years.

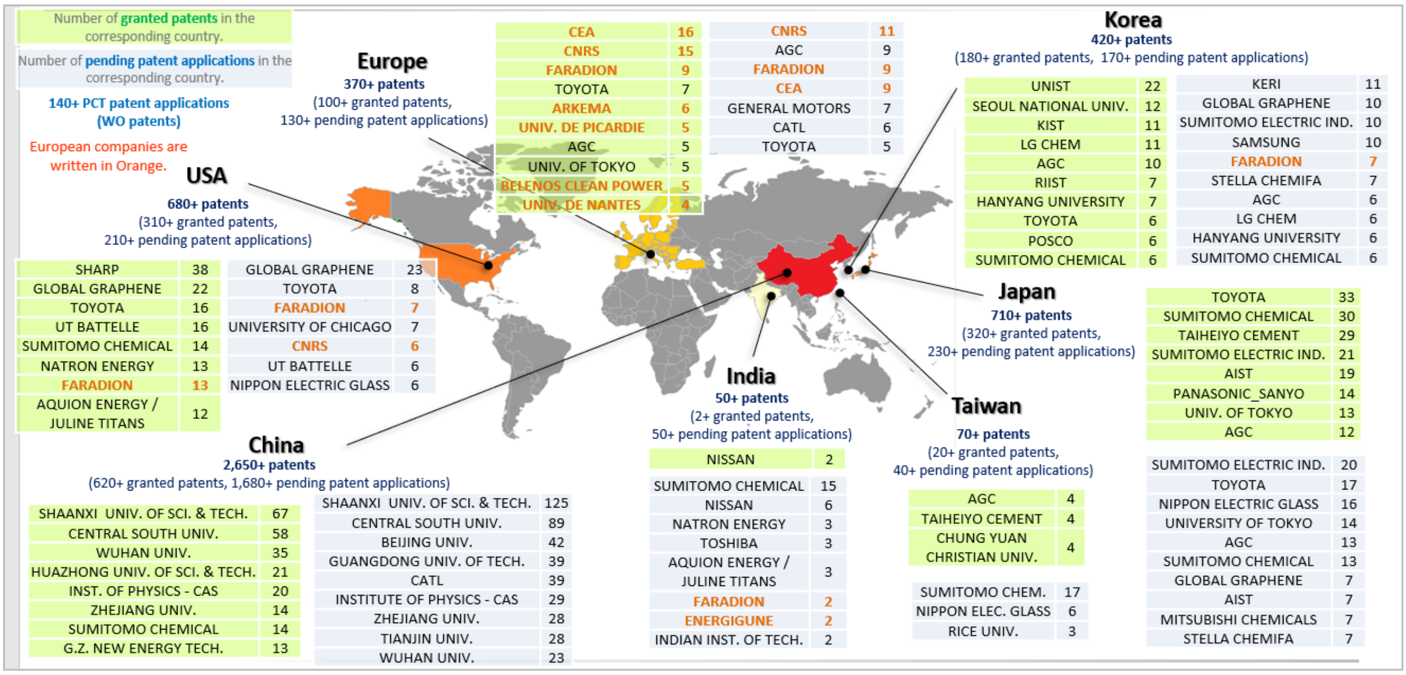


Figure 33: Main current patent assignees by Countries for Na-ion Battery

Patenting Activity of IP Leading Companies

- Most of main Chinese IP players only file patents in China, except **Shaanxi University of Science and Technology, Institute of Physics (CAS), CATL, South China University of Technology** who file WO patents or extend their patents in other countries (Table 23).
- Main IP players originating from other countries than China, including European companies, have a worldwide IP strategy (Table 23).
- **Nissan** is the sole company who has granted patents in India (Table 23). However, it is worth to note that several major companies in battery field (**Sumitomo Chemical, Toyota, Sharp, Faradion, etc**.) have pending patent applications in India (Table 23). In fact, India becomes an attractive market for battery manufacturers due to Indian government policies to push the conversion towards EVs/HEVs.

Assignee	Number of Patent families: All	Number of Patent families: Alive	Patent Legal status: Granted	Patent Legal status: Pending	Patent Legal status: Dead	Number of granted patents: USA	Number of granted patents: Europe	Number of granted patents: Japan	Number of granted patents: China	Number of granted patents: Korea	Number of granted patents: Taiwan	Number of granted patents: India	Number of pending patent applications: USA	Number of pending patent applications: Europe	Number of pending patent applications: Japan	Number of pending patent applications: China	Number of pending patent applications: Korea	Number of pending patent applications: Taiwan	Number of pending patent applications: India	Number of pending patent applications: PCT applications (WO patents)
SHAANXI UNIV. OF SCI. & TECH.	220	192	68	126	29	1			67				1			125				
CENTRAL SOUTH UNIV.	156	147	58	89	9				58							89				
WUHAN UNIV.	70	58	35	23	13				35							23				
TOYOTA	68	52	73	43	62	16	7	33	8	6			8	5	17	7	3		1	1
SUMITOMO CHEMICAL	67	50	66	63	153	14	2	30	14	6			1	3	13	6	6	17	15	2
BEIJING UNIV.	60	54	12	42	6				12							42				
INSTITUTE OF PHYSICS - CAS	58	49	26	35	14	1	2	3	20				1			29	2			3
ZHEJIANG UNIV.	50	42	14	28	8				14							28				
SUMITOMO ELECTRIC IND.	49	43	29	35	45	3		21	4		1		2		20	3	10			
GLOBAL GRAPHENE	46	44	22	64	8	22							23		7	11	10			13
SHARP	44	32	45	15	62	38	1	2	4				4	2		8			1	
HUAZHONG UNIV. OF SCI. & TECH.	43	41	21	20	3				21							20				
TIANJIN UNIV.	43	32	4	28	12				4							28				
CATL	41	41	1	56	2				1				5	6	2	39				4
CHINA THREE GORGES UNIV.	41	33	12	21	8				12							21				
GUANGDONG UNIV. OF TECH.	40	40	1	39					1							39				
NIPPON ELECTRIC GLASS	33	31	21	55	17	6		9	4	1	1		6		16	13	4	6		10
UNIV. OF TOKYO	33	28	36	25	26	6	5	13	5	5	2		3	2	14	4	1			1
AIST	32	28	27	17	20	3		19	1	3	1		1	2	7	2	2		1	2
FUDAN UNIV.	30	20	3	17	10				3							17				
UNIST	29	28	24	10	5	1			1	22			2			1	5			2
AGC	28	27	43	49	23	6	5	12	6	10	4		4	9	13	9	6	2		6
SOUTH CHINA UNIV. OF TECH.	28	26	7	22	2				7				1			19				2
FARADION	27	25	56	40	68	13	9	7	10	3			7	9	6	7	7		2	2
TAIHEIYO CEMENT	26	26	36	13	4	1		29	1	1	4		4	3		3	3			
KUNMING UNIV. OF SCI. & TECH.	24	22	1	21	2				1							21				
PANASONIC_SANYO	24	17	29	4	20	9		14	6						3	1				
CNRS	23	22	34	34	24	5	15	5	3	2			6	11	3	4	3			7

Table 23: Legal status of patents by countries for main patent assignees in Na-ion Battery patent landscape. European companies are written in orange color.

IP Leadership

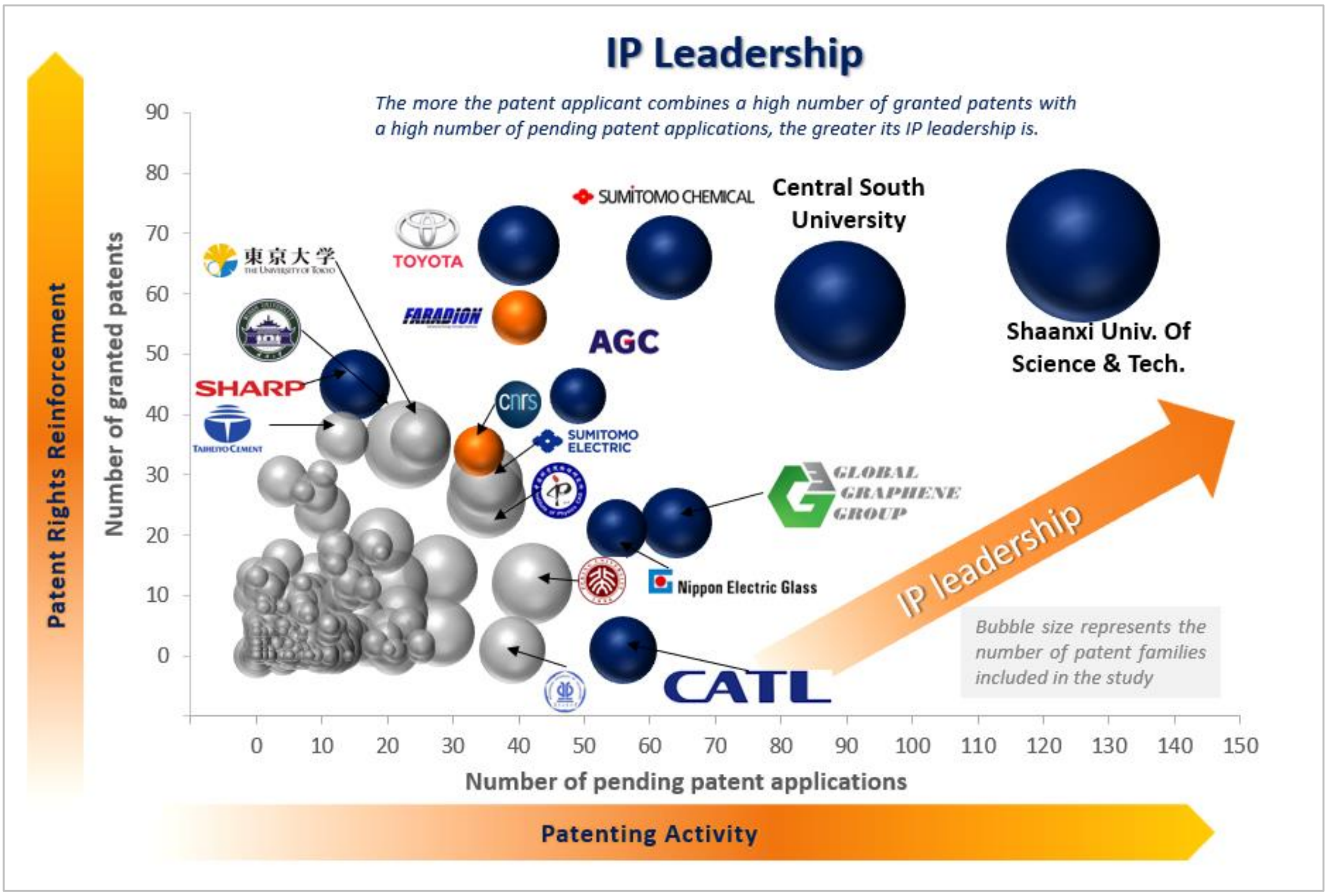


Figure 34: IP Leadership of Patent Assignees for Na-ion Battery. Orange bubbles indicate European companies with a notable IP leadership. Blue bubbles indicate Non-European companies with a notable IP leadership. Grey bubbles indicate companies without a notable IP leadership.

- In Figure 34, Only companies with a notable IP leadership (Orange and blue bubbles) have been annotated. Companies with a low IP leadership have grey bubbles and have not been annotated for more clarity on the graph. Thus, if a company having patent families related to Na-ion battery is not annotated in the graph, it means that it has a low IP leadership compared to other IP Players.
- **Shaanxi University of Science and Technology** leads Na-ion battery patent landscape. It holds the highest number of patent families and pending patent applications and the second highest number of granted patents worldwide. It is worth to note that **Shaanxi University of Science and Technology** has strongly increased its patenting activity on Na-ion battery since 2016.
- **Central South University** is an IP challenger with the second highest number of pending patent applications and the fourth highest number of granted patents worldwide. **Central South University** has a high patenting activity since 2016.
- **Toyota, Faradion and Sumitomo Chemical** are established IP players, with a high number of granted patents and numerous pending patent applications worldwide. **Sumitomo Chemical and Toyota** have decreased their patenting activity on Na-ion battery since 2016. **Faradion** has a stable patenting activity since its emergence in the patent landscape in 2012.
- **Global Graphene, Nippon Electric Glass and CATL** are also IP Challengers thanks to their notable number of pending patent applications.
- **AGC, CNRS, Sumitomo Electric Industries, University of Tokyo and Sharp** also have a notable number of alive patents.

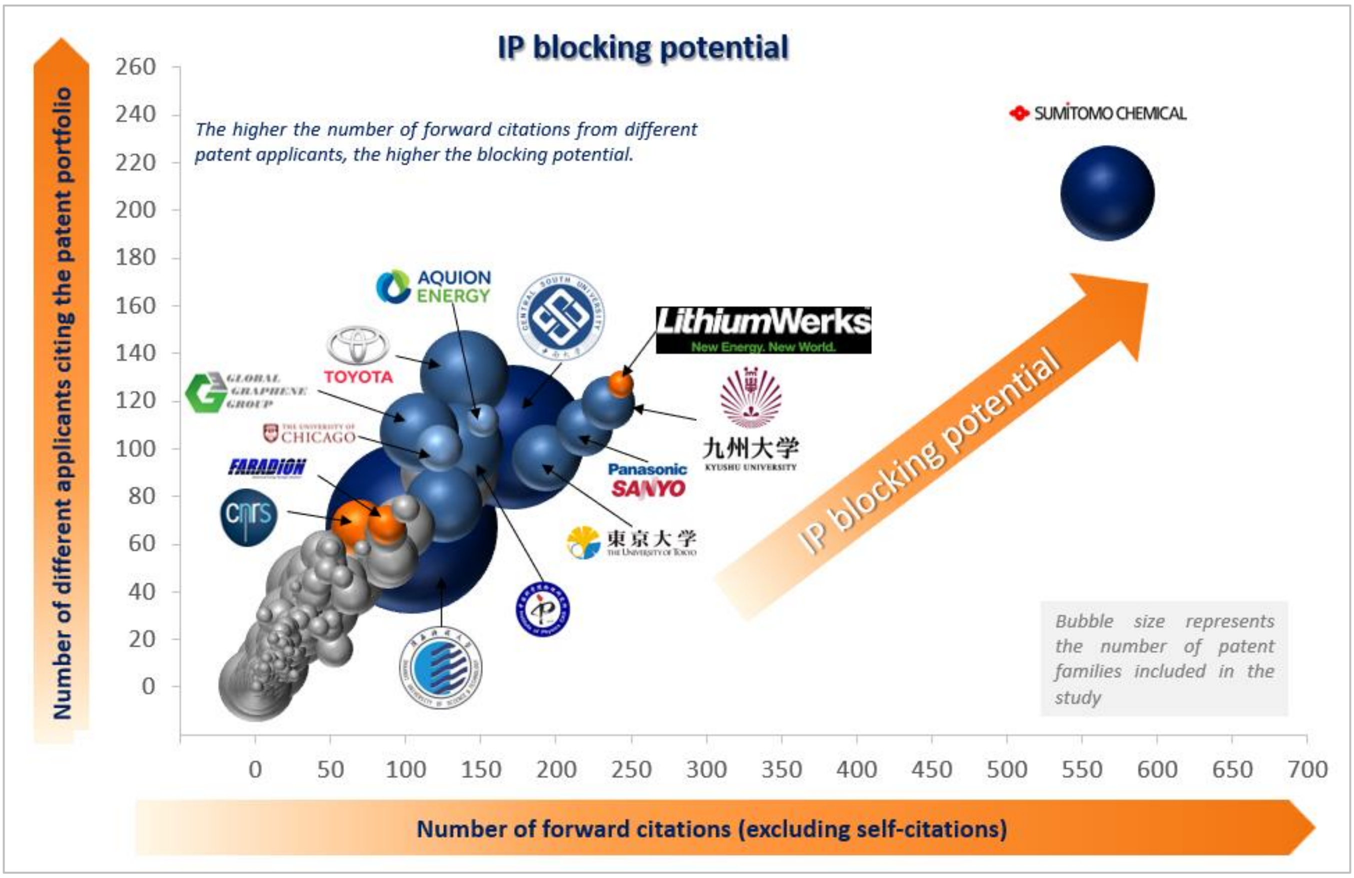


Figure 35: IP Blocking Potential of Patent Assignees for Na-ion Battery. Orange bubbles indicate European companies with a notable IP Blocking Potential. Blue bubbles indicate Non-European companies with a notable IP Blocking Potential. Grey bubbles indicate companies without a notable IP Blocking Potential.

- **Sumitomo Chemical** combines a large patent portfolio with the highest IP Blocking Potential far from other IP players. Its patents related to Na-ion battery strongly contribute to the prior art and have received numerous forward citations from a lot of different patent applicants. That means that its patent portfolio offers it the capability to block other firms involved in the field.
- **Lithium Werks / Valence Technology, Kyushu university, Panasonic/Sanyo, University of Tokyo, Aquion Energy, Toyota, Global Graphene, Institute of Physics (CAS) and University of Chicago** also have a notable IP Blocking potential.
- Despite their high IP leadership, **Shaanxi University of Science and Technology** and **Central South University** have a medium IP Blocking Potential. In fact, most of their patents have been filed after 2015 and thus receive only few forward citations. Their IP blocking potential could be improved within next years.
- Despite their notable IP leadership, European IP Players **CNRS** and **Faradion** have a medium IP Blocking potential.

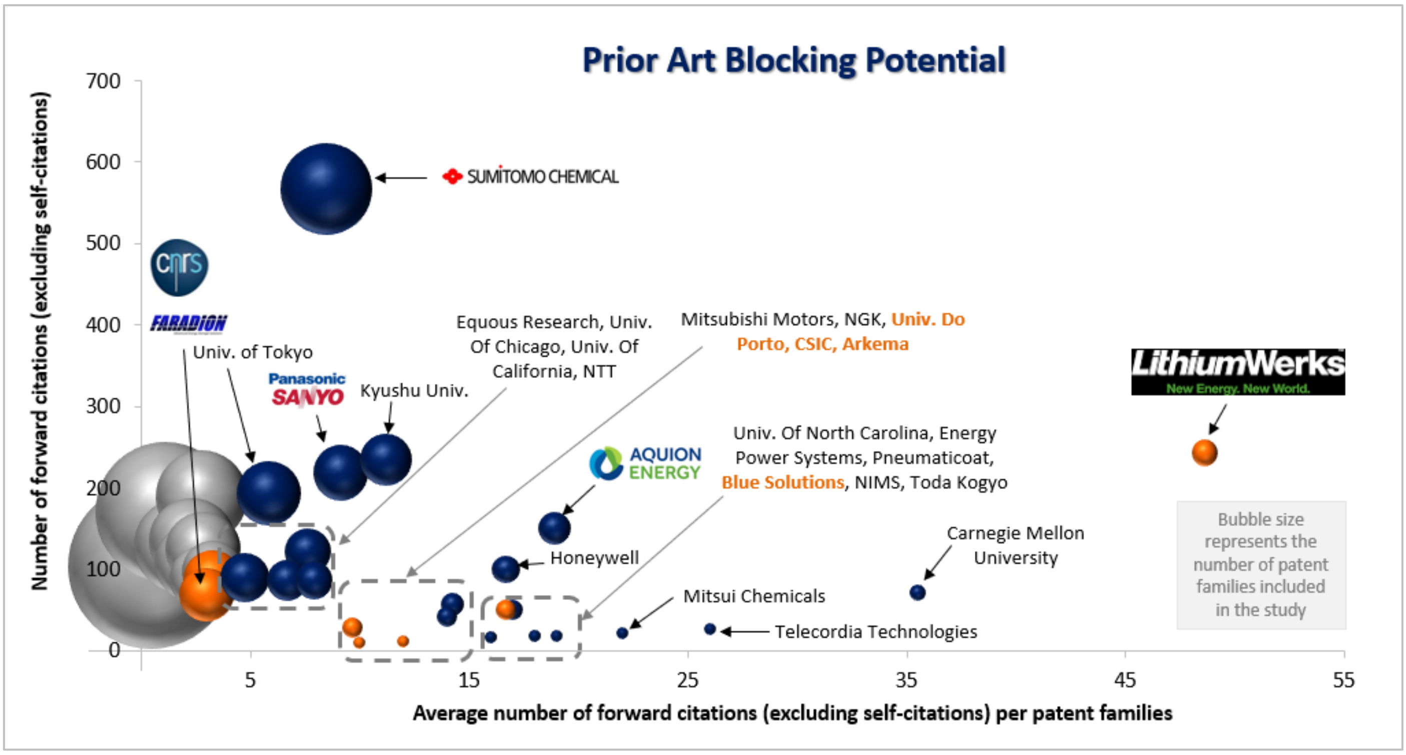


Figure 36: Prior Art Blocking Potential of Patent Assignees for Na-ion Battery. Orange bubbles indicate European companies with a notable Prior Art Blocking Potential. Blue bubbles indicate Non-European companies with a notable Prior Art Blocking Potential. Grey bubbles indicate companies without a notable Prior Art Blocking Potential.

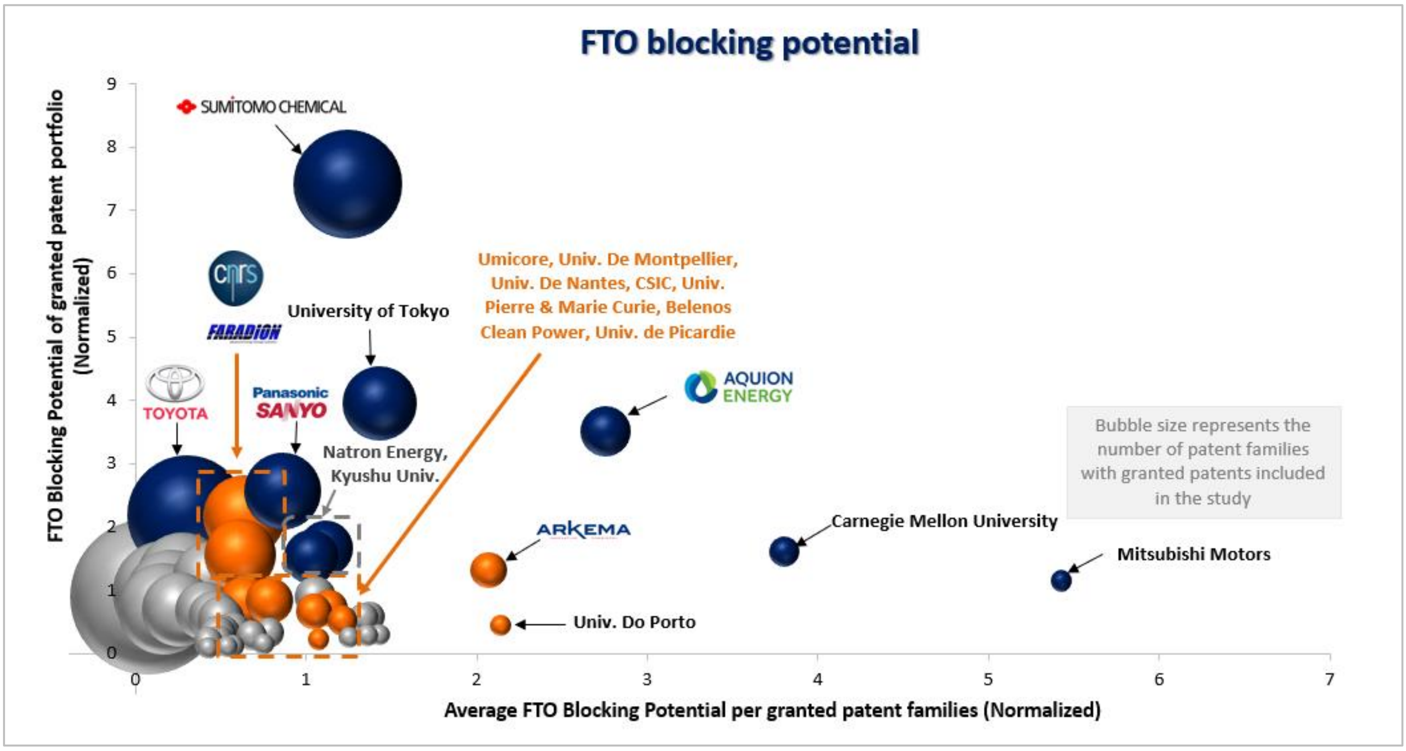


Figure 37: FTO Blocking Potential of Patent Assignees for Na-ion Battery. Orange bubbles indicate European companies with a notable FTO Blocking Potential. Blue bubbles indicate Non-European companies with a notable FTO Blocking Potential. Grey bubbles indicate companies without a notable FTO Blocking Potential.

