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State of the Art Report

on Storage Technologies, Opportunities and Trends

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Contents

List of abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management System
BMWi	Bundesministerium für Wirtschaft und Energie (DE) Federal Ministry for Economic Affairs and Energy (EN)
CAES	Compressed Air Energy Storage
DOD	Depth of Discharge
EBA	European Battery Alliance
EC	European Commission
EMS	Energy Management System
ES	Energy Storage
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FCR	Frequency Containment Reserve
FES	Flywheel Energy Storage
HESS	Hydrogen Energy Storage System
HTS	High Temperature Superconducting
LA	Lead Acid
LAES	Liquid Air Energy Storage
LFP	Lithium Ferrophosphate (lithium iron phosphate)
Li-ion	Lithium-ion
NCA	Nickel Cobalt Aluminium-oxides
NMC	Nickel Manganese Cobalt
NWE	North-West Europe
OCV	Open Circuit Voltage
P2G	Power to Gas
PCM	Phase Change Materials
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
R&I	Research and Innovation
SES	Supercapacitor Energy Storage
SMEs	Small and Medium-sized Enterprises
SMES	Super Magnetic Energy Storage
SOC	State of Charge
SOH	State of Health
TES	Thermal Energy Storage
TRLs	Technology Readiness Levels
UPS	Uninterruptible Power Supply

1. Scope

Panagiotis Mouratidis, Technical University of Darmstadt

The report in hand aims to capture the technological developments of energy storage as well as the status of the energy storage industries based in North-West Europe (NWE). The report is beneficial for Small and Medium-sized Enterprises (SMEs) that strive to establish their position in the competitive energy storage market.

The present report concerns energy storage products and installations in the medium capacity range, which is defined between 5 kWh and 2 MWh. The lower capacity limit aims to include home energy storage systems in combination with photovoltaic electricity generation. On the other hand, the lower limitation clearly excludes consumer electronics, which incorporate small battery storages such as laptops, mobile phones, electric bikes, power tools etc. The higher limit aims to exclude high capacity energy storage installations which are mainly realized nowadays as pumped hydro storage power plants. Energy storage systems for grid scale installations such as back-up for wind and solar farms also lie in the report's scope. Furthermore, electromobility for private as well as public transportation comprises a growing market to be considered.

For clarity and overview purposes, the various storage technologies can be classified depending on the type of energy acting as a reservoir. Depending on the properties of each storage technology their suitability for designated applications varies significantly. A method to select appropriate storage technologies for certain applications is therefore valuable.

Energy storage applications have constantly grown during the last decades, e.g. photovoltaic (PV) home storage systems constitute an actively growing market in Germany (Kairies, et al., 2019). The integration of renewable energies into the electricity grid increased the need for balancing power. The use of energy storage to buffer the stochastic character of renewable energy generation finds applications that redeem within a couple of years (Vivid Economics Limited , 2019). As the storage technologies improve, new applications arise. An overview of established and arising energy storage applications in the most important sectors provides useful advice for potential investments and targeted product development.

Established energy storage technologies still have potential for improvements, which can be considered expedient for investments. Arising technologies would very likely have an impact on the energy and transportation developments in northwest Europe. Emerging energy storage technologies, especially developments in lithium-ion batteries and the production of hydrogen and carbon-neutral fuels concern the current research. The Technological Readiness Levels (TRLs) of emerging technologies provide an indicator of the additional research and development effort required to achieve a commercial release.

The analysis of the competitive business environment in NWE exposes the challenges that SMEs face and supports them to improve their business models and spot new business cases. A survey and overview of the SMEs based in NWE constitutes an important starting point for further analysis and benchmarking. The analysis of feasible business models for energy storage enterprises provides valuable advice to SMEs. Furthermore, the analysis of value and supply chains for existing and arising storage products are valuable to identify manufacturing practices and prepare SMEs for economies of scale.

There are indisputable trends to be observed in energy storage research and applications. These trends exhibit a rather global than regional nature. For instance, the use of lithium-ion batteries in electromobility is unambiguously a global trend. Opportunities arising for energy storage enterprises active in the European region are related to the current trends. In this sense, trends and opportunities in energy storages technologies are worthwhile to a closer investigation.

2. Classification of energy storage technologies

Fien Vanden Hautte, Ghent University

Energy storage technologies can be classified according to the type of energy acting as a reservoir (EC, 2020). A broad categorization of different energy storage (ES) methods, according to their forms of energy, is presented in the figure below.

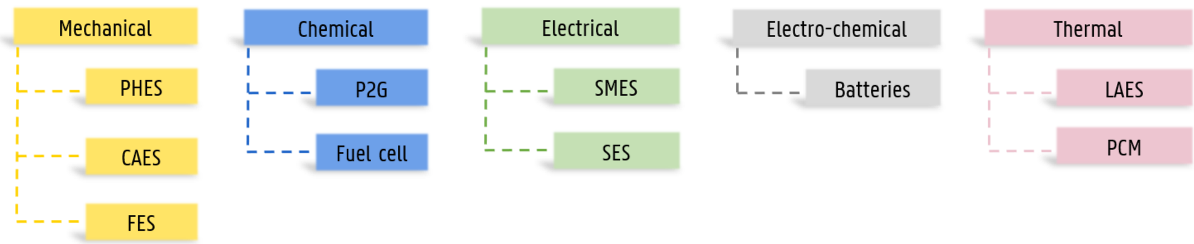

Figure 1: Categorization of energy storage methods. PHES = Pumped Hydro ES, CAES = Compressed Air ES, FES = Flywheel ES, P2G = Power to Gas, SMES = Superconducting Magnetic ES, SES = Supercapacitor ES, LAES = Liquid Air ES, PCM = Phase Change Materials.