- **Sumitomo Chemical** holds the highest Prior Art blocking potential and FTO blocking potential induced by a high number of patent families and highly cited patents. This indicates that it has a high capability to limit both patenting activity and freedom-to-operate of other companies.
- Despite their high IP leadership, **Shaanxi University of Science and Technology and Central South University** have a low Prior art blocking potential and FTO blocking potential. In fact, most of their patents have been filed after 2015, are still pending and thus receive only few forward citations. Moreover, their patenting activity is focused in China leading to a very low geographic coverage.
- Despite its high IP leadership, **Toyota** has a low Prior Art blocking potential and a medium FTO blocking potential induced by a high technological impact of its granted patents.
- Despite their very small patent portfolio, **Carnegie Mellon University, Telecordia Technologies, Mitsui Chemicals, Aquion Energy** have a high technological impact because they hold key patent families with numerous forward citations. It is worth to note that **Mitsui Chemicals and Telecordia Technologies** have no more granted patents and thus don't have the capability to limit freedom-to-operate of other companies. **Aquion Energy** is an American company founded in 2008 and acquired by **Juline Titans** after its bankruptcy in 2017. It develops and commercializes aqueous Na-ion battery.
- Similarly, despite its very small patent portfolio, **Mitsubishi Motors** have a high average FTO Blocking potential per patent families induced by a highly cited patent families granted in numerous countries.
- Among European IP players:
  - Despite their very small patent portfolio, **Lithium Werks / Valence Technology, Blue Solutions, Univ. Do Porto, CSIC** and **Arkema** have a high technological impact factor because they hold key patent families with numerous forward citations. It is worth to note that **Blue Solutions, Lithium Werks / Valence Technology and CSIC** don't have granted patents and thus don't have the capability to limit freedom-to-operate of other companies. **Arkema** and **Univ. do Porto** also have a notable capability to limit freedom-to-operate of other companies thanks to highly cited patent families granted in numerous countries.
  - Despite their relatively large patent portfolio, **CNRS** and **Faradion** have a medium prior art and relatively high FTO blocking potential induced by a medium technological impact factor and a relatively large geographic coverage. Thus, they have a notable capability to limit freedom-to-operate of other companies
  - Other European IP players **(Umicore, Université de Montpellier, Université de Nantes, CSIC, Université Pierre et Marie Curie, Belenos Clean Power and Université de Picardie)** have a notable average FTO blocking potential per patent families induced by a small number of key patents and a large geographic coverage.

PATENT SEGMENTATION BY SUPPLY CHAIN SEGMENTS

Overview of Patenting Activity by Supply Chain Segments

- Patenting activity by supply chain segments is correlated to main development axes envisioned to improve Na-ion battery performances and safety (electrode and electrolyte materials). Patents on Na-ion battery are mainly related to electrode materials (anode and cathode materials). There are less patents related to electrode and battery cell because they can be made with the same process than the one used for Li-ion battery electrodes. There are only few patents on separators because separators used in Na-ion batteries can be the same than the one used in Li-ion batteries.
- There are very few patents on Na-ion battery recycling. They are related to recycling of waste Na-ion battery and recovery of electrode materials and metals from Na-ion batteries. Recycling of Na-ion battery is not a topic of interest for the moment because there are no Na-ion batteries on the market yet. Companies specialized on battery recycling prefer to focus on recycling of Li-ion battery for which the demand is strongly increasing.

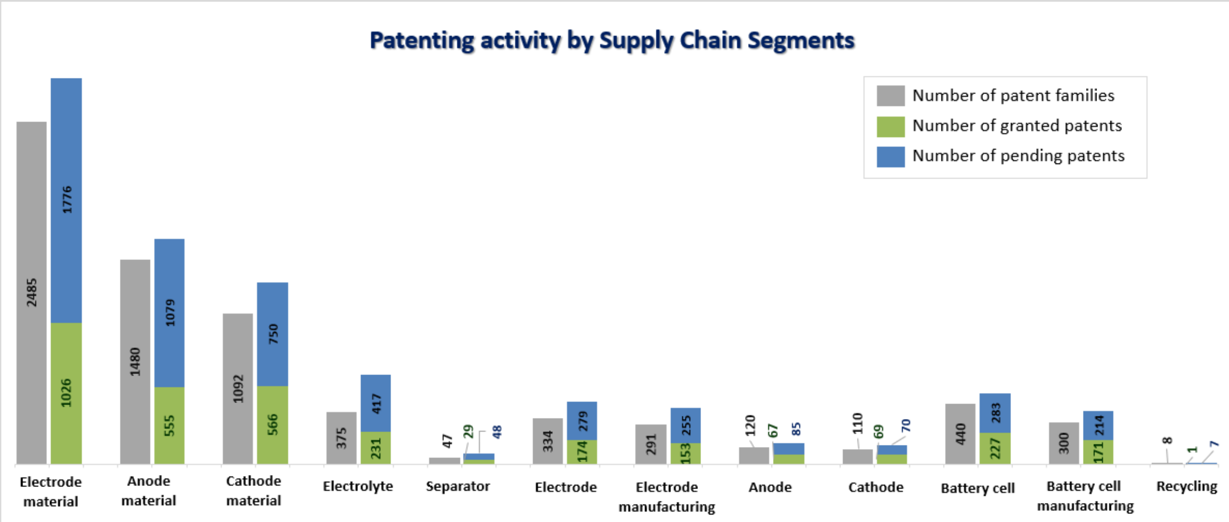


Figure 38: Patenting Activity by Supply Chain Segments for Na-ion Battery

IP Dynamics by Supply Chain Segments

The numbers represent the number of patent families.

Earliest publication year

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Supply Chain Segment	Number of patent families	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Electrode material	2485							1			1		4	2	2	3	5	2	3	4	13	5	16	33	59	133	190	292	466	530	690	29
Anode material	1480															1	2		1		6	1	3	10	29	70	105	193	288	316	435	18
Cathode material	1092							1			1		4	2	2	2	4	2	2	4	7	4	13	24	34	70	90	127	205	219	264	11
Electrolyte	375											1	1				1		1	4	1	4	4	6	7	16	21	65	50	67	120	6
Separator	47																								2	4	4	4	1	12	17	3
Electrode	334					1								1				2	1	1	1	5	5	11	17	24	32	38	53	64	70	5
Electrode manufacturing	291					1								1				2	1	1	1	5	3	10	15	22	24	35	47	57	61	4
Anode	120																	1				1	2		8	8	14	20	17	29	18	1
Cathode	110					1												1		1		3	2	5	8	10	11	16	14	10	25	1
Battery cell	440	6	6	2	2					1	2	1	1	1			1		7	8	3	14	12	16	21	51	56	46	47	71	56	3
Battery cell manufacturing	300	2								1	1	1	1	1			1		4	7	3	10	7	9	17	31	39	31	35	50	42	3
Recycling	8																										1			4	3	

Table 24: Time Evolution of patent families by supply chain segments and earliest publication year in Na-ion Battery patent landscape (Number of patent families annually published by earliest publication year and by supply chain segments)

Patenting activity on cathode and anode materials has strongly increased within last 10 years. Patenting activity on the electrolyte boomed in the mid 2010's. Patenting activity on electrode and battery cell is slightly increasing since 2011. Patenting activity on separators emerged more recently in 2018. Patenting activity on recycling started in 2015 but it is still anecdotic.

Main IP Players by Supply Chain Segments

IP positions	Electrode material	Anode material	Cathode material	Electrolyte	Separator
Main IP players *(Highest number of patent families)*	SHAANXI UNIV. OF SCI. & TECH., CENTRAL SOUTH UNIV., WUHAN UNIV., BEIJING UNIV., ZHEJIANG UNIV., TIANJIN UNIV., INST. OF PHYSICS – CAS, **SUMITOMO CHEM.,** GUANGDONG UNIV. OF TECH., CHINA THREE GORGES UNIV., HUAZHONG UNIV. OF SCIENCE & TECH.	SHAANXI UNIV. OF SCI. & TECH., CENTRAL SOUTH UNIV., BEIJING UNIV., TIANJIN UNIV., SHANGHAI UNIV., ZHEJIANG UNIV., WUHAN UNIV., GUANGDONG UNIV. OF TECH., **TOYOTA,** CHINA THREE GORGES UNIV.	CENTRAL SOUTH UNIV., SHAANXI UNIV. OF SCI. & TECH., WUHAN UNIV., INST. OF PHYSICS – CAS, HUAZHONG UNIV. OF SCI. & TECH., ZHEJIANG UNIV., **SUMITOMO CHEM.,** BEIJING UNIV., CHINA THREE GORGES UNIV., **UNIV. OF TOKYO**	**AGC, CATL, SUMITOMO ELECTRIC IND., TOYOTA,** INST. OF PHYSICS – CAS, UNIST, NANJING UNIV., BEIJING UNIV., **UT BATTELLE, UNIV. OF TOKYO**	SHENZHEN UNIV., ZHEJIANG UNIV., ZHENGZHOU UNIV., HARBIN INST. OF TECH., **KETI,** NIPPON KODOSHI, WUHAN BAIQI TECH., SHENZHEN ACAD. OF METROL. & QUALITY INSP., **CALTECH,** NINGBO ATMK LITHIUM ION TECH.
Most enforced IP players *(Highest number of granted patents)*	SHAANXI UNIV. OF SCI. & TECH., CENTRAL SOUTH UNIV., FARADION, **TOYOTA, SUMITOMO CHEMICAL,** WUHAN UNIV., **TAIHEIYO CEMENT, UNIVERSITY OF TOKYO,** INSTITUTE OF PHYSICS – CAS, BELENOS CLEAN POWER	CENTRAL SOUTH UNIV., SHAANXI UNIV. OF SCI. & TECH., **TAIHEIYO CEMENT,** BELENOS CLEAN POWER, **TOYOTA, SUMITOMO CHEMICAL,** HUAZHONG UNIV. OF SCI. & TECH., **TOSHIBA,** ZHEJIANG UNIV.	FARADION, SHAANXI UNIV. OF SCI. & TECH., **SUMITOMO CHEMICAL, TAIHEIYO CEMENT, TOYOTA,** WUHAN UNIV., UNIV. OF TOKYO, CENTRAL SOUTH UNIV., **CNRS,** INSTITUTE OF PHYSICS - CAS	**AGC, LG CHEM,** ARKEMA, CNRS, **TOYOTA,** ENERGIGUNE, UNIVERSITE DE NANTES, **UNIV. OF TOKYO, NATRON ENERGY, UT BATTELLE**	**SHARP,** WL GORE, **SUMITOMO CHEMICAL, DKJ NEW ENERGY S&T,** DONGHUA UNIV., NIPPON KODOSHI, SHANGHAI INST. OF SPACE POWER SCES, NINGBO ATMK LITHIUM ION TECH., NINGBO FLEXIBLE NANOMETER TECH.
Main active IP players *(Highest number of pending patent applications)*	SHAANXI UNIV. OF SCI. & TECH., CENTRAL SOUTH UNIV., **SUMITOMO CHEMICAL, NIPPON ELECTRIC GLASS,** BEIJING UNIV., GUANGDONG UNIV. OF TECH., TIANJIN UNIV., CNRS, INSTITUTE OF PHYSICS – CAS, **RICE UNIVERSITY**	SHAANXI UNIV. OF SCI. & TECH., CENTRAL SOUTH UNIV., BEIJING UNIV., **RICE UNIVERSITY,** GUANGDONG UNIV. OF TECH., TIANJIN UNIV., **SUMITOMO CHEMICAL, GLOBAL GRAPHENE,** SOUTH CHINA UNIV. OF TECH.	CENTRAL SOUTH UNIV., **NIPPON ELECTRIC GLASS, SUMITOMO CHEMICAL,** SHAANXI UNIV. OF SCI. &vTECH., CNRS, FARADION, **NATRON ENERGY,** ZHEJIANG UNIV. INSTITUTE OF PHYSICS – CAS, **TAIHEIYO CEMENT**	**AGC, STELLA CHEMIFA, CATL, UNIV. OF CALIFORNIA, NOHMS TECHNOLOGIES, TOYOTA, FORD, UT BATTELLE,** SOLVAY, **UNIV. OF TOKYO**	NIPPON KODOSHI, **GENERAL MOTORS,** SHENZHEN UNIV., ZHEJIANG UNIV., ZHENGZHOU UNIV., HARBIN INST. OF TECH., **SILA NANOTECHNOLOGIES,** BLUE SOLUTIONS_BOLLORE, KETI, WUHAN BAIQI TECH.

Table 25: Main IP Players by supply chain segments (electrode materials, electrolyte, separator) in Na-ion Battery patent landscape

IP positions	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
Main IP players *(Highest number of patent families)*	**SHARP, CATL, LG CHEM, TOYOTA, NISSAN,** UNIST, **SUMITOMO CHEMICAL,** SHAANXI UNIV. OF SCI. & TECH., **GLOBAL GRAPHENE, SUMITOMO ELEC. IND., UT BATTELLE**	**SHARP, LG CHEM, CATL,** UNIST, **SUMITOMO CHEMICAL,** SHAANXI UNIV. OF SCI. & TECH., **UT BATTELLE,** GZ. NEW ENERGY TECH., **NISSAN,** CHINA THREE GORGES UNIV., **GLOBAL GRAPHENE,** INSTITUTE CHEMISTRY CAS, CHINA ELECTRONIC NEW ENERGY RESEARCH INSTITUTE, **SUMITOMO ELECTRIC IND.**	**SHARP, LG CHEM,** SHAANXI UNIV. OF SCI. & TECH., **TOYOTA,** INSTITUTE CHEMISTRY CAS, **SUMITOMO ELEC. IND.,** SHENZHEN UNIV., ZHEJIANG UNIV., CHINA THREE GORGES UNIV., CHINA ELECT. NEW ENERGY RES. INST., TOTTORI UNIV., **KANEKA, UNIV. OF TEXAS**	**SHARP, CATL, SUMITOMO CHEMICAL, SUMITOMO ELEC. IND.,** SHANGHAI JIAO TONG UNIV., CENTRAL SOUTH UNIV., SHAANXI UNIV. OF SCI. & TECH., CHINA THREE GORGES UNIV., CHINA ELECTRONIC NEW ENERGY RES. INST.	**GLOBAL GRAPHENE, TOYOTA, SUMITOMO CHEMICAL, SUMITOMO ELEC. IND., SHOWA DENKO, PANASONIC/SANYO, NTT, HITACHI, NGK**	**GLOBAL GRAPHENE, SUMITOMO ELECTRIC IND., SUMITOMO CHEM.,** GUANGDONG ZHUGUANG NEW ENERGY TECHNOLOGY, **NGK, TOYOTA, NTT, PANASONIC/SANYO**	KUNMING UNIV. OF SCI. & TECH., NORTHEAST NORMAL UNIV., GUANGDONG UNIV. OF TECH., LIYANG ZHONGKEHAI SODIUM TECH., SHANGHAI INST. OF SPACE POWER SCES, ENPOWER ENERGY TECHNOLOGY, **NGK**
Most enforced IP players *(Highest number of granted patents)*	SHARP, **SUMITOMO CHEMICAL, AQUION ENERGY _ JULINE TITANS,** NIPPON SODA, UNIST, **GLOBAL GRAPHENE, SUMITOMO ELECTRIC INDUSTRIES, UT BATTELLE,** FARADION, **LG CHEM**	**SHARP, SUMITOMO CHEMICAL, AQUION ENERGY _ JULINE TITANS, NIPPON SODA,** UNIST, **SUMITOMO ELEC. IND., UT BATTELLE,** FARADION, **LG CHEM,** GUANGDONG ZHUGUANG NEW ENERGY TECH.	**SHARP, AQUION ENERGY _ JULINE TITANS, NIPPON SODA, SUMITOMO ELEC. IND., LG CHEM,** SHAANXI UNIV. OF SCI. & TECH., TOTTORI UNIV., **KANEKA, TOYOTA,** GZ. NEW ENERGY TECH.	**SHARP, SUMITOMO CHEMICAL, SUMITOMO ELEC. IND., 3M,** SHAANXI UNIV. OF SCI. & TECH., **PANASONIC/SANYO,** SOOCHOW UNIV., SHANGHAI JIAO TONG UNIV., **UNIV. OF MICHIGAN, QUANTUMSCAPE, SISOM THIN FILMS**	**AQUION ENERGY _ JULINE TITANS, TOYOTA, GLOBAL GRAPHENE, SUMITOMO ELEC. IND., PANASONIC/SANYO, SUMITOMO CHEM., SHARP,** G.Z. NEW ENERGY TECH., **NTT, CARNEGIE MELLON UNIV.**	**AQUION ENERGY _ JULINE TITANS, SUMITOMO ELEC. IND., TOYOTA, SHARP,** G.Z. NEW ENERGY TECH., **CARNEGIE MELLON UNIV., GLOBAL GRAPHENE, SUMITOMO CHEMICAL**	ENPOWER ENERGY TECHNOLOGY
Main active IP players *(Highest number of pending patent applications)*	**CATL, GLOBAL GRAPHENE,** NAT. UNIV. OF SINGAPORE, **SUMITOMO ELEC. IND., LG CHEM,** UNIV. DE NANTES, HUTCHINSON, INST. CHEMISTRY CAS, **CABOT,** UNIV. DE LIEGE	**CATL, GLOBAL GRAPHENE,** NAT. UNIV. OF SINGAPORE, **LG CHEM, SUMITOMO ELEC. IND.,** UNIV. DE NANTES, HUTCHINSON, INST. CHEMISTRY CAS, **CABOT,** UNIV. DE LIEGE	**CATL, SUMITOMO ELEC. IND.,** INST. CHEMISTRY CAS, **UNIV. OF TEXAS, NIPPON SODA,** SHENZHEN UNIV., ZHEJIANG UNIV., **AQUION ENERGY _ JULINE TITANS**	**CATL, SUMITOMO ELEC. IND., NIPPON SODA,** CENTRAL SOUTH UNIV., OSAKA UNIV., **SUMITOMO CHEMICAL, TOSHIBA,** JAPAN SCI. & TECH. AGENCY	**GLOBAL GRAPHENE,** BROADBIT BATTERIES, **SUMITOMO ELECTRIC IND.,** FARADION, **SUMITOMO CHEMICAL, TOYOTA, NIPPON ELECTRIC GLASS, SHARP,** NAT. UNIV. OF SINGAPORE, **AMPEREX TECH., AQUION ENERGY _ JULINE TITANS, NGK**	**GLOBAL GRAPHENE,** BROADBIT BATTERIES, **SUMITOMO ELEC. IND.,** FARADION, **SUMITOMO CHEMICAL, AQUION ENERGY _ JULINE TITANS,** SHENZHEN INST. OF ADV. TECH. CAS, **TOYOTA, SHARP, NGK**	KUNMING UNIV. OF SCI. & TECH., NORTHEAST NORMAL UNIV., GUANGDONG UNIV. OF TECH., LIYANG ZHONGKEHAI SODIUM TECH., SHANGHAI INST.OF SPACE POWER SCES, **NGK**

Table 26: Main IP Players by supply chain segments (electrode, battery cell, recycling) in Na-ion Battery patent landscape

Patents on active materials, electrolyte and separator are not only filed by material manufacturers and R&D labs but also by battery manufacturers and end-users. In fact, most of battery manufacturers have R&D department dedicated to the development and evaluation of new battery materials. Some of them also collaborates with R&D labs or material manufacturers.

Patenting Activity of Main IP Players by Supply Chain Segments

Assignee	Number of patent families	Supply Chain segments											
		Electrode material	Anode material	Cathode material	Electrolyte	Separator	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
SHAANXI UNIV. OF SCI. & TECH.	220	214	166	58			6	6	5	3			
CENTRAL SOUTH UNIV.	156	148	88	69	4		3	3		3	4	4	
WUHAN UNIV.	70	68	27	41	1						3	1	
TOYOTA	68	32	21	11	9		7	2	4	2	21	8	
SUMITOMO CHEMICAL	67	39	20	20	2	1	7	7		5	21	12	
BEIJING UNIV.	60	51	37	19	7		1	1			1	1	
INSTITUTE OF PHYSICS - CAS	58	43	21	23	9		4	4	1		2	2	
ZHEJIANG UNIV.	50	47	27	21	2	2	3	3	3		1	1	
SUMITOMO ELECTRIC IND.	49	15	6	9	10		6	5	4	4	19	15	
GLOBAL GRAPHENE	46	17	14	7	1		6	5			27	16	
SHARP	44	18	4	15	1	1	19	18	7	16	9	6	
HUAZHONG UNIV. OF SCI. & TECH.	43	36	16	24	4		2	2		1	1	1	
TIANJIN UNIV.	43	44	34	10	2		2	2	1		1	1	
CATL	41	9	1	8	15		15	9	2	9	3	2	
CHINA THREE GORGES UNIV.	41	34	21	18			5	5	3	3	2	2	
GUANGDONG UNIV. OF TECH.	40	34	23	11	2		2	2	2		1	1	1
NIPPON ELECTRIC GLASS	33	23	9	14	5						5	1	
UNIV. OF TOKYO	33	21	3	18	7		3	3		2	2	1	
AIST	32	34	14	21			4	4	1	2	3	2	
FUDAN UNIV.	30	20	13	8	3		1		1	1	7	4	
UNIST	29	12	6	6	8		7	7	1		2	2	
AGC	28	3	2	1	25								
SOUTH CHINA UNIV. OF TECH.	28	28	20	11									
FARADION	27	19	2	17	2		2	2			4	3	
TAIHEIYO CEMENT	26	24	12	16			2	2					
KUNMING UNIV. OF SCI. & TECH.	24	18	13	5	1		2	2			1		2
PANASONIC_SANYO	24	5	3	2	1		4	4	1	2	15	7	
CNRS	23	15	3	15	6	1					1	1	

Table 27: Number of patent families by main IP Players and by supply chain segments in Na-ion Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments. European companies are written in orange color.

- Most of main IP players file patents on all supply chain segments except recycling and separators. R&D labs, especially Chinese R&D labs focus their patenting activity on anode and cathode materials.
- **Toyota** mainly file patents on battery cell and anode materials. It also has a notable number of patent families on cathode materials and electrolyte.
- **Sumitomo Chemical** mainly files patents on battery cell, anode and cathode materials. **Sumitomo Electric Industries and Panasonic/Sanyo** mainly files patents on battery cell. **Global Graphene** mainly files patents on anode materials and battery cell. **Sharp** mainly files on cathode material and electrode. **CATL** mainly files patents on electrolyte and electrode. **AGC** mainly files patents on electrolyte. **Faradion** mainly files patents on cathode materials.

Main European IP Players

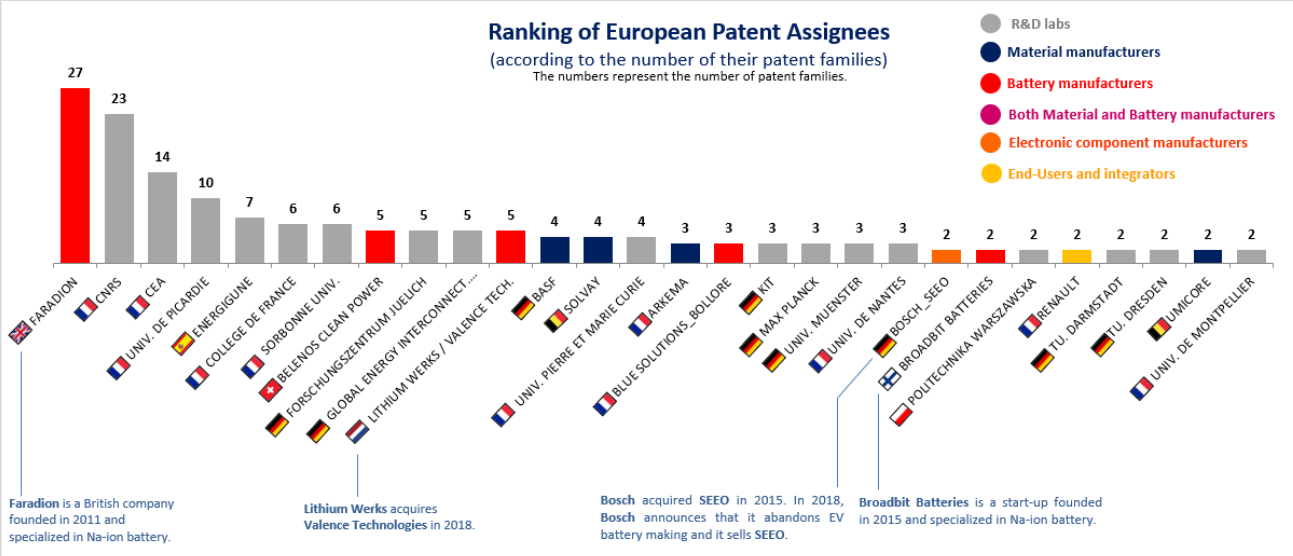


Figure 39: Ranking of main European Patent Assignees according to their number of patent families related to Na-ion Battery

- More than **60 European organizations** have filed patents related to Na-ion battery. European IP players are mainly originating from Germany and France and are mainly R&D labs and battery manufacturers.
- In 2018, **Bosch** announces that it abandons EV battery making. There is a strong collaboration network between French R&D labs internally and with German R&D labs. European IP players co-file patents on Na-ion battery with European and non-European companies (**Toyota, University of Tokyo, HydroQuebec, Sharp**, etc.)
- **Faradion** and **Broadbit Batteries** are pure play companies specialized in Na-ion battery. **Faradion** has already manufactured Na-ion battery prototypes and announces a future commercialization within next years. It is worth to notice that **Tiamat** (French spin-out from **CEA/CNRS** specialized on Na-ion battery) doesn't have published patents but it holds exclusive licenses on **CEA/CNRS** patent portfolio.

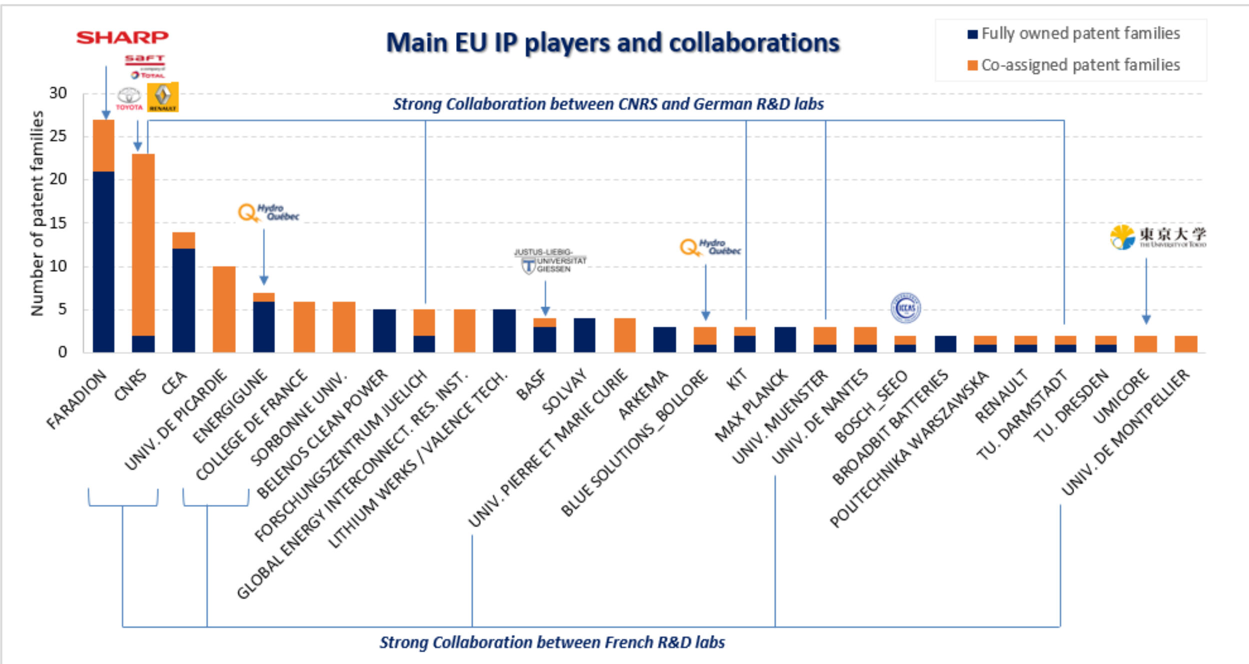


Figure 40: Number of co-assigned patent families by main European patent assignees in Na-ion Battery patent landscape

Main European IP Players by Type of Companies

Material Manufacturers

BASF	4
SOLVAY	4
ARKEMA	3
UMICORE	2
ALTRIS	1
DSM	1
ECHION TECHNOLOGY	1
HALDOR TOPSOE	1
HOGANAS	1
HUTCHINSON	1
IMERYS	1
IPCHEM	1
MORGAN ADVANCED MAT	1
SGL CARBON	1

Electronic Component Manufacturers

BOSCH / SEEO	2

Battery Manufacturers

FARADION	27
BELENOS CLEAN POWER	5
LITHIUM WERKS / VALENCE TECH.	5
BLUE SOLUTIONS_BOLLORE	3
BROADBIT BATTERIES	2
LIFESIZE	1
LITHOPS	1
SAFT_TOTAL	1

End-Users and Integrators

RENAULT	2
DAIMLER	1
EDF	1
SB SOLAR	1

R&D Labs

CNRS	23
CEA	14
UNIV. DE PICARDIE	10
ENERGIGUNE	7
COLLEGE DE FRANCE / SORBONNE UNIV.	6
FORSCHUNGSZENTRUM JUELICH	5
G.E.I. RES. INST.	5
UNIV. PIERRE ET MARIE CURIE	4
KIT	3
MAX PLANCK	3
UNIV. MUENSTER	3
UNIV. DE NANTES	3
POLITECHNIKA WARSZAWSKA	2
TU. DARMSTADT	2
TU. DRESDEN	2
UNIV. DE MONTPELLIER	2
UNIV. DE TOULOUSE	2
CSIC	1
UNIV. DE CAEN / ENSICAEN	1
GSI HELMHOLTZZENTRUM	1
LEIBNIZ INSTITUT	1
STOCKHOLMS UNIV.	1
UNIV. DO PORTO	1
UNIV. DEGLI STUDI DI ROMA	1
UNIV. GIESSEN	1
UNIV. DE LIEGE	1
UNIV. OF OSLO	1

Table 28: Ranking of main European Patent Assignees by type of companies according to their number of patent families related to Na-ion Battery. (Time period: 1986-2020, i.e. all patent families in the patent landscape). The numbers represent the number of patent families of the corresponding patent assignee in Na-ion Battery patent landscape.

Haldor Topsoe is Danish company founded in 1972. It develops and manufactures catalysts and battery materials for energy generation and storage.

Morgan Advanced Material is a British company founded in 1856. It manufactures specialty materials, such as carbon, advanced ceramics and composite for a broad range of markets.

Altris is a Swedish start-up founded in 2017 on the basis of R&D results obtained at **Uppsala University**. It develops and produce highly sustainable cathode materials for rechargeable sodium batteries.

Echion Technology is a British start-up founded in 2017 as a spin-off of **Cambridge University**. It develops unique materials for next-generation batteries, notably materials compatible with fast-charging.

Hoganas is a Swedish material manufacturer founded in 1902 specialized iron and non-ferrous metal powders and alloys and highly refined powders.

Belenos Clean Powder is a Swiss battery manufacturer founded in 2007. It is a subsidiary of Swatch group.

IPChem is a Polish material manufacturer incorporated in 2016.

Broadbit Batteries is a Finish start-up founded in 2015 and specialized in Na-ion battery.

Lifesize is Swedish company founded in 2006 as a spin-out from the **Angstrom Advanced Battery Center of Uppsala University** (Sweden). It develops materials for Na-ion and Li-ion batteries and corresponding battery cells.

Imerys is a French multinational company which specializes in the production and processing of industrial minerals and graphite materials, notably for battery applications.

Lithops is an Italian battery manufacturer founded in 2010. At the end of 2015, Lithops became part of the Seri Group, being incorporated in its subsidiary FIB (owner of the FAAM brand).

IP Dynamics of Main European IP Players

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Earliest year of publication for each patent family

Group	Assignee	Nb of patent families	Average age of the patent portfolio	1985 - 1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Old IP Player with a decreasing patenting activity	LITHIUM WERKS_VALENCE TECHNOLOGY	5	15						1		2	1			1												
	BLUE SOLUTIONS_BOLLORE	3	14		1		1																			1	
	T.U. DRESDEN	2	10											1						1							
	UNIV. DE MONTPELLIER	2	8														1				1						
	UNIV. DE NANTES	3	7														1		1					1			
	MAX PLANCK	3	7														1			1		1					
	LEIBNIZ INSTITUT	1	7																	1							
	CSIC	1	7																	1							
Most active IP players since last 10 years	FARADION	27	6															1	6	3	6	5	1		2	3	
	UNIV. GIESSEN	1	6																		1						
	HOGANAS	1	6																		1						
	LIFESIZE	1	6																		1						
Most active IP players since last 10 years	CNRS	23	5					1									1	2	1	2	2		3	3	3	5	
Most active IP players since last 10 years	UNIV. DE PICARDIE	10	5															1		3	1			2	2	1	
	BELENOS CLEAN POWER	5	5																		1	2	1	1			
	SOLVAY	4	5																		2	1			1		
	BASF	4	5																		3			1			
	ARKEMA	3	5																1			1			1		
	UMICORE	2	5																		1		1				
	SB SOLAR	1	5																			1					
	UNIV. DEGLI STUDI DI ROMA	1	5																			1					
	UNIV. DO PORTO	1	5																			1					
	HUTCHINSON	1	5																			1					
	LITHOPS	1	5																			1					
	UNIV. PIERRE & MARIE CURIE	4	4															1					1	1		1	
	TU. DARMSTADT	2	4																			1			1		
	BROADBIT BATTERIES	2	4																				1	1			
	RENAULT	2	4																			1		1			
	POLITECHNIKA WARSZAWSKA	2	4																				2				
	UNIV. DE TOULOUSE	2	4																				2				
	IPCHEM	1	4																				1				
	DAIMLER	1	4																				1				
	UNIV. OF OSLO	1	4																				1				
Most active IP players since last 10 years	CEA	14	3									1						1				1		3	5	6	
	ENERGIGUNE	7	3																		1	1	2	1		2	
	BOSCH_SEEO	2	3																				1		1		
New comers	HALDOR TOPSOE	1	3																					1			
New comers	EDF	1	3																					1			
New comers	IMERYS	1	3																					1			
New comers	DSM	1	3																					1			
	COLLEGE DE FRANCE	6	2																				3			3	
	SORBONNE UNIVERSITÉ	6	2																				3			3	
	FORSCHUNGSZENTRUM JUELICH	5	2																			1		1		3	
	G.E.I. RESEARCH INST.	5	2																					2		3	
	UNIV. MUENSTER	3	2																			1				2	
New comers	GSI HELMHOLTZZENTRUM	1	2																						1		
New comers	MORGAN ADVANCED MAT	1	2																						1		
New comers	UNIV. DE LIEGE	1	2																						1		
New comers	ALTRIS	1	2																						1		
New comers	STOCKHOLMS UNIVERSITY	1	2																						1		
New comers	KIT	3	1																						1	2	
New comers	SAFT_TOTAL	1	1																							1	
New comers	UNIV. DE CAEN / ENSICAEN	1	1																							1	
New comers	ECHION TECHNOLOGY	1	1																							1	
New comers	SGL CARBON	1	1																							1	

Table 29: Time Evolution of Patent Publications by main European Patent Assignees and by earliest year of publication for each patent family in Na-ion Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignee). R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green. In each cell referring to a publication year, the numbers represent the number of patent families.

Patenting Activity of Main European IP Players

Most of European IP Players extend their patents in other countries. Some European IP players have no more alive patents.

IP players focused on Europe

IP players no more active

	Number of Patent families		Patent Legal status			Number of granted patents							Number of pending patent applications							
	All	Alive	Granted	Pending	Dead	USA	Europe	Japan	China	Korea	Taiwan	India	USA	Europe	Japan	China	Korea	Taiwan	India	PCT applications (WO patents)
FARADION	27	25	56	40	68	13	9	7	10	3			7	9	6	7	7		2	2
CNRS	23	22	34	34	24	5	15	5	3	2			6	11	3	4	3			7
CEA	14	13	22	17	9	3	16	2					3	9	2	1	1			1
UNIV. DE PICARDIE	10	9	13	14	13	2	5	3	1	2			2	4	1	2	2			3
ENERGIGUNE	7	7	11	17	4	2	3	1	1	1			2	3	4	1	2		2	1
COLLEGE DE FRANCE	6	6	4	11	3		2						3	2	1	1	1			3
SORBONNE UNIVERSITÉ	6	6	4	11	3		2						3	2	1	1	1			3
BELENOS CLEAN POWER	5	5	27	7	2	5	5	5	4	3			1			1	3	1		
FORSCHUNGSZENTRUM JUELICH	5	5	5	12	4		1	1					2	4	1	2				3
G.E.I. RESEARCH INST.	5	5		5										5						
LITHIUM WERKS_VALENCE TECH.	5	2			45															
BASF	4	3	3	2	15	1	1	1						1	1					
SOLVAY	4	3	5	11	4	1	1	2	1				2	2	1	2	2			1
UNIV. PIERRE & MARIE CURIE	4	4	7	8	5		3	1	1	2			1	2	1	2	1			1
ARKEMA	3	3	17	19	4	4	6	1	2	1	2		2	2	4	3	3	1	1	1
BLUE SOLUTIONS	3	1		2	12									1						1
KIT	3	3		4										3						1
MAX PLANCK	3	2	4		7		2		1	1										
UNIV. MUENSTER	3	2		3	2									1						2
UNIV. DE NANTES	3	3	12	7	5	3	4	2	1						1	1	1		1	
BOSCH_SEEO	2	2	2	3	1	1	1									2				1
BROADBIT BATTERIES	2	2	1	20	2								1	4	2	2	2	1	1	
POLITECHNIKA WARSZAWSKA	2	2	1	1	1		1							1						
RENAULT	2	2	5	4	3		2	1	1	1				2		1	1			
T.U. DARMSTADT	2	2	2	1	3		1													1
T.U. DRESDEN	2				3															
UMICORE	2	2	9	2	2	2	1	2	1	2	1			1		1				
UNIV. DE MONTPELLIER	2	2	8	2	3	2	2	1	2					1	1					
UNIV. DE TOULOUSE	2	2	1	6	2		1						2	1	1	1	1			
ALTRIS	1	1	1	6									1	1	1	1	1			1
CSIC	1	1	4		1	1	2	1												
DAIMLER	1				1															
DSM	1	1		5	1								1	1	1	1	1			
ECHION TECHNOLOGY	1	1		1										1						
EDF	1	1	1	1	1		1							1						
UNIV. DE CEAN / ENSICAEN	1	1		2										1						1
GSI HELMHOLTZZENTRUM	1	1		1	1															1
HALDOR TOPSOE	1	1	1	2	1		1									1			1	
HOGANAS	1	1		1	5												1			
HUTCHINSON	1	1	3	7	1			1		1	1		1	1		1				
IMERYS	1	1		7	1								1	1	1	1	1			
IPCHEM	1	1		1	1									1						
LEIBNIZ INSTITUT	1				2															
LIFESIZE	1	1		1	5												1			
LITHOPS	1				1															
MORGAN ADVANCED MAT	1	1		4									1	1		1				1
SAFT_TOTAL	1	1		2										1						1
SB SOLAR	1	1	2		1	1			1											
SGL CARBON	1	1		4										1		1	1			1
STOCKHOLMS UNIV.	1				1															
UNIV. DO PORTO	1	1	2	5	1	1			1					1	1	1	1			
UNIV. DEGLI STUDI DI ROMA	1	1	2		1	1			1											
UNIV. GIESSEN	1	1		2	4									1	1					
UNIV. DE LIEGE	1	1		6	1								1	1		1	1			1
UNIV. DIN BUCURESTI	1	1		1																
UNIV. OF OSLO	1				2															

Table 30: Legal status of patents by countries for main European patent assignees in Na-ion Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

Patenting Activity of Main European IP Players by Supply Chain Segments

Assignee	Number of patent families	Supply Chain segments											
		Electrode material	Anode material	Cathode material	Electrolyte	Separator	Electrode	Electrode manufacturing	Anode	Cathode	Battery cell	Battery cell manufacturing	Recycling
FARADION	27	19	2	17	2		2	2			4	3	
CNRS	23	15	3	15	6	1					1	1	
CEA	14	13	7	6			2	2			3	3	
UNIV. DE PICARDIE	10	6	1	6	2	1					1	1	
ENERGIGUNE	7	2		2	5						1		
COLLEGE DE FRANCE	6	4	1	4	2								
SORBONNE UNIV.	6	4	1	4	2								
BELENOS CLEAN POWER	5	4	4		1								
FORSCHUNGSZENTRUM JUELICH	5	1	1		3						1	1	
G.E.I. RESEARCH INST.	5	4		4							1		
LITHIUM WERKS_VALENCE TECH.	5	4		4							1	1	
BASF	4	3		3		1							
SOLVAY	4				4								
UNIV. PIERRE & MARIE CURIE	4	1	1	1	2						1	1	
ARKEMA	3	1	1		2								
BLUE SOLUTIONS	3				1	1					2	2	
KIT	3	2		2	1								
MAX PLANCK	3	3	1	2							1		
UNIV. MUENSTER	3	2	2		1								
UNIV. DE NANTES	3				2		1	1					
BOSCH_SEEO	2	2	2										
BROADBIT BATTERIES	2										2	2	
POLITECHNIKA WARSZAWSKA	2				2								
RENAULT	2				1		1	1			1	1	
T.U. DARMSTADT	2					1					1		
T.U. DRESDEN	2	1		1	1								
UMICORE	2	2		2									
UNIV. DE MONTPELLIER	2	1	1	1	1								
UNIV. DE TOULOUSE	2	2	1	2									
ALTRIS	1	1		1									
CSIC	1	1	1	1									
DAIMLER	1				1								
DSM	1				1								
ECHION TECH.	1	1	1										
EDF	1						1	1					
ENSICAEN / UNIV. DE CAEN	1	1		1									
GSI HELMHOLTZZENTRUM	1					1							
HALDOR TOPSOE	1	1		1									
HOGANAS	1						1	1					
HUTCHINSON	1						1	1					
IMERYS	1	1	1										
IPCHEM	1				1								
LEIBNIZ INSTITUT	1	1		1									
LIFESIZE	1						1	1					
LITHOPS	1				1								
MORGAN ADVANCED MAT	1	1	1										
SAFT_TOTAL	1	1		1									
SB SOLAR	1										1	1	
SGL CARBON	1	1	1										
STOCKHOLMS UNIV.	1	1		1									
UNIV. DO PORTO	1				1								
UNIV. DEGLI STUDI DI ROMA	1										1	1	
UNIV. GIESSEN	1					1							
UNIV. DE CAEN / ENSICAEN	1	1		1									
UNIV. DE LIEGE	1						1	1					
UNIV. DIN BUCURESTI	1	1		1									
UNIV. OF OSLO	1	1	1										

Table 31: Number of patent families by main European IP Players and by supply chain segments in Na-ion Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments.

- No European IP players file patents on Na-ion battery recycling, anode and cathode. Only few European IP players file patents on electrode manufacturing.
- **Faradion, CNRS/Université de Picardie/Sorbonne Université/College de France/UPMC** and **BASF** mainly file on cathode materials. **CNRS** also has a notable number if patents related to electrolyte. **Energigune** mainly files patents on Electrolyte. **CEA** mainly files patents on anode materials, cathode materials and battery cell. **Belenos Clean Power** mainly files patents on anode materials. **Solvay** only file patents on electrolyte. **Umicore** only file patents on cathode materials.

IP Position of Main European IP Players

Relative size and strength of Na-ion battery patent portfolio held by European IP players have been evaluated in comparison with patent portfolio of all IP players (cf. Identification of key IP players). **Faradion** and **CNRS** have a good IP position in the patent landscape. Even if **Tiamat** (French pure play company spin-out from CEA/CNRS) does not have patents on Na-ion battery, it holds exclusive licenses on CNRS patent portfolio. Thus, **Tiamat** has indirectly a good IP position.

	Relative size of patent portfolio	Relative size of granted patent portfolio	Relative size of pending patent portfolio	Relative Prior Art Blocking Potential	Relative FTO Blocking Potential
FARADION	Medium	High	High	Medium	High
CNRS	Medium	High	High	Medium	High
CEA	Medium	Medium	Medium	Medium	Medium
UNIV. DE PICARDIE	Medium	Medium	Medium	Medium	Medium
ENERGIGUNE	Low	Medium	Medium	Low	Medium
COLLEGE DE FRANCE	Low	Low	Medium	Very Low	Low
SORBONNE UNIV.	Low	Low	Medium	Very Low	Low
BELENOS CLEAN POWER	Low	High	Low	Medium	Medium
FORSCHUNGSZENTRUM JUELICH	Low	Low	Medium	Low	Low
LITHIUM WERKS_VALENCE TECH.	Low	Null	Null	High	Null
G.E.I. RESEARCH INST.	Low	Null	Low	Null	Null
UNIV. PIERRE & MARIE CURIE	Low	Low	Low	Medium	Medium
SOLVAY	Low	Low	Medium	Low	Low
BASF	Low	Very low	Very low	Low	Very low
ARKEMA	Very low	Medium	Medium	Medium	High
UNIV. DE NANTES	Very low	Medium	Low	Medium	Medium
MAX PLANCK	Very low	Low	Null	Medium	Low
BLUE SOLUTIONS	Very low	Null	Very low	Medium	Null
KIT	Very low	Null	Low	Null	Null
UNIV. MUENSTER	Very low	Null	Very low	Null	Null
UMICORE	Very low	Low	Very low	Low	Medium
UNIV. DE MONTPELLIER	Very low	Low	Very low	Medium	Medium
BROADBIT BATTERIES	Very low	Very low	Medium	Very Low	Low
UNIV. DE TOULOUSE	Very low	Very low	Low	Very Low	Low
RENAULT	Very low	Low	Low	Very Low	Low
T.U. DARMSTADT	Very low	Very low	Very low	Very Low	Very low
T.U. DRESDEN	Very low	Null	Null	Very Low	Null
BOSCH_SEEO	Very low	Very low	Very low	Null	Null
POLITECHNIKA WARSZAWSKA	Very low	Very low	Very low	Null	Null
UNIV. DO PORTO	Very low	Very low	Low	Medium	Medium
CSIC	Very low	Low	Null	Medium	Medium
HUTCHINSON	Very low	Very low	Low	Very Low	Low
HALDOR TOPSOE	Very low	Very low	Very low	Very Low	Very low
HOGANAS	Very low	Null	Very low	Very Low	Null
LIFESIZE	Very low	Null	Very low	Very Low	Null
IMERYS	Very low	Null	Low	Very Low	Null
LEIBNIZ INSTITUT	Very low	Null	Null	Very Low	Null
LITHOPS	Very low	Null	Null	Very Low	Null
DSM	Very low	Null	Low	Very Low	Null
ALTRIS	Very low	Very low	Low	Null	Null
UNIV. DE LIEGE	Very low	Null	Low	Null	Null
MORGAN ADVANCED MAT	Very low	Null	Low	Null	Null
SGL CARBON	Very low	Null	Low	Null	Null
UNIV. DE CAEN / ENSICAEN	Very low	Null	Very low	Null	Null
SAFT_TOTAL	Very low	Null	Very low	Null	Null
UNIV. GIESSEN	Very low	Null	Very low	Null	Null
EDF	Very low	Very low	Very low	Null	Null
ECHION TECHNOLOGY	Very low	Null	Very low	Null	Null
GSI HELMHOLTZZENTRUM	Very low	Null	Very low	Null	Null
IPCHEM	Very low	Null	Very low	Null	Null
UNIV. DIN BUCURESTI	Very low	Null	Very low	Null	Null
SB SOLAR	Very low	Very low	Null	Null	Null
UNIV. DEGLI STUDI DI ROMA	Very low	Very low	Null	Null	Null
DAIMLER	Very low	Null	Null	Null	Null
STOCKHOLMS UNIV.	Very low	Null	Null	Null	Null
UNIV. OF OSLO	Very low	Null	Null	Null	Null

Table 32: IP Position of main European IP Players in Na-ion Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

ORGANIC REDOX-FLOW BATTERY

Principle

A redox flow battery is a type of electrochemical cell where chemical energy is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane. Ion exchange (accompanied by flow of electric current) occurs through the membrane while both liquids circulate in their own respective space.

In the case of organic redox flow battery, redox shuttles are organic molecules, such as Polymers, coordinated metal complex, i.e. metal ion + organic ligands: metallocene (ex: ferrocene), other (ex: ferrocyanide, bipyridine ruthenium) and Metal-free molecules (Ex: quinone-based, etc.).

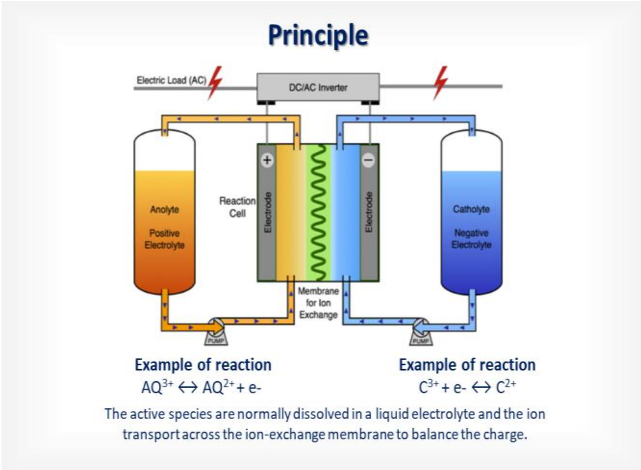


Figure 41: Principle of Organic Redox-flow Battery

Advantages and Drawbacks

Advantages	Drawbacks
• Scalable in power and energy • Unlimited number of cycles, virtually no ageing of electrolyte • Non-hazardous, non-explosive	• Huge volumes, Expensive electrolytes • Restricted to large-scale stationary applications • Reliability concerns related to the pump use

Table 33: Main advantages and drawbacks of Organic Redox-flow Battery

Challenges and Envisioned Solutions

- **Improve performances** (energy density, life duration)
  - Develop new redox couple associations
  - Improve separator membranes
  - Improve battery cell and pack designs
  - Develop integrated electrolyte regeneration systems
- **Improve safety**
  - Develop reliable pumps and flow distributors
  - Improve battery cell and pack designs to avoid leakages

Main Market Players

UET, Rongke Power, Vanadis Power, Redflow Energy Storage Solutions, Sumitomo Electric, EnSysnc Energy Systems (formely **ZBB Energy**), **ViZn, Primus Power, Enervault**, **Voltstorage** (start-up founded in 2014**)**, **Avalon Battery** (start-up founded in 2015), **JenaBatteries** (start-up founded in 2013), **FTORION** (start-up founded in 2012), **Proxhima** (start-up founded in 2013), **Hydraredox** (start-up founded in 2013), **KemiWatt** (start-up founded in 2014)

Main Applications envisioned for Organic Redox Flow Battery

Stationary applications

IP Dynamics

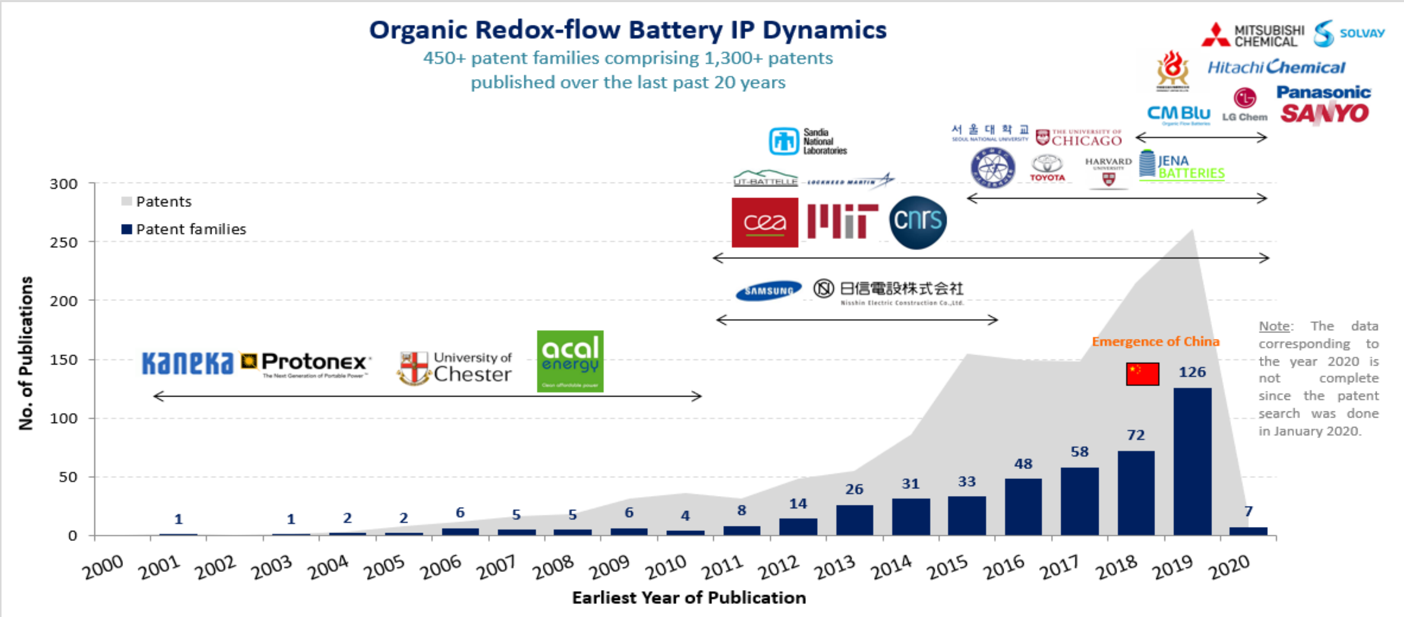


Figure 42: IP Dynamics for Organic Redox-flow Battery (Number of patent families and patents annually published by earliest publication year)

Pioneer patents on organic redox-flow battery have been published in the 1960's by **Exxon Mobile, Lockheed Martin / UT Battelle** and **Corning**. They were related to redox-flow battery containing quinone-based materials, metallic complexes or ferrocyanides as redox shuttles materials. Patenting activity on Organic redox flow battery emerged in the 2000's with the high patenting activity of **Acal Energy** and **University of Chester**. Since 2010, the entry of Korean battery manufacturers (**Samsung, LG Chem**), European and American IP players (**CEA, CNRS, MIT, Sandia,** etc.) and pure play companies (**Jena Batteries, CMBLU, Kemwatt**, etc.) in the patent landscape induced a continuous increase of patenting activity on Organic Redox-flow battery (+69% CAGR between 2006 and 2019). This indicates that companies show a growing interest for this technology. Patenting activity on organic redox-flow batteries has strongly increased in 2019 due to the emergence and high patenting activity of Chinese R&D labs and companies.

IP Dynamics by Countries

- Before 2010, main IP players were **Acal Energy** and **University of Chester**, explaining the domination of patenting activity in Europe. Between 2009 and 2014, numerous American R&D labs entered the patent landscape, leading to a patenting activity focused in the US. Between 2015 and 2019, the internationalization of IP players leads to almost similar in the US, Europe, Korea and Japan.
- Since 2019, patenting activity has strongly increased in China due to the entry of numerous Chinese R&D labs and industrial companies. At the same period patenting activity in Europe has also strongly increased.

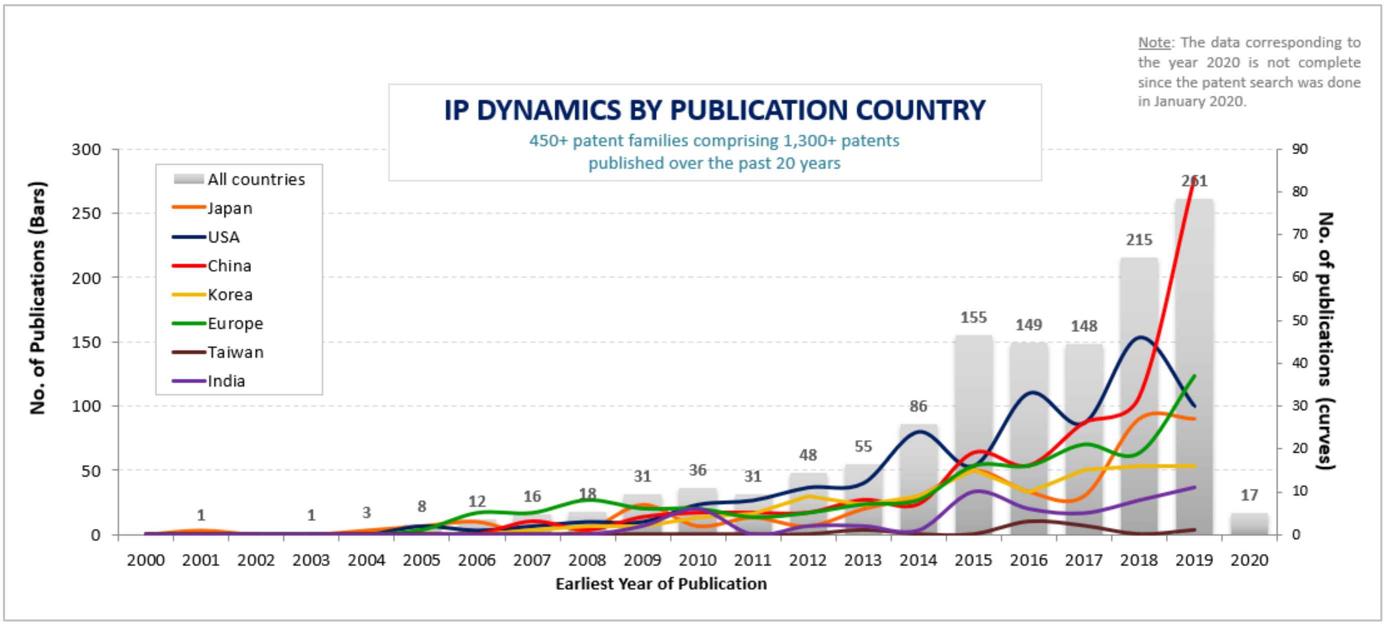


Figure 43: IP Dynamics by Publication Countries for Organic Redox-flow Battery (Number of patents annually published by earliest publication year and by countries)

Main IP Players

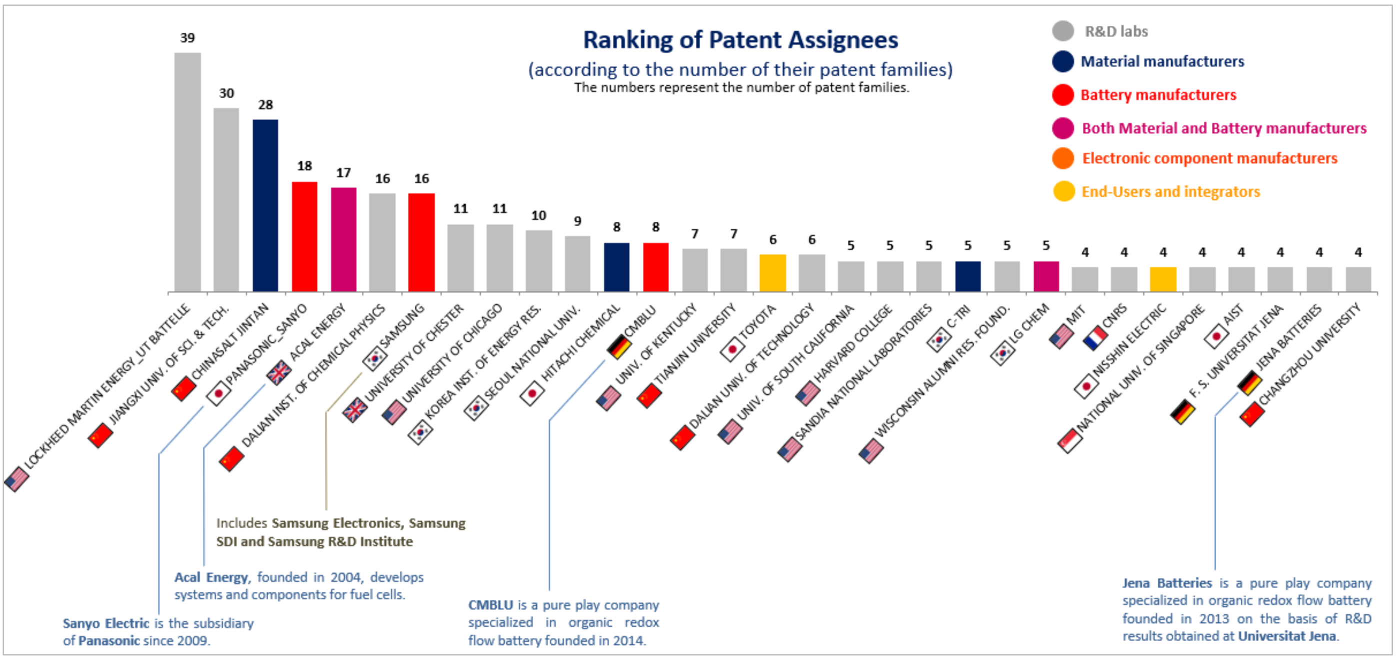


Figure 44: Ranking of Patent Assignees according to the number of their patent families related to Organic Redox-flow Battery

- More than **180 organizations** have filed patents related to organic redox-flow battery. 60% of patent assignees holds only one patent family. **The top 10 and top 5** patent applicants hold respectively **43%** and **29%** of the patent families. Main patent assignees are mainly American and Korea R&D labs. However, there are also several industrial companies from the whole supply chain confirming their strong interest for this trendy technology. Among main IP players, there are also several companies specialized in organic redox flow battery (**Acal Energy, CMBLU, Jena Batteries**), major battery manufacturer (**Samsung, Panasonic/Sanyo, LG Chem**, etc.) and end-users (**Toyota, Nisshin Electric**, etc.). Most of patent co-filings gather an industrial company and one or several R&D labs.

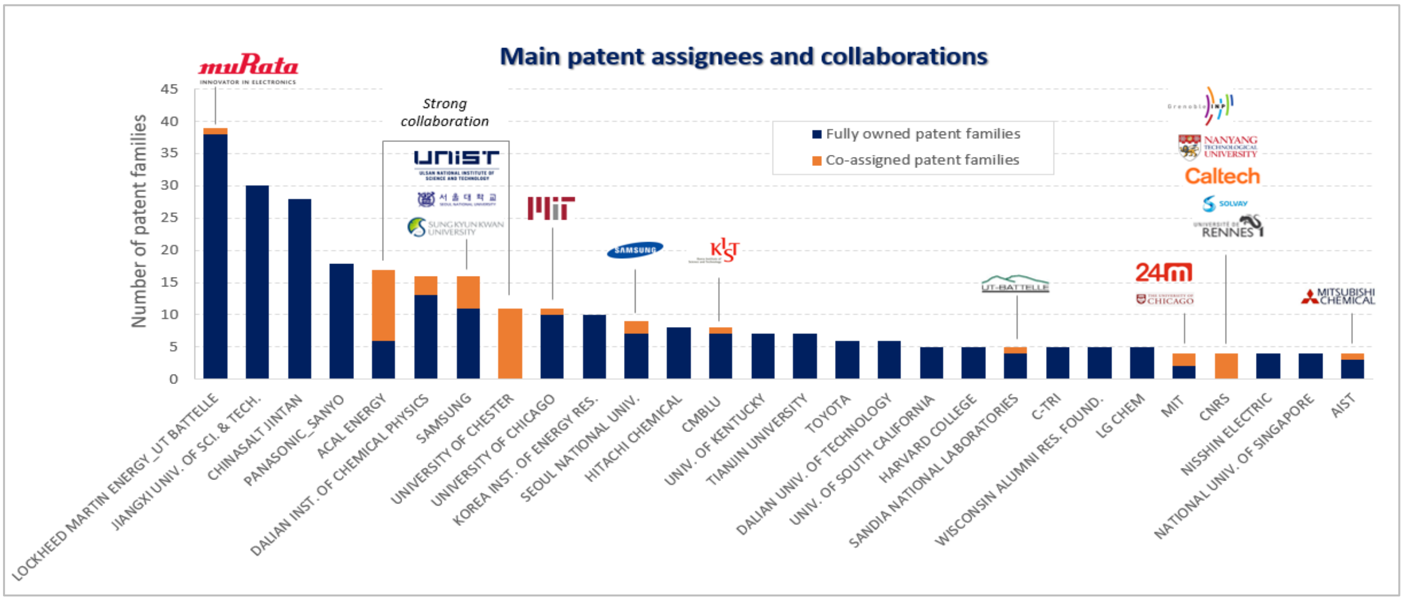


Figure 45: Number of co-assigned patent families by main patent assignees in Organic Redox-flow Battery patent landscape

Main IP Players by Type of Companies

Material Manufacturers

CHINASALT JINTAN	28
HITACHI CHEMICAL	8
C-TRI	5
SOLVAY	3
LANXESS SOLUTIONS	3
TOYOBO	2
KANEKA	2
YIYANG KINGLON NEW MAT.	2
CRISTAL INORGANIC CHEM.	2
ARAMCO SERVICES	2
SAUDI ARABIAN OIL	2
MITSUBISHI CHEMICALS	2
EXXONMOBIL	1
CORNING	1
KURITA WATER INDUSTRIES	1
DUPONT	1
INNOVIA FILMS	1
ASAHI KASEI	1
TAIWAN CARBON NANOTECH.	1
3M	1
OSAKA GAS	1
NANOTECH ENERGY	1
SEKISUI CHEMICAL	1
ENI	1

Battery Manufacturers

PANASONIC_SANYO	18
ACAL ENERGY	17
SAMSUNG	16
CMBLU	8
LG CHEM	5
JENA BATTERIES	4
REDCHOICE	3
RM TECHNOLOGY	2
J.Z.H. NEW ENERGY TECHNOLOGY	2
PROTONEX TECHNOLOGY	1
NEC	1
SCALAR TECHNOLOGIES	1
24M TECHNOLOGIES	1
BYD	1
DALIAN RONGKE POWER	1
MURATA / SONY	1
VIZN ENERGY SYSTEMS	1
FTORION	1
EPSILOR	1
CHROME PLATED POWER	1
INDUSTRIE DE NORA	1
KEMWATT	1
POWER MIGRATION	1
FORM ENERGY	1

Electronic Component Manufacturers

ESC	1
SUMITOMO ELECTRIC INDUSTRIES	1

End-Users and Integrators

TOYOTA	6
NISSHIN ELECTRIC	4
DAIMLER	3
CAMBRIDGE DISPLAY TECHNOLOGY	2
ENERGETICS	1
GENERAL ELECTRIC	1
SHARP	1
SHANGHAI ELECTRIC	1
MIDWEST ENERGY	1
ENSYNC	1
JFE ENGINEERING	1
BMW	1
SIEMENS	1
ILMA BIOCHEM	1

R&D Labs

LME / UT BATTELLE	39
JIANGXI UNIV. OF SCI. & TECH.	30
DALIAN INST. OF CHEMICAL PHYSICS	16
UNIVERSITY OF CHESTER	11
UNIVERSITY OF CHICAGO	11
KOREA INST. OF ENERGY RES.	10
SEOUL NATIONAL UNIV.	9
UNIV. OF KENTUCKY	7
TIANJIN UNIVERSITY	7
DALIAN UNIV. OF TECHNOLOGY	6
UNIV. OF SOUTH CALIFORNIA	5
HARVARD COLLEGE	5
SANDIA NATIONAL LABORATORIES	5
WISCONSIN ALUMNI RES. FOUND.	5
MIT	4
CNRS	4
NATIONAL UNIV. OF SINGAPORE	4
AIST	4
F. S. UNIVERSITAT JENA	4
CHANGZHOU UNIVERSITY	4
CALTECH	3
SANGMYUNG UNIVERSITY	3
BEIJING UNIVERSITY	3
UNIVERSITY OF ILLINOIS	3
KIST	3

Table 34: Ranking of main patent assignees by type of companies according to their number of patent families related to Organic Redox-flow Battery. (Time period: 1960-2020, i.e. all patent families in the patent landscape). European companies are written in orange color. The numbers represent the number of patent families of the corresponding patent assignee in Organic Redox-flow Battery patent landscape.

IP Dynamics of Main IP Players

Earliest year of publication for each patent family

	Assignee	Nb of patent families	Average age of the patent portfolio	1979 - 2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	UNIVERSITY OF CHESTER	11	12			4	1	2	1			2	1							
	ACAL ENERGY	17	11			4	2	3	3			2	2		1					
	SAMSUNG	16	7								4	4	4	3			1			
	NISSHIN ELECTRIC	4	7									1	2	1						
	MIT	4	6						1			1			1			1		
	CNRS	4	6							1			1		1		1			
Old IP player still active	LME / UT BATTELLE	39	5	1								1	1	11	2	7	5	9	1	1
	SANDIA NATIONAL LABORATORIES	5	5											1	3			1		
	DALIAN INST. OF CHEMICAL PHYSICS	16	4				1						1		2	1	4	3	4	
	KOREA INST. OF ENERGY RESEARCH	10	4										1	1	1	4		1	2	
	TOYOTA	6	4											1		2	2	1		
	DALIAN UNIVERSITY OF TECHNOLOGY	6	4											1	1	1	2	1		
	HARVARD COLLEGE	5	4											1	1	1		1	1	
	AIST	4	4										2	1					2	
	JENA BATTERIES	4	4											1	1		2			
	UNIVERSITY OF CHICAGO	11	3										2		1		3	3	2	
	SEOUL NATIONAL UNIVERSITY	9	3										1	1	1	1	2	1	1	1
	UNIVERSITY OF KENTUCKY	7	3									1			1		1	4		
	NATIONAL UNIVERSITY OF SINGAPORE	4	3										1			1			2	
	FRIEDRICH SCHILLER UNIVERSITAT JENA	4	3											1			2		1	
Most active IP players since 2018	JIANGXI UNIV. OF SCI. & TECH.	30	2													7			23	
Most active IP players since 2018	PANASONIC_SANYO	18	2			1										1		9	7	
Most active IP players since 2018	CMBLU	8	2														1	2	5	
	HITACHI CHEMICAL	8	2													1	2	1	4	
	TIANJIN UNIVERSITY	7	2												1		2	2	2	
	LG CHEM	5	2														1	2	2	
	UNIVERSITY OF SOUTH CALIFORNIA	5	2											1				1	3	
	C-TRI	5	2												1		1	1	2	
	WISCONSIN ALUMNI RES. FOUND.	5	2												1			2	2	
	CHANGZHOU UNIVERSITY	4	2														1	2	1	
Most active IP players since 2018	CHINASALT JINTAN	28	1																27	1

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Table 35: Time Evolution of patent publications by main patent assignees and by earliest year of publications for each patent family in Organic Redox-flow Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignee). European companies are written in orange color. In each cell referring to a publication year, the numbers represent the number of patent families.

- Patents held by **Lockheed Martin Energy / UT Battelle** are related to redox flow battery with redox shuttles composed of iron hexacyanides, metal ligand coordination compounds, coordinated complexes containing catecholate ligands and more recently pure organic compounds (phenothiazine, hydroquinone, nitroxide radicals).
- Patents held by **Samsung** are related to ion exchange membranes, electrolytes for redox flow battery comprising redox shuttles composed of quinone-based compounds or metal-ligand coordination complexes and their use in redox flow battery.
- Patents held by **Toyota** are related to redox-flow battery with catechol-based or polysulfides redox shuttles and organic active materials for redox flow battery (nitroxide radicals, quinone-based).
- Patents held by **Hitachi Chemical** are related to redox-flow battery with ferrocyanides, quinone-based organic molecules or complex compounds.
- Patents held by **LG Chem** are related to organic positive active materials and electrolytes for redox flow battery.
- Patents held by **Panasonic/Sanyo** are related to redox-flow battery mentioning a list of redox shuttles including organic molecules.
- Patents held by **Acal Energy and University of Chester** are related to redox fuel cells containing ligated metal complexes or ferrocene.
- Patents held by **Jena Batteries** and **University of Jena** are related to redox flow battery with organic anolyte and/or catholyte.
- Patents held by **CMBLU** are related to redox flow battery electrolytes containing quinone-based redox shuttles.
- **Chinasalt Jintan** is a Chinese company specialized in the manufacturing of inorganic and organic salts. Its patents on organic redox flow battery are related to redox shuttles based on bipyridine and anthraquinone and redox flow batteries using them.

Newcomers in the Patent Landscape

- Newcomers are companies who started their patenting activity in 2017. There are more than 70+ newcomers in the organic redox-flow battery patent landscape.
- They are numerous Chinese R&D labs (*Changzhou University, Xi'An Jiao Tong University, UESTC, etc.*) and Companies (*Chinasalt Jintan, etc*.).
- Among newcomers, there are also notable American IP players (*University of California, 3M, Ensync, Nanotech Energy, University of Massachusetts, Case Western Reserve University, Utah State University, Northwestern University, Boston College, Columbia University, Michigan State University, Form Energy* etc.), European IP Players (*CEA, Kemwatt, IFP Energy Nouvelles, Power Migration, Innventia, BMW, ENI, Delft University of Technology, RISE Acreo, Siemens, Ilma Biochem* etc.), Japanese IP Players (*JFE Engineering, Osaka Gas, Sekisui Chemical, Mitsubishi Chemicals, Sumitomo Electric Industries,* etc.) and Korean IP Players (*LG Chem, UNIST, KIST,* etc.).

Ensync Energy is an American company founded in 1986 and specialized in energy storage for stationary applications. In 2019, it intends to initiate insolvency and cuts nearly all employees.

Nanotech Energy is an American start-up founded in 2014 on the basis of R&D results of **UCLA**. It develops and manufactures graphene-based materials for energy storage applications. They hold an exclusive license on patents held by **UCLA** on graphene and graphene oxide for battery applications.

Form Energy is an American start-up founded in 2017 on the basis or R&D results of **MIT.** It develops a “new class of ultra-low-cost, long-duration energy storage systems”.

Kemwatt is a French start-up founded in 2014 on the basis of R&D results of. **Univ. de Rennes/CNRS.** It develops organic redox flow batteries.

Power Migration is a British battery manufacturer founded in 2013 and known under its brand name (StorTera). It develops and manufactures redox flow battery, notably graphite-sulfur single liquid flow battery.

Innventia and RISE Acreo are Swedish R&D labs.

Ilma Biochem is a German consulting company incorporated in 2018. It provides scientific and technical services to exclusive business partners.

Current Legal Status of Patents

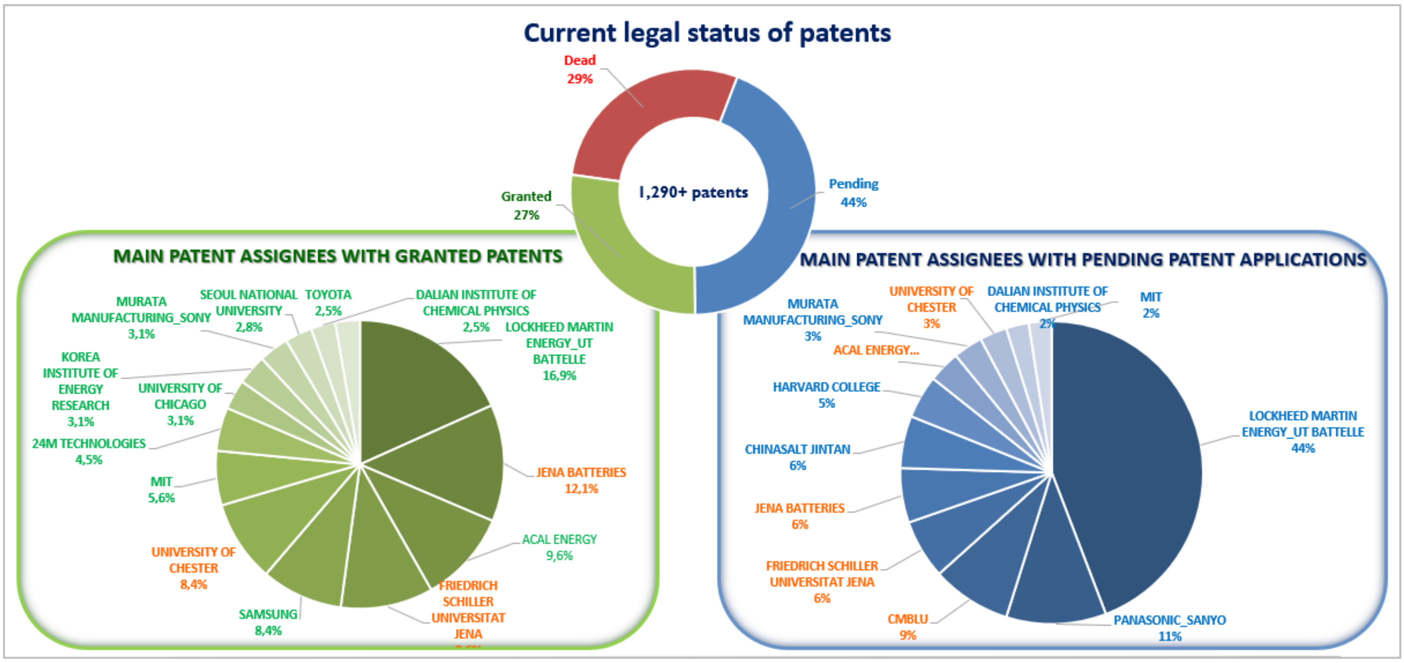


Figure 46: Current legal status and main patent assignees with granted patents and pending patent applications for Organic Redox-flow Battery. European companies are written in orange color.

More than 70% of the patents in organic redox-flow battery patent landscape are currently pending or granted. This reflects that many R&D developments are still on-going to solve current technical issues related to Organic Redox-flow battery. **Lockheed Martin / UT Battelle, Jena Batteries/Universitat Jena, Acal Energy/University of Chester, Samsung and MIT** hold the highest number of granted patents. **Lockheed Martin/UT Battelle, Panasonic/Sanyo, CMBLU and Jena Battery/Universitat Jena** hold the highest number of pending patent applications.

Legal Status by Countries

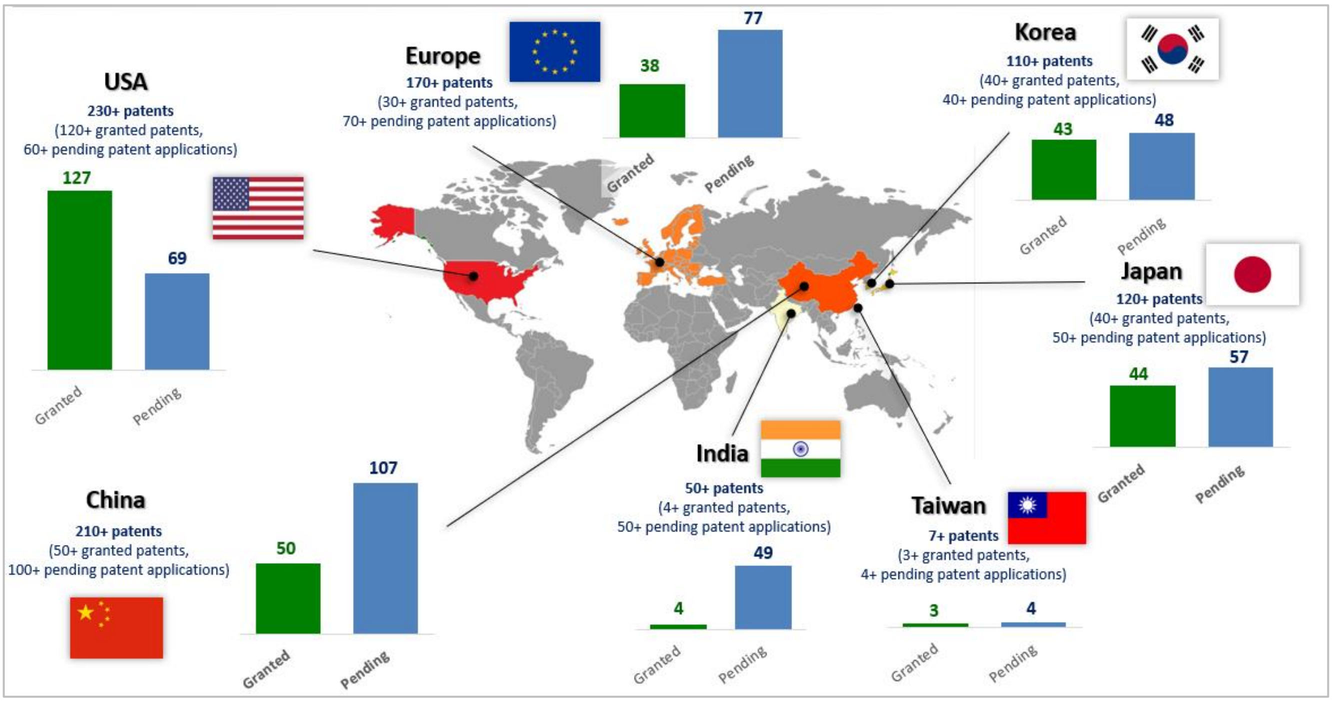


Figure 47: Mapping of Legal Status by Countries for Organic Redox-flow Battery

Contrary to Li-S, Na-ion and Li-ion battery for which the patent landscape is dominated by Asian countries, for organic redox flow battery patents are mainly filed in the US. However, this trend could shift rapidly due to the strong increase of patenting activity in China in 2019. This trend explains why the highest number of pending patent applications is observed in China. It is worth to note that more than 13% of pending applications have been filed in Europe.

Most Active IP Players by Countries

Patents in Europe are not only filed by European IP Players but also by foreign companies (**MIT, UT Battelle/Lockheed Martin, 24M technologies, Panasonic/Sanyo, Technion, Harvard College,** etc.). The demand for energy storage for stationary applications is growing in Europe. Thus, patenting activity should be increasing in Europe within next years.

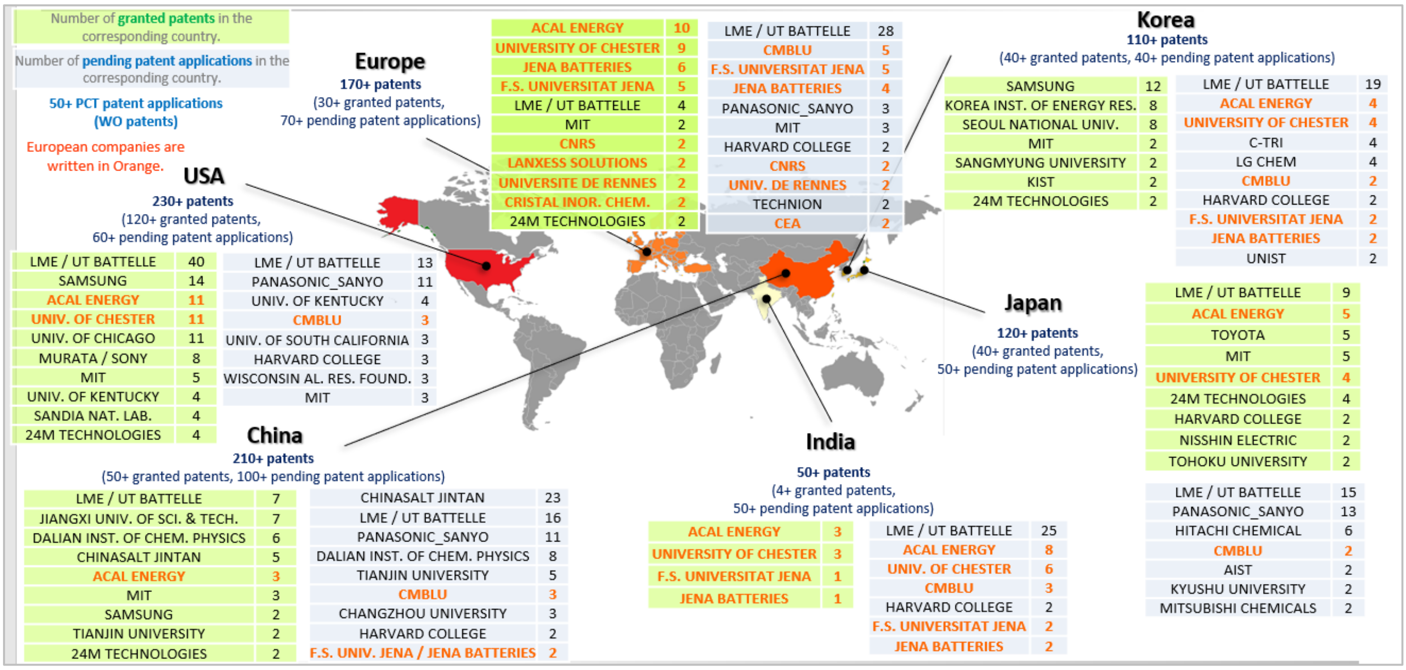


Figure 48: Main current patent assignees by countries for Organic Redox-flow Battery

Patenting Activity of IP Leading Companies

	Number of Patent families		Patent Legal status			Number of granted patents							Number of pending patent applications							
	All	Alive	Granted	Pending	Dead	USA	Europe	Japan	China	Korea	Taiwan	India	USA	Europe	Japan	China	Korea	Taiwan	India	PCT applications (WO patents)
LME / UT BATTELLE	39	35	60	182	60	40	4	9	7				13	28	15	16	19		25	9
JIANGXI UNIV. OF SCI. & TECH.	30	8	7	1	22				7							1				
CHINASALT JINTAN	28	28	5	23					5							23				
PANASONIC_SANYO	18	18	5	44	5	2	1	1	1				11	3	13	11			1	5
ACAL ENERGY	17	14	34	14	89	11	10	5	3	1		3		1	1		4		8	
DALIAN INSTITUTE OF CHEMICAL PHYSICS	16	14	9	10	3	1	1	1	6							8				1
SAMSUNG	16	16	30	2	2	14	1	1	2	12				1			1			
UNIVERSITY OF CHESTER	11	11	30	12	68	11	9	4	1	1		3		1	1		4		6	
UNIVERSITY OF CHICAGO	11	11	11	2	1	11							2							
KOREA INSTITUTE OF ENERGY RESEARCH	10	9	11	2	1	3				8							1			1
SEOUL NATIONAL UNIVERSITY	9	9	10	2	2	2				8			1				1			
HITACHI CHEMICAL	8	7		7	1										6					1
CMBLU	8	8		35	2								3	5	2	3	2		3	9
UNIVERSITY OF KENTUCKY	7	7	4	4	3	4							4							
TIANJIN UNIVERSITY	7	7	2	6					2							5				1
TOYOTA	6	6	9	2		3		5	1				1		1					
DALIAN UNIVERSITY OF TECHNOLOGY	6	2		2	4											2				
UNIVERSITY OF SOUTH CALIFORNIA	5	5	2	7	1	1			1				3	1					1	2
HARVARD COLLEGE	5	5	5	19	4	1		2					3	2	1	2	2		2	2
SANDIA NATIONAL LABORATORIES	5	4	4	1	2	4							1							
C-TRI	5	4		5	2												4			1
WISCONSIN ALUMNI RESEARCH FOUND.	5	5	2	4		2							3							1
LG CHEM	5	5	1	9						1			1	1	1	1	4			1
MIT	4	4	20	10	10	5	2	5	3	2			3	3		1			1	1
CNRS	4	2	2	6	14		2						1	2	1	1				
NISSHIN ELECTRIC	4	2	4	1	7	1	1	2											1	
NATIONAL UNIVERSITY OF SINGAPORE	4	4	3	7	5			1	1		1		1					1		2
AIST	4	4	1	3				1							2					1
FRIEDRICH SCHILLER UNIVERSITAT JENA	4	4	34	26	4	1	5	1	1			1	2	5	1	2	2		2	1
JENA BATTERIES	4	4	43	24	6	1	6	1	1			1	2	4	1	2	2		2	
CHANGZHOU UNIVERSITY	4	4	1	3					1							3				

Table 36: Legal status of patents by countries for main patent assignees in Organic Redox-flow Battery patent landscape. European companies are written in orange color.

- Most of main Chinese IP players only file patents in China, except **Dalian Institute of Chemical Physics** and **Tianjin University** who file WO patents or extend their patents in other countries (Table 36).
- Main IP players originating from other countries than China, including European companies, have a worldwide IP strategy, except University of Chicago and AIST who focuses on their originating countries, respectively the US and Japan (Table 36).
- Only few IP Players (**Acal Energy, University of Chester, Jena Batteries, Universitat Jena**) have granted patents in India (Table 36). However, it is worth to note that several major IP players (**Lockheed Martin Energy / UT Battelle, Panasonic / Sanyo, CMBLU, Harvard College, Sandia, etc**.) have pending patent applications in India (Table 36). In fact, India becomes an attractive market for battery manufacturers.

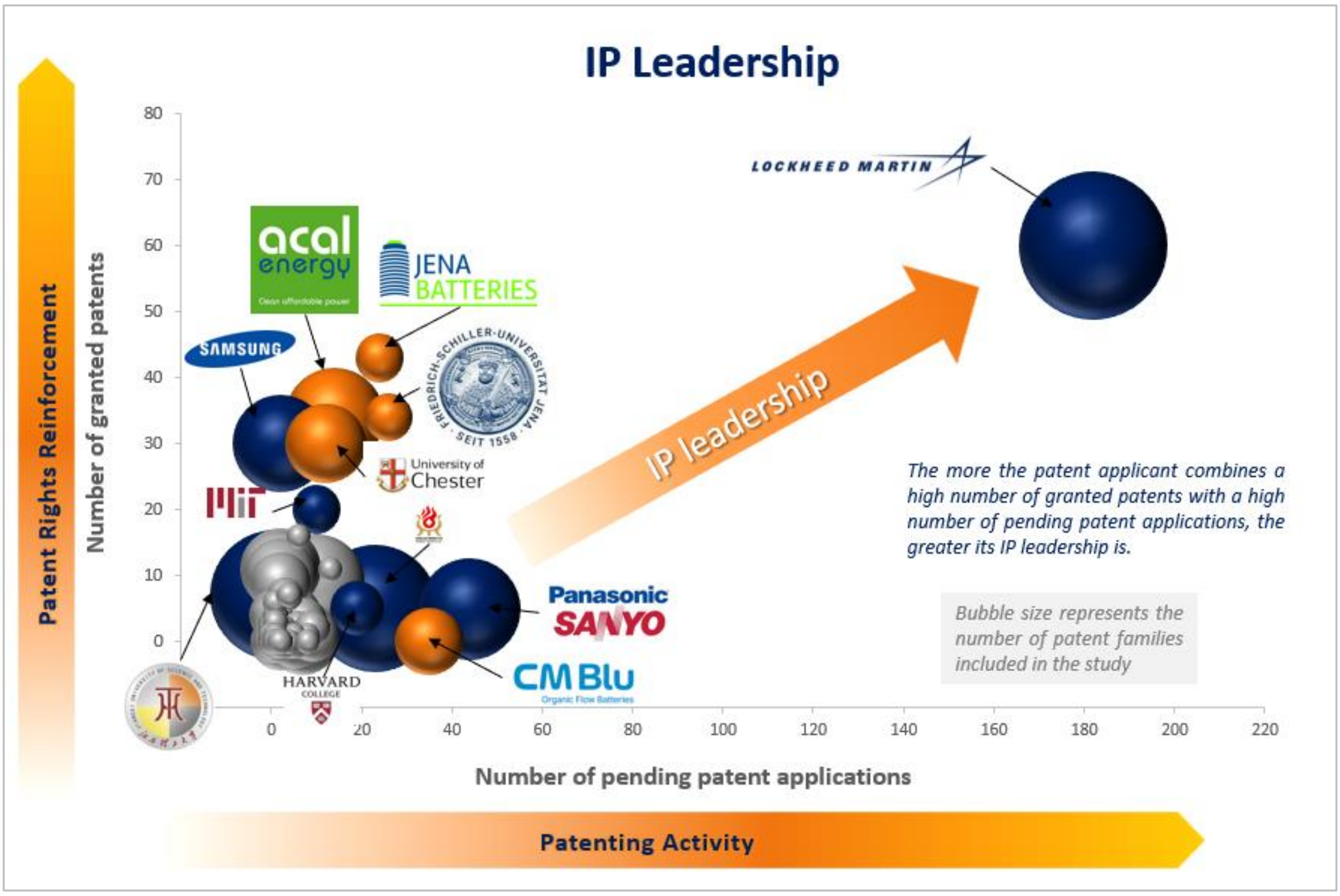


Figure 49: IP Leadership of Patent Assignees for Organic Redox-flow Battery. Orange bubbles indicate European companies with a notable IP leadership. Blue bubbles indicate Non-European companies with a notable IP leadership. Grey bubbles indicate companies without a notable IP leadership.

- In Figure 49, only companies with a notable IP leadership (Orange and blue bubbles) have been annotated. Companies with a low IP leadership have grey bubbles and have not been annotated for more clarity on the graph. Thus, if a company having patent families related to Organic Redox-flow battery is not annotated in the graph, it means that it has a low IP leadership compared to other IP Players.
- **Lockheed Martin Energy / UT Battelle** leads organic redox-flow battery patent landscape. It holds the highest number of patent families, granted patents and pending patent applications worldwide. **Lockheed Martin Energy / UT Battelle** is a pioneer IP player still having a strong patenting activity on organic redox flow battery.
- **Panasonic/Sanyo** and **CMBLU** are IP challengers with the second and third highest number of pending patent applications worldwide. Both start their patenting activity on organic redox flow battery recently in 2016-2017.
- **Samsung, Acal Energy, University of Chester, Jena Batteries/ Universitat Jena and MIT** are established IP players, with a high number of granted patents and numerous pending patent applications worldwide. **Acal Energy and University of Chester** are pioneer IP players who stopped their patenting activity on organic redox flow battery in 2015. **Samsung** concentrates its patenting activity on organic redox flow battery between 2010 and 2015 and has decreased its patenting activity on this topic since this date. **MIT** only files few patent families since 2009 and is still active. MIT extends its patents in numerous countries that’s why it has a high IP leadership.
- **Havard College and Chinasalt Jintan** also have a notable number of pending patent applications.
- Despite a high number of patent families, Chinese IP Players have a relatively low IP leadership because most of them focus their patenting activity in China, i.e. there is only one patent (filed in China) by patent family.

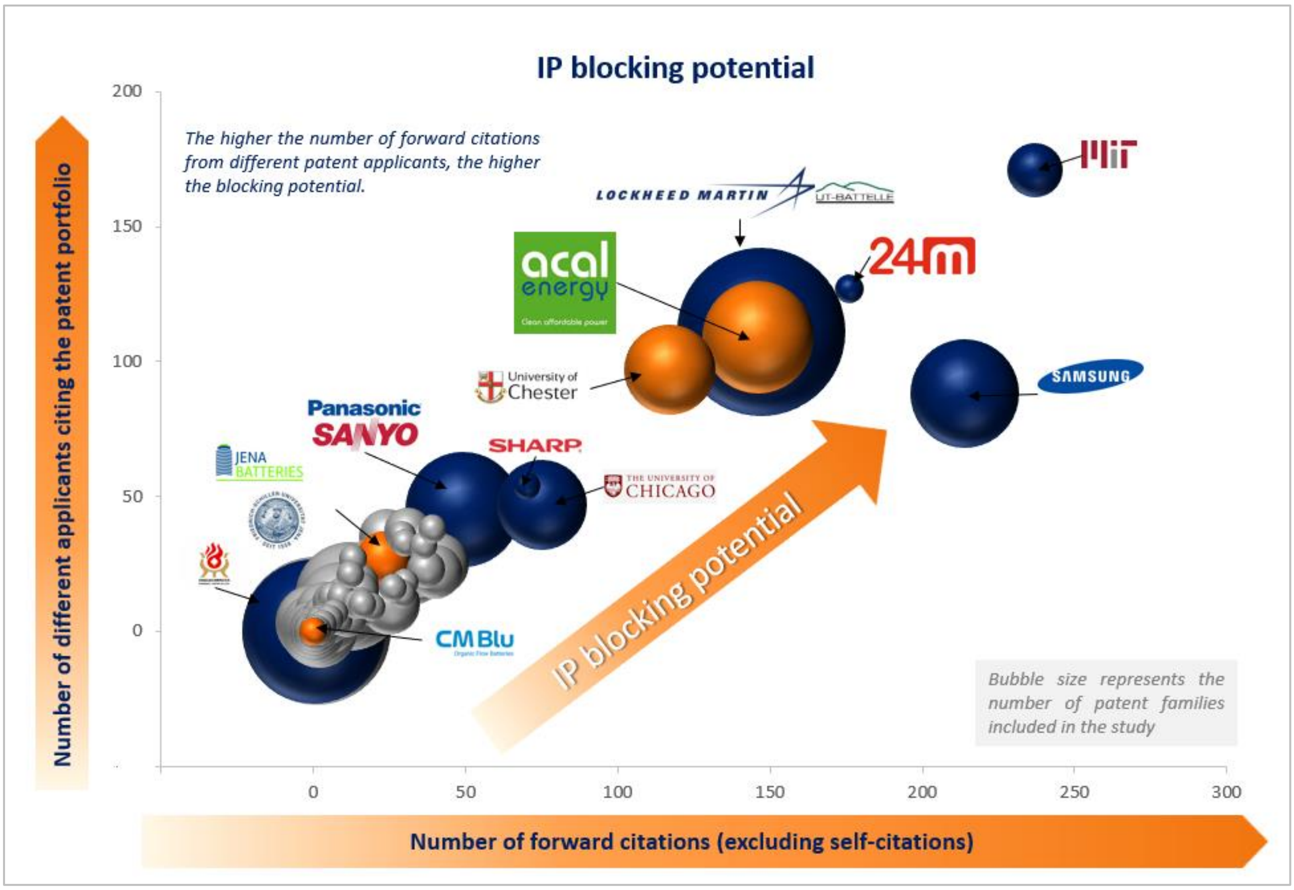


Figure 50: IP Blocking Potential of Patent Assignees for Organic Redox-flow Battery. Orange bubbles indicate European companies with a notable IP Blocking Potential. Blue bubbles indicate Non-European companies with a notable IP Blocking Potential. Grey bubbles indicate companies without a notable IP Blocking Potential.

- Despite its medium IP leadership, **MIT** has the highest IP blocking potential. **24M, Lockheed Martin/UT Battelle, Samsung, Acal Energy** and **Univ. of Chester** also have a high IP blocking potential. Their patents related to organic redox-flow battery strongly contribute to the prior art and have received numerous forward citations from a lot of different patent applicants. That means that their patent portfolios offer them the capability to block other firms involved in the field. It is worth to remind that **Lockheed Martin / UT Battelle, Acal Energy and University of Chester** are pioneer IP players in organic redox-flow battery field that benefit from a strong prior art contribution. Contrary to **Lockheed Martin / UT Battelle** who is still among most active IP Players during last 5 years, **Samsung, Acal Energy and University of Chester** have strongly decreased their patenting activity since 2014. **24M Technologies** holds only one patent family related to high energy density organic redox flow batteries (co-filed with MIT). **24M Technologies** is an American start-up spun-out from **MIT** in 2010 who develops semi-solid li-ion batteries.
- Despite their notable IP leadership, **Jena Batteries / University of Jena, Chinasalt Jintan** and **CMBLU** have respectively a medium and very small IP Blocking Potential. In fact, most of their patents have been filed after 2014 and thus receive only few forward citations. Their IP blocking potential could be improved within next years.
- **Panasonic/Sanyo** and **University of Chicago** have a notable IP Blocking Potential. **Panasonic/Sanyo** and **University of Chicago** increase their patenting activity on organic redox flow batteries recently in 2017-2018.

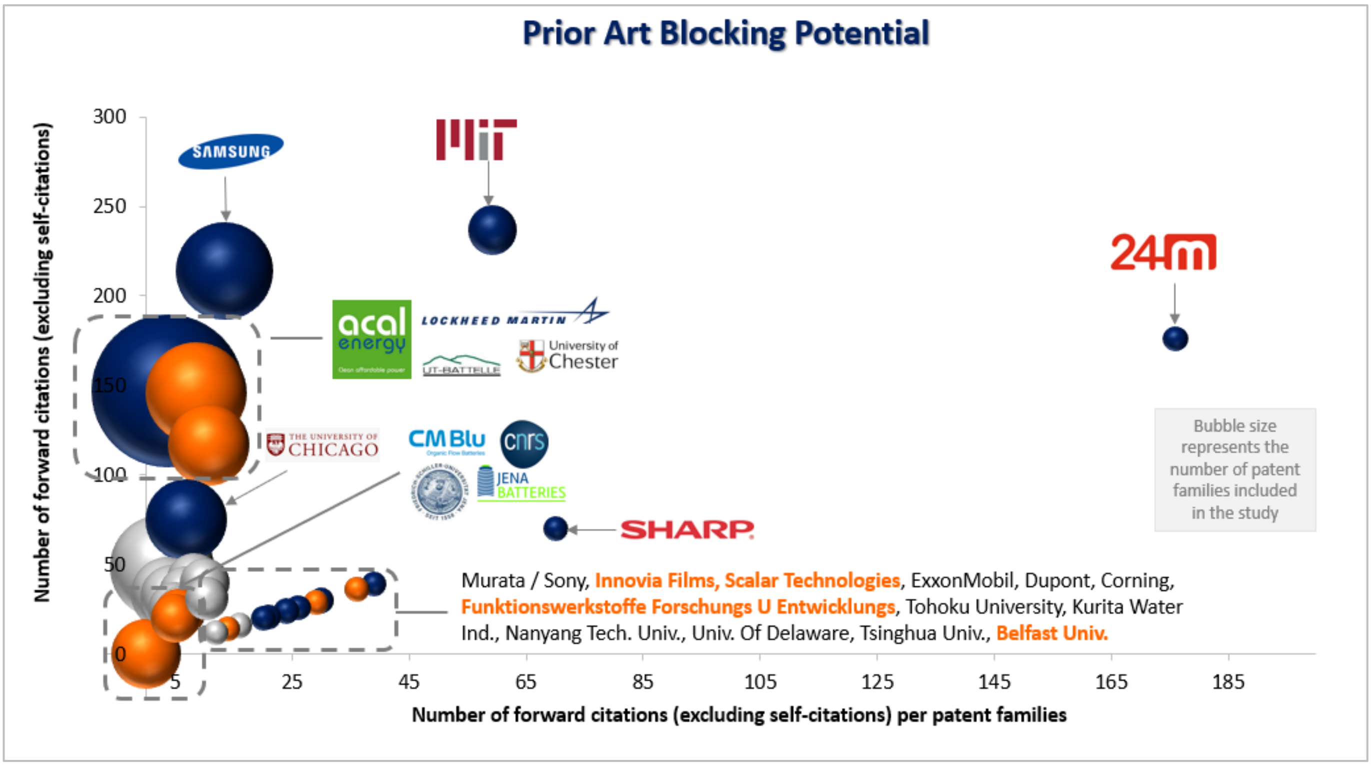


Figure 51: Prior Art Blocking Potential of Patent Assignees for Organic Redox-flow Battery. Orange bubbles indicate European companies with a notable Prior Art Blocking Potential. Blue bubbles indicate Non-European companies with a notable Prior Art Blocking Potential. Grey bubbles indicate companies without a notable Prior Art Blocking Potential.

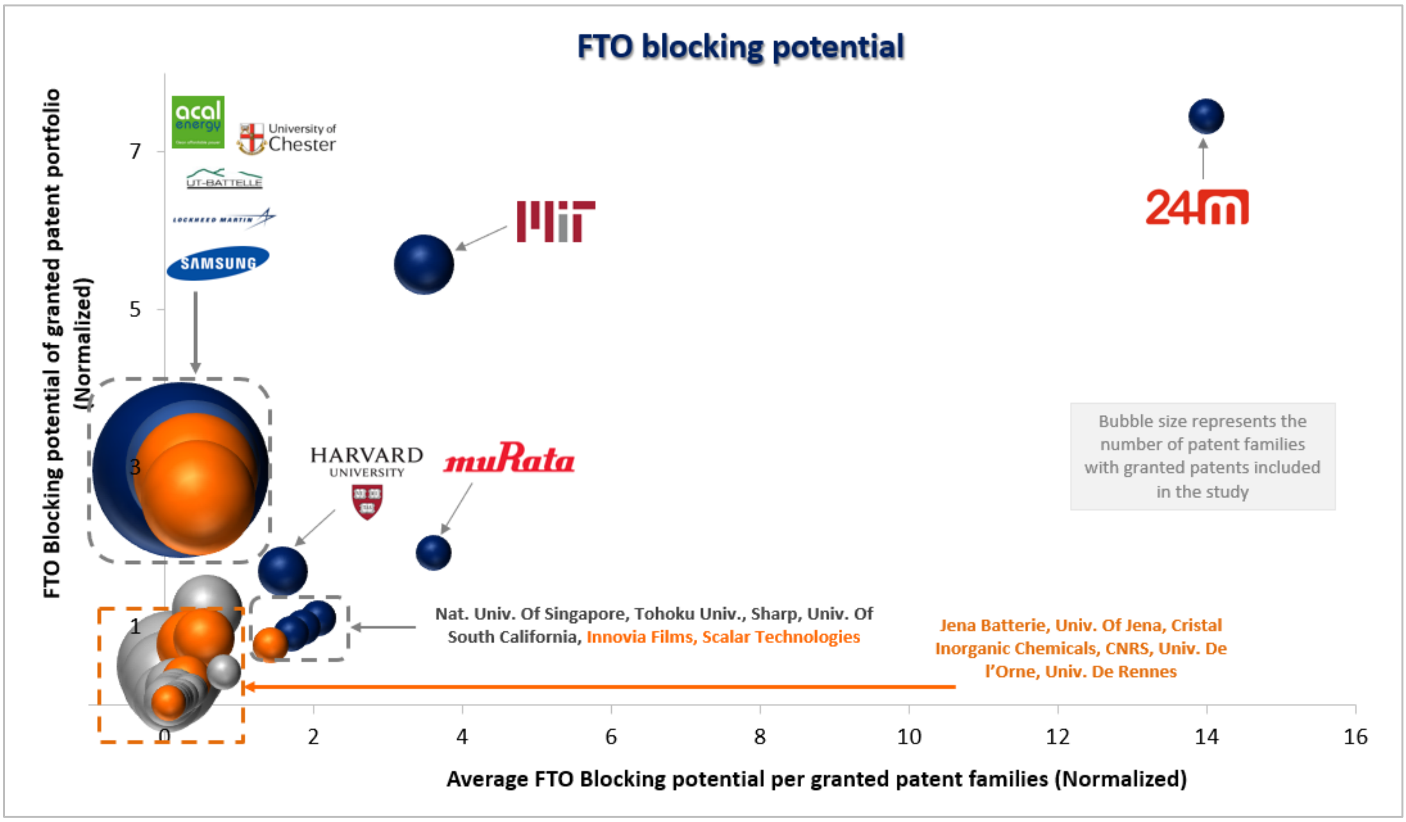


Figure 52: FTO Blocking Potential of Patent Assignees for Organic Redox-flow Battery. Orange bubbles indicate European companies with a notable FTO Blocking Potential. Blue bubbles indicate Non-European companies with a notable FTO Blocking Potential. Grey bubbles indicate companies without a notable FTO Blocking Potential.

- **24M** holds the highest average prior art blocking potential per patent family and FTO blocking potential induced by a highly cited patent family granted in numerous countries. This indicates that it has a high capability to limit both patenting activity and freedom-to-operate of other companies on inventions closed to the one claimed in this patent, i.e. high energy density organic redox flow battery.
- Despite its medium-sized patent portfolio, **MIT** holds the highest average prior art blocking potential and the second highest FTO blocking potential induced by highly cited patents granted in numerous countries. This indicates that it has a high capability to limit both patenting activity and freedom-to-operate of other companies on inventions closed to the one claimed in its patents.
- **Samsung, Lockheed Martin/UT Battelle, Acal Energy and University of Chester** combine a high prior art blocking potential and FTO blocking potential induced by a high number of patent families and key patents. This indicates that they have a high capability to limit both patenting activity and freedom-to-operate of other companies.
- Despite its notable IP leadership, **Panasonic/Sanyo, Jena Batteries/University of Jena** and **CMBLU** have a low Prior art blocking potential and FTO blocking potential. In fact, most of their patents have been filed after 2014, are still pending and thus receive only few forward citations. Their IP position could be improved within next years.
- Despite its notable prior art blocking potential, **University of Chicago** has a low FTO blocking potential due to the low geographic coverage of its granted patents.
- Despite their very small patent portfolio, **Sharp, Murat/Sony, Innovia Films, Scalar technologies, Exxon Mobil, Dupont, Corning, Tohoku University, Belfast University, etc.** have a notable technological impact because they hold key patent families with numerous forward citations. It is worth to note that **Exxon Mobil, Dupont, Corning** and **Belfast University** have no more granted patents and thus don't have the capability to limit freedom-to-operate of other companies.
- Similarly, despite their very small patent portfolio, **Murata, Harvard College, Sharp, National University of Singapore, Tohoku University, University of South California, Innovia Films and Scalar Technologies** have a high average FTO Blocking Potential per patent families induced by highly cited patent families granted in numerous countries.

PATENT SEGMENTATION BY SUPPLY CHAIN SEGMENTS

Overview of Patenting Activity by Supply Chain Segments

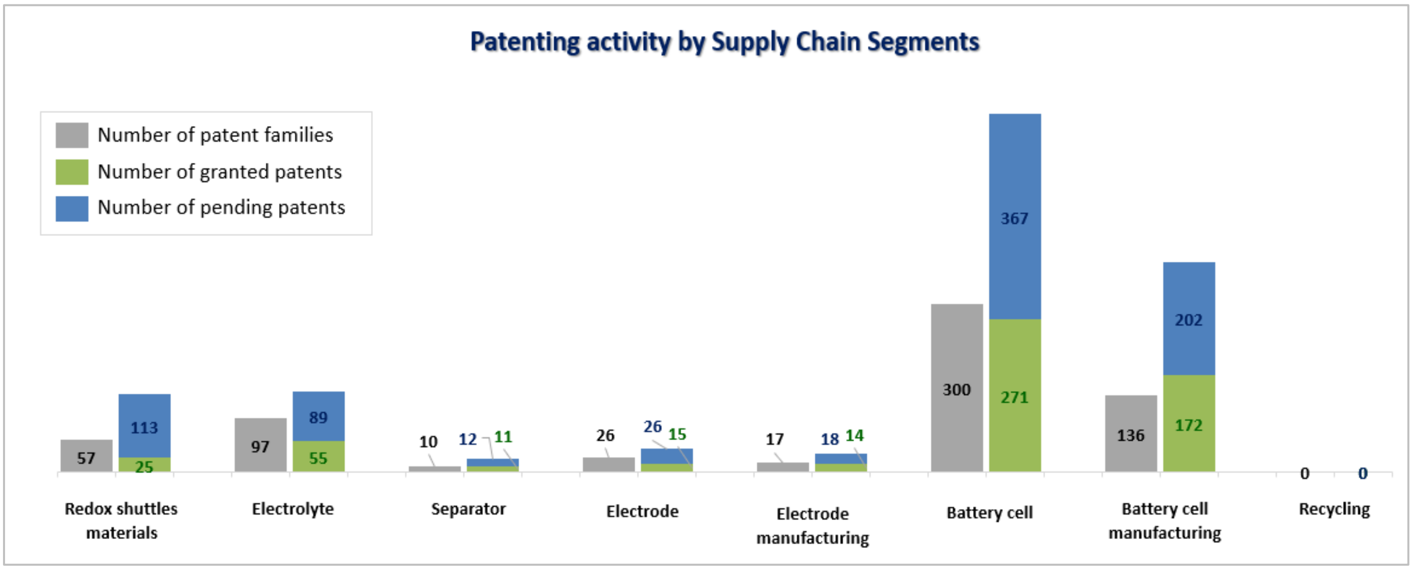


Figure 53: Patenting Activity by Supply Chain Segments for Organic Redox-flow Battery

Patenting activity by supply chain segments is correlated to main development axes envisioned to improve Organic Redox-flow battery performances (battery cell, redox shuttles and electrolytes). Patents on Organic Redox-flow battery are mainly related to battery cells. There are only few patents on redox shuttles materials because common organic redox shuttles are molecules already synthesized and used for other applications. Thus, most of patents related to their synthesis does not mention redox-flow batteries and thus have not been selected for this study. There are no patents on Organic Redox-flow battery recycling. Recycling of organic redox-flow battery is not a topic of interest for the moment because Organic Redox-flow battery represents a very small part of the battery market. Companies specialized on battery recycling prefer to focus on recycling of Li-ion battery for which the demand is strongly increasing.

IP Dynamics by Supply Chain Segments

The numbers represent the number of patent families.

Earliest publication year

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Supply Chain Segment	Number of patent families	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Redox shuttles materials	57					1		1					1		2	2	3	6	5	17	18	1
Electrolyte	97												4	1	2	5	7	16	17	19	25	1
Separator	10														3	2			4		1	
Electrode	26		1				1							2	1	2	2	5	2	2	8	
Electrode manufacturing	17		1												1	2	1	3	1	2	6	
Battery cell	300				1	1	1	5	5	5	6	4	7	12	20	22	22	24	32	42	83	4
Battery cell manufacturing	136					1	1	4	4	2	3	4	3	5	8	9	11	10	13	20	36	
Recycling	0																					

Table 37: Time evolution of patent families by supply chain segments and earliest publication year in Organic Redox-flow Battery patent landscape (Number of patent families annually published by earliest publication year and by supply chain segments)

First patents on Organic Redox-flow battery were related to battery cells. Patenting activity on redox shuttles and electrolytes have increased within last 5 years. Patenting activity on the electrode slightly increased in 2019. In fact, first organic redox flow batteries were developed with well-known organic molecules and within last years, new organic redox shuttles molecules have been specifically developed for organic redox flow battery applications in order to improve their performances.

Main IP Players by Supply Chain Segments

Patents on redox shuttles materials, electrolyte and separator are not only filed by material manufacturers and R&D labs but also by battery manufacturers and end-users. In fact, most of battery manufacturers have R&D department dedicated to the development and evaluation of new battery materials. Some of them also collaborates with R&D labs or material manufacturers.

IP positions	Redox shuttles materials	Electrolyte	Separator	Electrode	Electrode manufacturing
Main IP players *(Highest number of patent families)*	**LOCKHEED MARTIN ENERGY / UT BATTELLE,** UNIV. OF CHICAGO, CHINASALT JINTAN, UNIV. OF SOUTH CALIFORNIA, CMBLU, UNIV. OF KENTUCKY, WISCONSIN ALUMNI RESEARCH FOUND., SOLVAY, **SANDIA NATIONAL LAB., TOYOTA**	JIANGXI UNIV. OF SCI. & TECH., SEOUL NATIONAL UNIV., CMBLU, **SAMSUNG, LOCKHEED MARTIN ENERGY / UT BATTELLE,** C-TRI, CHINASALT JINTAN, TIANJIN UNIV., KIST, KOREA INST. OF ENERGY RESEARCH, UNIV. OF KENTUCKY, BEIJING UNIV., REDCHOICE	DALIAN INST. OF CHEMICAL PHYSICS, **LOCKHEED MARTIN ENERGY / UT BATTELLE,** CHANGSHA UNIV. OF SCI. & TECH., DALIAN UNIV. OF TECH., POWER MIGRATION, SEJONG UNIV., **SAMSUNG, VIZN ENERGY SYSTEMS,** UNIV. OF DELAWARE, **DALIAN RONGKE POWER**	CHINASALT JINTAN, **LOCKHEED MARTIN ENERGY / UT BATTELLE, TECHNION,** DALIAN INST. OF CHEMICAL PHYSICS, KOREA INST. OF ENERGY RESEARCH, **TOYOBO,** KETI	CHINASALT JINTAN, **LOCKHEED MARTIN ENERGY / UT BATTELLE,** DALIAN INST. OF CHEMICAL PHYSICS, KOREA INST. OF ENERGY RESEARCH, TIANJIN UNIV., SOLVAY, **NANOTECH ENERGY, UNIVERSITY OF CALIFORNIA,** YIHUA INVESTMENT, CNRS, ACREO RISE, INNVENTIA, **TOYOBO, TAIWAN CARBON NANO TECHNOLOGY,** INDUSTRIE DE NORA, INPG
Most enforced IP players *(Highest number of granted patents)*	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** UNIV. OF CHICAGO, **TOYOTA,** SANDIA NATIONAL LAB., UNIVERSITY OF ILLINOIS, SOLVAY, ALLIANCE FOR SUSTAINABLE ENERGY, CRISTAL INORGANIC CHEMICALS SWITZERLAND, SHANGHAI INST. OF CERAMICS	**SAMSUNG,** SEOUL NATIONAL UNIV., **LOCKHEED MARTIN ENERGY / UT BATTELLE,** CRISTAL INORGANIC CHEMICALS SWITZERLAND, JIANGXI UNIV. OF SCI. & TECH., KOREA INST. OF ENERGY RESEARCH, UNIV. OF KENTUCKY, 3M, CHINASALT JINTAN, KIST	**SAMSUNG, LOCKHEED MARTIN ENERGY_UT BATTELLE,** UNIV. OF DELAWARE, DALIAN INST. OF CHEMICAL PHYSICS, SEJONG UNIVERSITY	INDUSTRIE DE NORA, KOREA INST. OF ENERGY RESEARCH, **TAIWAN CARBON NANO TECHNOLOGY, LOCKHEED MARTIN ENERGY_UT BATTELLE,** ACREO RISE, INNVENTIA, KETI	INDUSTRIE DE NORA, KOREA INST. OF ENERGY RESEARCH, **TAIWAN CARBON NANO TECHNOLOGY, LOCKHEED MARTIN ENERGY_UT BATTELLE,** ACREO RISE, INNVENTIA
Main active IP players *(Highest number of pending patent applications)*	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** CMBLU, **LG CHEM,** ENERGIGUNE, CHINASALT JINTAN, UNIV. OF SOUTH CALIFORNIA, UNIV.OF KENTUCKY, WISCONSIN ALUMNI RESEARCH FOUND., SOLVAY, UNIV. OF MASSACHUSETTS	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** CMBLU, C-TRI, KYUSHU UNIVERSITY, ARAMCO SERVICES, SAUDI ARABIAN OIL, CNRS, UNIV. DE L'ORNE, UNIV. DE RENNES	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** UNIV. OF DELAWARE, CHANGSHA UNIV. OF SCI. & TECH., POWER MIGRATION, SAMSUNG	**TECHNION, NANOTECH ENERGY,** UNIV. OF CALIFORNIA, INDUSTRIE DE NORA, CHINASALT JINTAN, DALIAN INST. OF CHEM. PHYSICS, **SUMITOMO ELECTRIC IND., TAIWAN CARBON NANO TECH.**	**NANOTECH ENERGY,** UNIV. OF CALIFORNIA, INDUSTRIE DE NORA, CHINASALT JINTAN, DALIAN INST. OF CHEMICAL PHYSICS, **TAIWAN CARBON NANO TECHNOLOGY,** TIANJIN UNIVERSITY, YIHUA INVESTMENT, ACREO RISE

Table 38: Main IP Players by supply chain segments (redox shuttles materials, electrolyte, separator, electrode) in Organic Redox-flow Battery patent landscape

IP positions	Battery cell	Battery cell manufacturing	Recycling
Main IP players *(Highest number of patent families)*	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** JIANGXI UNIV. OF SCI. & TECH., CHINASALT JINTAN, **PANASONIC_SANYO,** ACAL ENERGY, **SAMSUNG,** DALIAN INST. OF CHEMICAL PHYSICS, UNIV. OF CHESTER, UNIV. OF CHICAGO	JIANGXI UNIVERSITY OF SCIENCE AND TECHONOLOGY, ACAL ENERGY, **LOCKHEED MARTIN ENERGY_UT BATTELLE,** UNIVERSITY OF CHESTER, **PANASONIC_SANYO,** CHINASALT JINTAN, DALIAN INSTITUTE OF CHEMICAL PHYSICS, JENA BATTERIES, **SAMSUNG**	-
Most enforced IP players *(Highest number of granted patents)*	**LOCKHEED MARTIN ENERGY_UT BATTELLE,** JENA BATTERIES, FRIEDRICH SCHILLER UNIVERSITAT JENA, ACAL ENERGY, UNIVERSITY OF CHESTER, **SAMSUNG, MIT , 24M TECHNOLOGIES, MURATA MANUFACTURING_SONY,** UNIVERSITY OF CHICAGO	JENA BATTERIES, FRIEDRICH SCHILLER UNIVERSITAT JENA, ACAL ENERGY, UNIVERSITY OF CHESTER, **LOCKHEED MARTIN ENERGY_UT BATTELLE, MIT, 24M TECHNOLOGIES, MURATA MANUFACTURING_SONY,** TOHOKU UNIVERSITY,**SAMSUNG**	-
Main active IP players *(Highest number of pending patent applications)*	**LOCKHEED MARTIN ENERGY_UT BATTELLE, PANASONIC_SANYO,** FRIEDRICH SCHILLER UNIVERSITAT JENA, JENA BATTERIES, HARVARD COLLEGE, CHINASALT JINTAN, ACAL ENERGY, **MURATA MANUFACTURING_SONY,** UNIVERSITY OF CHESTER, **MIT**	**LOCKHEED MARTIN ENERGY_UT BATTELLE, PANASONIC_SANYO,** FRIEDRICH SCHILLER UNIVERSITAT JENA, JENA BATTERIES, **MURATA MANUFACTURING_SONY,** ACAL ENERGY, UNIVERSITY OF CHESTER, ARAMCO SERVICES, SAUDI ARABIAN OIL, HARVARD COLLEGE, CHROME PLATED POWER, **MIT**	-

Table 39: Main IP Players by supply chain segments (battery cell, recycling) in Organic Redox-flow Battery patent landscape

Patenting Activity of Main IP Players by Supply Chain Segments

Assignee	Number of patent families	Supply Chain Segments: Redox shuttles materials	Electrolyte	Separator	Electrode	Electrode manufacturing	Battery cell	Battery cell manufacturing	Recycling
LOCKHEED MARTIN ENERGY_UT BATTELLE	39	9	5	1	2	2	25	10	
JIANGXI UNIVERSITY OF SCI. & TECH.	30		11				19	16	
CHINASALT JINTAN	28	3	4		3	3	18	7	
PANASONIC_SANYO	18						18	8	
ACAL ENERGY	17						17	11	
DALIAN INSTITUTE OF CHEMICAL PHYSICS	16		1	2	2	2	11	6	
SAMSUNG	16		6	1			13	3	
UNIVERSITY OF CHESTER	11						11	9	
UNIVERSITY OF CHICAGO	11	4					10	1	
KOREA INSTITUTE OF ENERGY RESEARCH	10	1	3		2	2	4	2	
SEOUL NATIONAL UNIVERSITY	9		7				3		
HITACHI CHEMICAL	8		1				7		
CMBLU	8	3	6						
UNIVERSITY OF KENTUCKY	7	3	3				3	1	
TIANJIN UNIVERSITY	7		3		1	1	3	2	
TOYOTA	6	2	1				3	1	
DALIAN UNIVERSITY OF TECHNOLOGY	6		2	1			3		
UNIVERSITY OF SOUTH CALIFORNIA	5	3					5	1	
HARVARD COLLEGE	5	1	2				5	1	
SANDIA NATIONAL LABORATORIES	5	2	1				2		
C-TRI	5		5						
WISCONSIN ALUMNI RESEARCH FOUND.	5	2					1	1	
LG CHEM	5	1	2				2	1	
MIT	4						4	2	
CNRS	4		1		1	1	2	2	
NISSHIN ELECTRIC	4						4	1	
NATIONAL UNIVERSITY OF SINGAPORE	4						4		
AIST	4		1				4	1	
FRIEDRICH SCHILLER UNIVERSITAT JENA	4						4	2	
JENA BATTERIES	4						4	3	
CHANGZHOU UNIVERSITY	4	1	1				2	2	

Table 40: Number of patent families by main IP Players and by supply chain segments in Organic Redox-flow Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments. European companies are written in orange color.

- Main IP players have different IP strategies. Most of them mainly file patents on battery cells.
- **Panasonic/Sanyo, Acal Energy, University of Chester, MIT, University of Jena and Jena Batteries** only file patents on battery cells.
- **CMBLU and C-TRI** only file patents on redox shuttle molecules and electrolyte.
- Some of main IP players file patents on battery cells and one or several other supply chain segments. **Lockheed Martin / UT Battelle** file patents on all supply chain segments, except recycling. **Jiangxi Univ.** files patents on electrolyte and battery cell. **Chinasalt Jintan** and **KIER** file patents on all supply chain segments, except recycling and separator. **Samsung** and **Seoul National University** file patents on battery cell and electrolyte. **University of Chicago** and **University of South California** file patents on battery cells and redox shuttle materials.

Main European IP Players

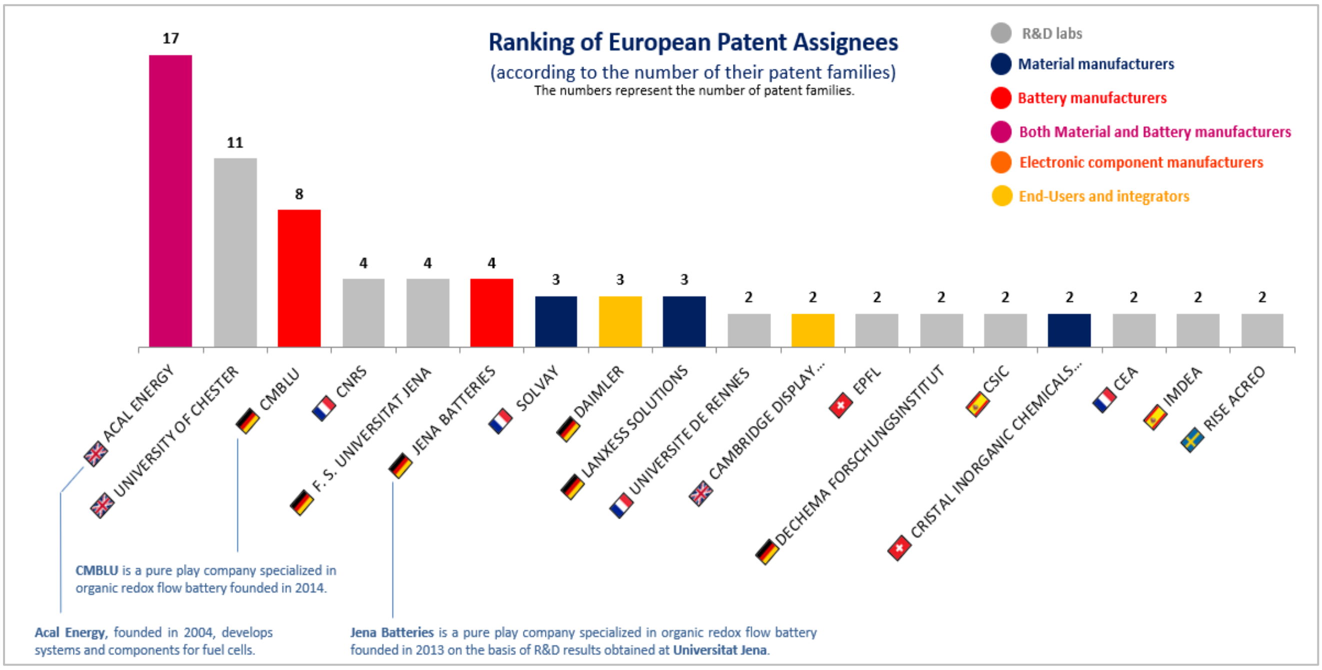


Figure 54: Ranking of main European Patent Assignees according to their number of patent families related to Organic Redox-flow Battery

- More than **40 European organizations** have filed patents related to organic redox-flow battery. European IP players are mainly originating from Germany, United Kingdom and France and are mainly R&D labs and pure-play companies.
- A French start-up focused on organic redox flow batteries (**Kemwatt**) was founded in 2014 on the basis of R&D results of. **Univ. de Rennes/CNRS.** It develops
- European IP players mainly co-file patents on Organic Redox-flow battery with European companies and R&D labs. Only few of them have patents co-filed with a non-European company.

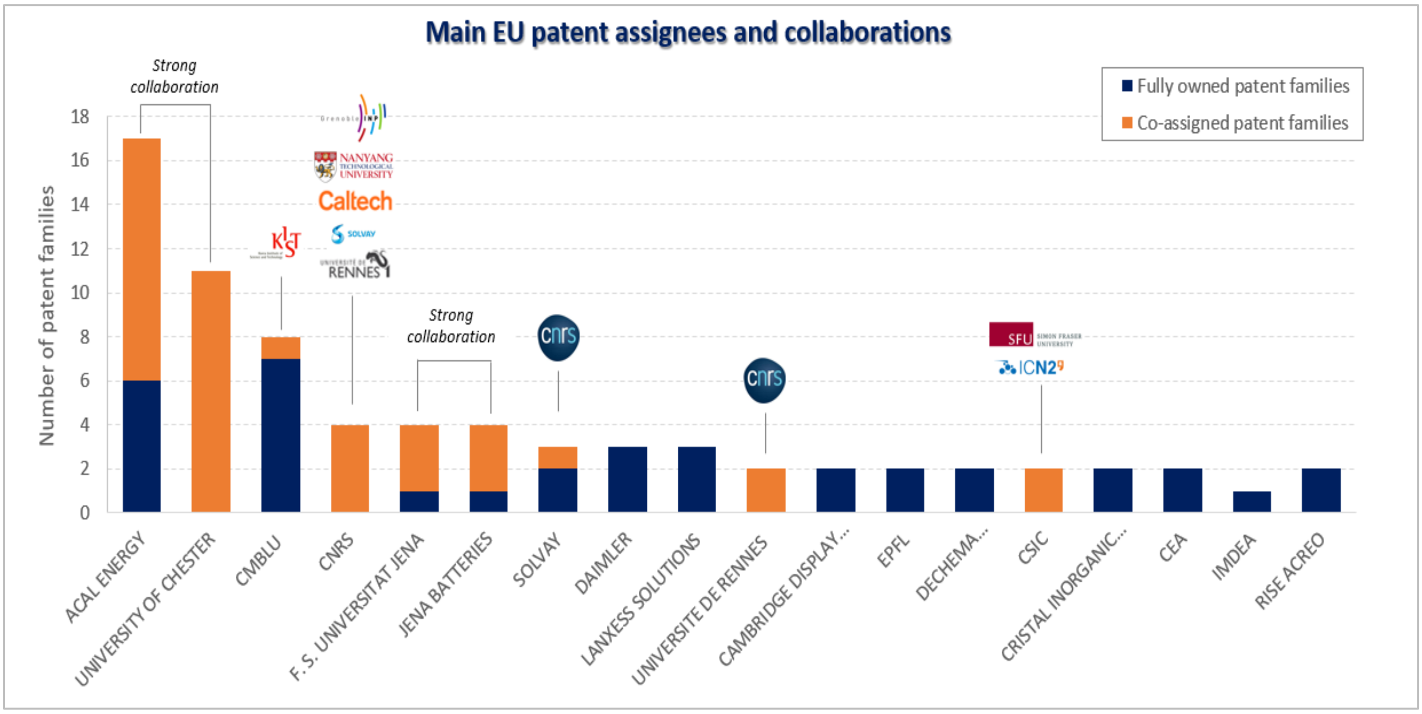


Figure 55: Number of co-assigned patent families by main European patent assignees in Organic Redox-flow Battery patent landscape

Main European IP Players by Type of Companies

Material Manufacturers

SOLVAY	3
LANXESS SOLUTIONS	3
CRISTAL INORGANIC CHEM.	2
INNOVIA FILMS	1
ENI	1

Battery Manufacturers

ACAL ENERGY	17
CMBLU	8
JENA BATTERIES	4
SCALAR TECHNOLOGIES	1
CHROME PLATED POWER	1
INDUSTRIE DE NORA	1
KEMWATT	1
POWER MIGRATION	1

End-Users and Integrators

DAIMLER	3
CAMBRIDGE DISPLAY TECHNOLOGY	2
BMW	1
SIEMENS	1
ILMA BIOCHEM	1

R&D Labs

UNIVERSITY OF CHESTER	11
CNRS	4
F. S. UNIVERSITAT JENA	4
UNIVERSITE DE RENNES	2
EPFL	2
DECHEMA FORSCHUNGSINSTITUT	2
CSIC	2
CEA	2
IMDEA	2
RISE ACREO	2
FUNKTIONSWERK. FORSCHUNGS U ENTWICKLUNGS	1
QUEENS UNIVERSITY BELFAST	1
UNIVERSIDAD AUTONOMA DE MADRID	1
T.U. BRAUNSCHWEIG	1
INPG	1
TEKNOLOGIAN TUTKIMUSKESKUS VTT	1
ENERGIGUNE	1
UNIVERSITE DE L'ORNE	1
IFP ENERGIES NOUVELLES	1
INNVENTIA	1
DELFT UNIVERSITY OF TECHNOLOGY	1

Table 41: Ranking of main European patent assignees by type of companies according to their number of patent families related to Organic Redox-flow Battery. (Time period: 1960-2020, i.e. all patent families in the patent landscape). The numbers represent the number of patent families of the corresponding patent assignee in Organic Redox-flow Battery patent landscape.

- **Lanxess Solutions** is a German chemical manufacturer founded in 2004 via the spin-off of the Chemical division and part of the polymers business from **Bayer.** In 2016, the company began to focus on the market for additives for lubricants and fire retardants by acquiring **Chemtura (US)** and placing its rubber business into a joint venture with **Aramco**.
- **Cristal Inorganic Chemicals Switzerland** is a company founded in 2011. It manufactures and sells chemical products. It's a subsidiary of **Cristal** group, acquired by **Tronox (US)** in 2019.
- **Innovia Films** is a British polymer material manufacturer. It notably produces biaxially-oriented polypropylene (BOPP). It is a subsidiary of **CCL Industries** (Canada) since 2016.
- **Acal Energy** is a British battery manufacturer founded in 2004. It develops systems and components for fuel cells.
- **CMBLU** is a German pure play company specialized in organic redox flow battery founded in 2014.
- **Jena Batteries** is a German pure play company specialized in organic redox flow battery founded in 2013 on the basis of R&D results obtained at **Universitat Jena**.
- **Scalar Technologies** is a British battery manufacturer no more active. **Chrome Plated Power** was a French battery manufacturer founded in 2017. It filed for bankruptcy in 2019.
- **Industrie de Nora** is an Italian company founded in 2003. It provides chemicals and electrodes for various applications.
- **Kemwatt** is a French start-up founded in 2014 on the basis of R&D results of. **Univ. de Rennes/CNRS.** It develops organic redox flow batteries.

• **Power Migration** is a British battery manufacturer founded in 2013 and known under its brand name (StorTera). It develops and manufactures redox flow battery, notably graphite-sulfur single liquid flow battery.

IP Dynamics of Main European IP Players

Earliest year of publication for each patent family

Assignee	Nb of patent families	Average age of the patent portfolio	2000 - 2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
FUNKTIONSWERK. FORSCH. U ENTWICKLUNGS	1	13			1													
UNIVERSITY OF CHESTER	11	12		4	1	2	1			2	1							
INNOVIA FILMS	1	12				1												
SCALAR TECHNOLOGIES	1	12				1												
ACAL ENERGY	17	11		4	2	3	3			2	2		1					
QUEENS UNIVERSITY BELFAST	1	10						1										
CNRS	4	6						1			1		1		1			
IMPERIAL INNOVATIONS	1	6										1						
UNIVERSIDAD AUTONOMA DE MADRID	1	6										1						
T.U. BRAUNSCHWEIG	1	6										1						
UNIVERSITE DE RENNES	2	5									1				1			
INPG	1	5											1					
TEKNOLOGIAN TUTKIMUSKESKUS VTT	1	5											1					
JENA BATTERIES	4	4										1	1		2			
LANXESS SOLUTIONS	3	4												3				
CSIC	2	4												1	1			
CRISTAL INORGANIC CHEMICALS SWITZERLAND	2	4												1	1			
CAMBRIDGE DISPLAY TECHNOLOGY	2	4											1	1				
CHROME PLATED POWER	1	4												1				
ENERGIGUNE	1	4												1				
INDUSTRIE DE NORA	1	4												1				
FRIEDRICH SCHILLER UNIVERSITAT JENA	4	3										1			2		1	
DAIMLER	3	3												2		1		
EPFL	2	3												1		1		
DECHEMA FORSCHUNGSINSTITUT	2	3												1		1		
CEA	2	3													2			
KEMWATT	1	3													1			
UNIVERSE DE L'ORNE	1	3													1			
IFP ENERGIES NOUVELLES	1	3													1			
POWER MIGRATION	1	3													1			
INNVENTIA	1	3													1			
BMW	1	3													1			
CMBLU	8	2													1	2	5	
SOLVAY	3	2											1				2	
ENI	1	2														1		
DELFT UNIVERSITY OF TECHNOLOGY	1	1															1	
RISE ACREO	1	1															1	
SIEMENS	1	1															1	
ILMA BIOCHEM	1																	1

Main EU IP players with decreasing patenting activity (University of Chester, Acal Energy)

New comers (CEA, Kemwatt, Universe de l'Orne, IFP Energies Nouvelles, Power Migration, Innventia, BMW; ENI, Delft University of Technology, Rise Acreo, Siemens, Ilma Biochem)

Most active IP player since last 10 years (CMBLU)

Note: The data corresponding to the year 2020 is not complete since the patent search was done in January 2020.

Table 42: Time evolution of patent publications by main European patent assignees and by earliest year of publication for each patent family in Organic Redox-flow Battery patent landscape (Number of patent families annually published by earliest publication year and by patent assignees). R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green. In each cell referring to a publication year, the numbers represent the number of patent families.

Patenting Activity of Main European IP Players

Most active European IP Players **(Acal Energy, University of Chester, CMBLU, CNRS, Universitat of Jena, Jena batteries)** have an international IP strategy, i.e. extend their patents in other countries. Some European IP players have no more alive patents.

IP players focused on Europe

IP players no more active

	Number of Patent families		Patent Legal status			Number of granted patents							Number of pending patent applications							
	All	Alive	Granted	Pending	Dead	USA	Europe	Japan	China	Korea	Taiwan	India	USA	Europe	Japan	China	Korea	Taiwan	India	PCT applications (WO patents)
ACAL ENERGY	17	14	34	14	89	11	10	5	3	1		3		1	1		4		8	
UNIVERSITY OF CHESTER	11	11	30	12	68	11	9	4	1	1		3		1	1		4		6	
CMBLU	8	8		35	2								3	5	2	3	2		3	9
CNRS	4	2	2	6	14		2						1	2	1	1				
F.S. UNIVERSITAT JENA	4	4	34	26	4	1	5	1	1			1	2	5	1	2	2		2	1
JENA BATTERIES	4	4	43	24	6	1	6	1	1			1	2	4	1	2	2		2	
DAIMLER	3	1		1	2									1						
LANXESS SOLUTIONS	3	3	4		1	2	2													
SOLVAY	3	2	1	2	2		1							1						1
CAMBRIDGE DISPLAY TECHNOLOGY	2	2	1	1	1	1								1						
CEA	2	2		2	1									2						
CRISTAL INORGANIC CHEM. SWITZ.	2	2	7	3	2	2	2	1		1						1		2		
CSIC	2	1	1	2	2								1	1						
DECHEMA FORSCHUNGSINSTITUT	2	2		2										2						
EPFL	2				3															
UNIVERSITE DE RENNES	2	2	2	6	7		2						1	2	1	1				
BMW	1	1		1										1						
CHROME PLATED POWER	1	1	1	8	1		1						1		1	1			1	
DELFT UNIVERSITY OF TECHNOLOGY	1	1	1	1																1
ENERGIGUNE	1	1		4	1								1	1	1	1				
ENI	1	1		8	1								1	2	1	1	1			
FUNKTIONSWERK. FORSCH.S U ENTWICK.	1				2															
IFP ENERGIES NOUVELLES	1	1	1		1		1													
ILMA BIOCHEM	1	1		1										1						
IMPERIAL INNOVATIONS	1				2															
INDUSTRIE DE NORA	1	1	7	4	1	1	1	1	1		1			1			1			
INNOVIA FILMS	1	1	4	1	11	3	1												1	
INNVENTIA	1	1	1	1	1									1						
INPG	1				2															
KEMWATT	1	1	1		1		1													
POWER MIGRATION	1	1		1										1						
QUEENS UNIVERSITY BELFAST	1				2															
RISE ACREO	1	1		2										2						
SCALAR TECHNOLOGIES	1	1	4	1	11	3	1												1	
SIEMENS	1	1		1										1						
T.U. BRAUNSCHWEIG	1				1															
TEKNOLOGIAN TUTKIMUSKESKUS VTT	1				2															
UNIVERSITE DE L'ORNE	1	1	1	5	1		1						1	1	1	1				
UNIVERSIDAD DE MADRID	1	1	1				1													

Table 43: Legal status of patents by countries for main European patent assignees in Organic Redox-flow Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

Patenting Activity of Main European IP Players by Supply Chain Segments

Assignee	Number of patent families	Supply chain segments: Redox shuttles materials	Electrolyte	Separator	Electrode	Electrode manufacturing	Battery cell	Battery cell manufacturing	Recycling
ACAL ENERGY	17						17	11	
UNIVERSITY OF CHESTER	11						11	9	
CMBLU	8	3	6						
CNRS	4		1		1	1	2	2	
F.S. UNIVERSITAT JENA	4						4	2	
JENA BATTERIES	4						4	3	
SOLVAY	3	2			1	1			
DAIMLER	3	1	2				1	1	
LANXESS SOLUTIONS	3						3	2	
UNIVERSITE DE RENNES	2		1				1	1	
CAMBRIDGE DISPLAY TECHNOLOGY	2						2	2	
EPFL	2	1					1		
DECHEMA FORSCHUNGSINSTITUT	2						2		
CSIC	2		1				1	1	
CRISTAL INORGANIC CHEM. SWITZ.	2	1	1						
CEA	2						2		
FUNKTIONSWERK. FORSCH. U ENTWICK.	1						1	1	
INNOVIA FILMS	1						1	1	
SCALAR TECHNOLOGIES	1						1	1	
QUEENS UNIVERSITY BELFAST	1						1	1	
IMPERIAL INNOVATIONS	1						1		
UNIVERSIDAD DE MADRID	1						1		
T.U. BRAUNSCHWEIG	1	1	1						
INPG	1				1	1			
TEKNOLOGIAN TUTKIMUSKESKUS VTT	1	1							
CHROME PLATED POWER	1						1	1	
ENERGIGUNE	1	1	1						
INDUSTRIE DE NORA	1				1	1			
KEMWATT	1						1		
UNIVERSITE DE L'ORNE	1		1						
IFP ENERGIES NOUVELLES	1						1	1	
POWER MIGRATION	1			1					
INNVENTIA	1				1	1			
BMW	1						1	1	
ENI	1						1		
DELFT UNIVERSITY OF TECHNOLOGY	1						1	1	
RISE ACREO	1						1	1	
SIEMENS	1						1		
ILMA BIOCHEM	1		1						

Table 44: Number of patent families by main European IP Players and by supply chain segments in Organic Redox-flow Battery patent landscape. The numbers represent the number of patent families. A patent family can belong to several segments. European IP players have different IP strategies.

- Most of European IP Players only file patents on battery cell, notably **Acal Energy, University of Chester, Jena Batteries, University of Jena, Lanxess Solutions, CEA, BMW**, **Kemwatt**, etc.
- Some other IP players (**CMBLU**, **VTT, Energigune,** etc.) have an IP strategy focused on electrolyte and/or redox shuttles materials.
- Some other IP players file patents on several supply chain segments. **CNRS** files patent on electrolyte, electrode and battery cell. **Solvay** files patents on redox shuttles materials and electrode. **Daimler** files patents on redox shuttles materials, electrolyte and battery cells.

IP Position of Main European IP Players

Relative size and strength of organic redox-flow battery patent portfolio held by European IP players have been evaluated in comparison with patent portfolio of all IP players (cf. Identification of key IP players). **Acal Energy, University of Chester, Jena Batteries, CNRS** and **University of Jena** have a good IP position organic redox-flow battery patent landscape. **CMBLU** is an emerging and leading European IP player with a high number of pending patent applications. It still has a weak IP position, but it could be improved within next years.

	Relative size of patent portfolio	Relative size of granted patent portfolio	Relative size of pending patent portfolio	Relative Prior Art Blocking Potential	Relative FTO Blocking Potential
ACAL ENERGY	Medium	Medium	Very low	High	High
UNIVERSITY OF CHESTER	Medium	Medium	Null	High	High
CMBLU	Medium	Null	Medium	Null	Null
F.S. UNIVERSITAT JENA	Low	Low	Very low	Medium	Medium
JENA BATTERIES	Low	Low	Null	Medium	Medium
CNRS	Low	Very low	Null	Medium	Very low
LANXESS SOLUTIONS	Low	Low	Null	Very low	Very low
SOLVAY	Low	Very low	Very low	Null	Null
DAIMLER	Low	Null	Very low	Null	Null
CRISTAL INORGANIC CHEM. SWITZ.	Very low	Very low	Null	Low	Low
UNIVERSITE DE RENNES	Very low	Very low	Null	Very low	Very low
DECHEMA FORSCHUNGSINSTITUT	Very low	Null	Very low	Very low	Null
RISE ACREO	Very low	Null	Very low	Very low	Null
CEA	Very low	Null	Very low	Null	Null
CAMBRIDGE DISPLAY TECHNOLOGY	Very low	Very low	Very low	Null	Null
CSIC	Very low	Very low	Null	Null	Null
IMDEA	Very low	Very low	Null	Null	Null
EPFL	Very low	Null	Null	Null	Null
INNOVIA FILMS	Very low	Very low	Null	Medium	Medium
SCALAR TECHNOLOGIES	Very low	Very low	Null	Medium	Medium
UNIVERSITE DE L'ORNE	Very low	Very low	Null	Very low	Very low
FUNKTIONSWERKST. FORSCH. U ENTWICKLUNGS	Very low	Null	Null	Medium	Null
QUEENS UNIVERSITY BELFAST	Very low	Null	Null	Low	Null
ENERGIGUNE	Very low	Null	Very low	Very low	Null
T.U. BRAUNSCHWEIG	Very low	Null	Null	Very low	Null
IMPERIAL INNOVATIONS	Very low	Null	Null	Very low	Null
POWER MIGRATION	Very low	Null	Very low	Null	Null
BMW	Very low	Null	Very low	Null	Null
ENI	Very low	Null	Very low	Null	Null
SIEMENS	Very low	Null	Very low	Null	Null
ILMA BIOCHEM	Very low	Null	Very low	Null	Null
UNIVERSIDAD DE MADRID	Very low	Very low	Null	Null	Null
CHROME PLATED POWER	Very low	Very low	Null	Null	Null
INDUSTRIE DE NORA	Very low	Very low	Null	Null	Null
KEMWATT	Very low	Very low	Null	Null	Null
IFP ENERGIES NOUVELLES	Very low	Very low	Null	Null	Null
INNVENTIA	Very low	Very low	Null	Null	Null
DELFT UNIVERSITY OF TECH.	Very low	Very low	Null	Null	Null
INPG	Very low	Null	Null	Null	Null
TT VTT	Very low	Null	Null	Null	Null

Table 45: IP Position of main European IP Players in Organic Redox-flow Battery patent landscape. R&D labs are written in Grey. Material Manufacturers are written in Blue. Battery manufacturers are written in red. Companies being both battery and material manufacturers are written in purple. Electronic component manufacturers are written in Orange. End-Users and integrators are written in light brown. Equipment/apparatus manufacturers are written in Green.

CONCLUSIONS

Since last ten years, patenting activities on Li-S battery, Na-ion battery and organic redox-flow battery are strongly increasing. After the economic crisis in the late 2000's, the renewal of automotive industry leads to a reinforcement of researches on Na-ion and Li-S batteries enabling the removal of technological barriers and opening new doors to Li-S and Na-ion technologies. The development of organic redox-flow battery is driven by the increasing demand for performant, safe, long-life and cheaper batteries for stationary applications. Li-S battery, Na-ion battery and organic redox-flow battery are at different stages of their developments. For each technology, there are European IP players with a notable IP position (Bosch/SEEO, BASF, Oxis Energy for Li-S Battery; Faradion, CNRS and CEA for Na-ion Battery and Acal Energy, CMBLU and Jena Batteries/University of Jena for Organic Redox-flow Battery).

Li-S Battery

- **Li-S battery** has the most established and competitive IP landscape where major companies have started to strongly develop their patenting activity worldwide. Pioneer patents on Li-S battery have been published in the 1970's by **Aerojet Rocketdyne, Nifco, Rockwood lithium** and **Varta**. Patenting activity on Li-S battery emerged in the mid 1990's thanks to the high patenting activity of Japanese and Korean battery manufacturers (**Panasonic, Hitachi Maxell, Samsung**) and American and British pure play companies (**PolyPlus Battery, Sion Power, Oxis Energy, Optodot**). Since 2010, patenting activity on Li-S battery is booming (+75% CAGR between 2006 and 2019) mainly due to the emergence and the high patenting activity of numerous Chinese R&D labs and companies. At the same time, numerous material manufacturers (**BASF, Solvay, Nagase, Adeka, Schott, Global Graphene, etc.**), battery manufacturers (**LG Chem, Murata, BAK, CATL, ATL, Nohms Technology, etc.**), R&D labs (**AIST, KAIST, CEA, CNRS, Fraunhofer, KIST, UT Battelle, University of Texas, etc.**) and end-users (**Toyota, Hyundai, Positec, Bosch, Volkswagen, GM, Ford, Daimler, etc.**) have entered the patent landscape. The second wave of patent filings combined with an increase in patent extensions worldwide is an indication of the technology growing maturity and market interest for Li-S batteries.
- **Sion Power, PolyPlus Battery** and **Samsung** have the best IP position in Li-S battery patent landscape. **LG Chem and Global Graphene** are IP challengers. They lead the patent landscape but have a weak IP position. In fact, most of their patents have been filed after 2015 and thus receive only few forward citations. Their IP blocking potential could be improved within next years.
- Key European IP players are **Bosch/SEEO**, **BASF** and **Oxis Energy**. They have relatively small patent portfolios (number of patent families) but show a good balance between their number of granted and pending patent as well as a worldwide geographic coverage that ensure their IP position and could support their product development and release.
    - **Bosch/SEEO** starts its patenting activity on Li-S battery in 2010. **Bosch/SEEO** mainly files on cathode material and battery cell.
    - **BASF** starts its patenting activity on Li-S battery in 2011. It has a strong partnership with **Sion Power**. **BASF** mainly files patents on cathode materials, electrode manufacturing, electrolyte, anode and battery cell.
    - **Oxis Energy** starts its patenting activity on Li-S battery in 2004. **Oxis Energy** mainly files patents on battery cell, separator and electrodes.
- There are other notable start-ups in Li-S battery patent landscape:
    - **Perpetuus R&D** is a British advanced material manufacturer primarily founded in 2013 and focused on surface engineered carbon structures such as Graphene and Carbon Nanotubes.
    - **Blue Sky** is a German company founded in 2012 and specialized in battery for stationary applications.

- **Grabat Energy** is a Spanish battery manufacturer founded in 2012 (subsidiary of **GrapheneNano**). It manufactures graphene polymer cells for different types of batteries. It works with the **University of Cordoba** and has a strategic agreement with the **CHINT Group**.
- **Monolith Materials** is an American start-up founded in 2012. It produces and markets carbon materials, especially carbon black.
- **Graphene Batteries** is a Norwegian start-up founded in 2012. It is engaged in the development of Li-S battery technology enhanced with Graphene derivatives (supplied by its sister company **Abalonyx**).
- **Iontech Systems** is a Swiss company founded in 2016. It develops and manufactures equipment, materials and accessories for the battery market.
- **Abri** is a Japanese joint venture established in 2017 between **Furukawa Battery** and **Tokyo Metropolitan University**. It develops higher performance Li-ion and post Li-ion batteries and materials used therein.
- **Ubatt** is a Korean start-up founded in 2016 based on R&D developments of UNIST. Ubatt's core technologies include non-flammable solid-state electrolytes and Lithium-based batteries.

Na-ion Battery

❖ Na-ion battery is a younger technology than Li-S battery and a very promising technology. Despite a less established patent landscape, it enters in the pre-industrialization phase. Na-ion battery protypes shows very promising results thus its commercialization could start within next years.

❖ Pioneer patents on Na-ion battery have been published in the mid 1980's by **Honeywell** and **Japanese companies (Hitachi Chemical, Showa Denko, etc**.). Patenting activity on Na-ion battery emerged in the mid 2000's thanks to the entry of numerous companies and R&D labs in the patent landscape (**CEA, CNRS, NTT, Faradion, Panasonic, Sharp, University of Texas, Aquion Energy,** etc.). Since 2010, patenting activity on Na-ion battery is booming (+69% CAGR between 2006 and 2019) mainly due to the emergence and high patenting activity of numerous Chinese R&D labs and companies. More recently, several major battery manufacturers (**LG Chem, Samsung, CATL**, etc.) and end-users (**Huawei, General Motors, Nissan,** etc.) have entered the patent landscape. The strong increase in patent filings, the entry of major companies in the patent landscape and the emergence of several American and European start-ups (**Tiamat, Altris, Natron Energy, Ubatt, Echion Technology, Nohms Technology,** etc.) confirm the growing maturity and strong market potential of Na-ion battery.

❖ IP players in Na-ion battery patent landscape are mainly Chinese R&D labs. **Sumitomo Chemical, Lithiumwerks/Valence Technology, University of Tokyo, Aquion Energy and Carnegie Mellon University** hold the best IP Position. Several major battery manufacturers (**LG Chem, Samsung, CATL**, etc.) enter the patent landscape within the last 5 years attracted by the promising results obtained on Na-ion batteries. This could lead to some major changes in the IP landscape in the coming years. We can wonder if they will continue to develop this technology by their own and in collaboration with R&D labs or if they will acquire one pure play companies.

❖ The patenting activity from European players is still weak compare to the one from Asian players. Aside **Faradion** and some big French institutes (**CNRS, CEA**) all EU IP players have less than 10 patent families.

- **Faradion** and **CNRS** start their patenting activity in 2010-2011. **Faradion** and **CNRS** mainly files patents on cathode materials. **CNRS** also has a notable number if patents related to electrolyte.
- **CEA** starts its patenting activity in 2015. **CEA** mainly files patents on anode materials, cathode materials and battery cell.

❖ There are other notable start-ups in Na-ion battery patent landscape:

- **Belenos Clean Powder** is a Swiss battery manufacturer founded in 2007. It is a subsidiary of Swatch group. **IPChem** is a Polish material manufacturer incorporated in 2016. **Broadbit Batteries** is a Finish start-up founded in 2015 and specialized in Na-ion battery.
- **Lifesize** is Swedish company founded in 2006 as a spin-out from the **Angstrom Advanced Battery Center of Uppsala University** (Sweden). It develops and manufactures materials for Na-ion and Li-ion batteries as well as corresponding battery cells.
- **Lithops** is an Italian battery manufacturer founded in 2010. It mainly develops Li-ion battery with LFP cathode material. At the end of 2015, Lithops became part of the Seri Group, being incorporated in its subsidiary FIB (owner of the FAAM brand).
- **Nohms Technologies** is an American company founded in 2011. It develops non-flammable and high voltage electrolyte solutions for battery applications.
- **Farad Power** is an American company founded in 2012. It develops carbon materials for next-generation applications in energy storage.
- **Ubatt** is a Korean start-up founded in 2016 based on R&D developments of UNIST. Ubatt's core technologies include non-flammable solid-state electrolytes and Lithium-based batteries.
- **Altris** is a Swedish start-up founded in 2017 based on R&D results obtained at **Uppsala University**. It develops and produce highly sustainable cathode materials for rechargeable sodium batteries.
- **Echion Technology** is a British start-up founded in 2017 as a spin-off of **Cambridge University**. It develops unique materials for next-generation batteries.
- **Tiamat** is a French start-up founded in 2017 based on R&D results obtained at **CEA and CNRS**. It develops rechargeable Na-ion batteries. It is worth to note that **Tiamat** does not have published patents on Na-ion batterie but has an exclusive license on CNRS/CEA patents related to Na-ion battery.

Organic Redox Flow Battery

❖ Organic redox-flow battery is the less develop and youngest IP landscape. Organic redox flow battery emerged more recently than Li-S and Na-ion battery. It is at the first development stage and is less mature than Na-ion battery and Li-S battery. Contrary to Na-ion and Li-S battery, organic redox flow battery patent landscape is not yet dominated by Chinese IP Players. The number of players as well as their patenting activity remains relatively small compared to those in Na-ion and Li-S battery IP landscape.

❖ Pioneer patents on organic redox-flow battery have been published in the 1960's by **Exxon Mobile, Lockheed Martin / UT Battelle** and **Corning**. Patenting activity on organic redox-flow battery emerged in the 2000's with the high patenting activity of **Acal Energy** and **University of Chester**. Since 2010, the entry of Korean battery manufacturers (**Samsung, LG Chem**), European and American IP players (**CEA, CNRS, MIT, Sandia,** etc.) and pure play companies (**Jena Batteries, CMBLU, Kemwatt**, etc.) in the patent landscape induced a continuous increase of patenting activity on organic redox-flow battery (+69% CAGR between 2006 and 2019). This indicates that companies show a growing interest for this technology. Patenting activity on organic redox-flow batteries has strongly increased in 2019 due to the emergence and high patenting activity of Chinese R&D labs and companies.

❖ Key European IP players are **Acal Energy, University of Chester, Jena Batteries, University of Jena and CMBLU**.

- **Acal Energy** is a British battery manufacturer founded in 2004. It develops systems and components for fuel cells. It filed patents on organic redox-flow battery between 2006 and 2015. **Acal Energy** only files patents on battery cells.

- **Jena Batteries** is a German pure play company specialized in organic redox-flow battery founded in 2013 on the basis of R&D results obtained at **Universitat Jena**. It filed patents on organic redox-flow battery between 2014 and 2017. **Jena Batteries** only files patents on battery cells.
- **CMBLU** is a German pure play company specialized in organic redox-flow battery founded in 2014. It has filed patents on organic redox-flow battery since 2017. **CMBLU** only has pending patent applications. It still has a weak IP position, but its IP position could be improved within next years. **CMBLU** files patents on electrolyte and redox shuttles materials.

- There are other notable start-ups in organic redox-flow battery patent landscape:
  - **Nanotech Energy** is an American start-up founded in 2014 on the basis of R&D results of **UCLA**. It develops and manufactures graphene-based materials for energy storage applications.
  - **Form Energy** is an American start-up founded in 2017 on the basis or R&D results of **MIT.** It develops a "new class of ultra-low-cost, long-duration energy storage systems".
  - **Kemwatt** is a French start-up founded in 2014 on the basis of R&D results of. **Univ. de Rennes/CNRS.** It develops organic redox-flow batteries.
  - **Power Migration** is a British battery manufacturer founded in 2013 and known under its brand name (StorTera). It develops redox-flow battery, notably graphite-sulfur single liquid flow battery.
  - **Innventia** and **RISE Acreo** are Swedish R&D labs. **Ilma Biochem** is a German consulting company incorporated in 2018. It provides scientific and technical services to exclusive business partners.
  - **Cristal Inorganic Chemicals Switzerland** is a company founded in 2011. It manufactures and sells chemical products. It's a subsidiary of **Cristal** group, acquired by **Tronox (US)** in 2019.
  - **Kemwatt** is a French start-up founded in 2014 on the basis of R&D results of **Univ. de Rennes/CNRS**.

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