In the following we provide an overview of the *basic working principles*, as well as the *properties* of each subcategory. *It is essential to take these properties into account when determining the appropriate storage solution for a specific application.* The application specific requirements, for example low self-discharge for seasonal storage, or high response rates for a dynamical application, should be linked to the properties of the technologies available. It is clear that in order to do this, the first step should be to ask oneself: "what do I want to achieve with the storage system?" From this point of view, the following guidelines may be used as a roadmap to appoint appropriate storage systems to specific applications. This report concentrates on mechanical, chemical, electrical and electrochemical storage.

2.1 Mechanical

The most commonly implemented system in mechanical energy storage over the years is **pumped hydro storage (PHES)**. This is visualized in Figure 2, where the share of present global installed energy storage systems (ESSs) capacity is presented in a pie chart. However, pumped hydro power plants can easily account for several MWh of available capacity. Since this report concentrates on the medium capacity range, pumped hydro storage is not taken further into account.

Another mechanical storage system that will not be discussed further is **compressed air energy storage (CAES)**, which is also typically deployed as a large-scale storage system, in the range of hundreds of MWh.

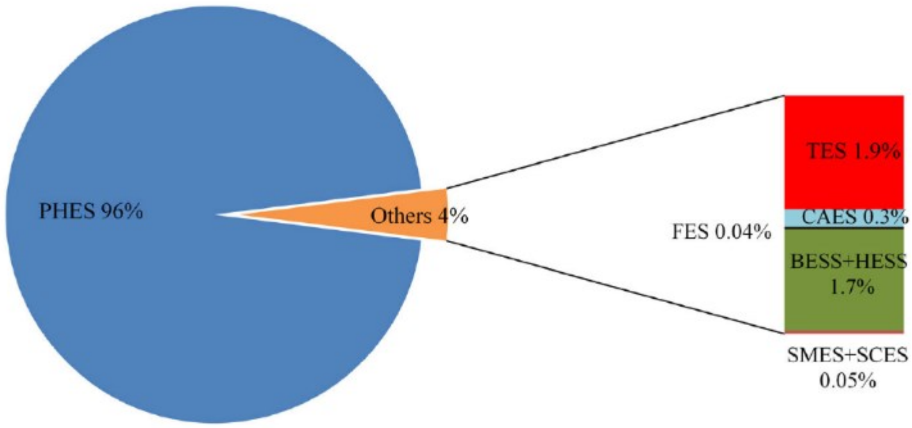

Figure 2: Share of present global installed ESSs capacity. TES = thermal ES, BESS = Battery ESS, HESS = Hydrogen ESS. (Krishan & Suhag, 2019)

A third mechanical storage system is **flywheel energy storage (FES)**. In FES, energy is stored mechanically as rotational (kinetic) energy by accelerating a rotor (flywheel) to a very high speed. The speeding up process takes place with the help of an electric machine which acts as a *motor during charging*. The same machine behaves as a *generator when discharging*, by delivering energy from the flywheel to the power system, slowing the flywheel down.

The amount of energy stored (E) in this flywheel is a function of its moment of inertia (I) and angular velocity (ω)

$$E = \frac{1}{2} I \, \omega^2 \, ,$$

where the inertia of a cylindrical flywheel with radius r and mass m is given by

$$I = m \, r^2,$$

finally yielding

$$E = \frac{1}{2} m \, r^2 \omega^2 \, .$$

First, it is clear that the flywheel can be “charged” by increasing its angular velocity and “discharged” by slowing it down. Second, the capacity of the flywheel increases with its radius and mass. Therefore, a flywheel made of a high mass density material, such as steel, can store more energy than a low mass density flywheel, and the storage capacity will increase with the size of the flywheel.

An important parameter is the tensile strength of the flywheel material; the amount of energy stored in the flywheel is limited by the tensile strength, since the flywheel will break if the internal stresses exceed the tensile strength (ActivePower, 2008).

To reduce the friction at high speed, the rotating mass can be supported on two magnetic bearings and additionally, the flywheel may be contained in a vessel with absolute or partial vacuum to reduce losses due to friction.

We distinguish between two kinds of FES operation: the *low-speed FES*, being relatively cheap but having an inferior performance, and the *high-speed FES*, 5 times more expensive, but highly performant. Their features are shown in Table 1. An example of a high-speed FES is shown in Figure 3. We conclude with an overview the (dis)advantages of FES in Table 2. An overview of the properties of FES can be found in Table 12.

Table 1: Comparison of low-speed and high-speed FES systems. (HTS = high temperature superconducting.) (Krishan & Suhag, 2019)

Feature	Low-Speed FES	High-Speed FES
Rotor material	Steel	Composite material: glass and carbon fiber
Electrical machine	Asynchronous, permanent magnet synchronous, switched reluctance	Permanent magnet synchronous, switched reluctance
Bearing	Mechanical, ball bearing	Magnetic, HTS bearing
Housing	Partial vacuum or light gas	Absolute vacuum
Applications	Power quality, frequency regulation	Spacecrafts, transportation
Cost	1	5

Table 2: Advantages and disadvantages of FES (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Fast charge/discharge cycle ➢ Low maintenance required ➢ Long life ➢ High power density independent of stored energy	➢ Very low energy density ➢ High self-discharge ➢ Need extra power for energizing magnetic bearing

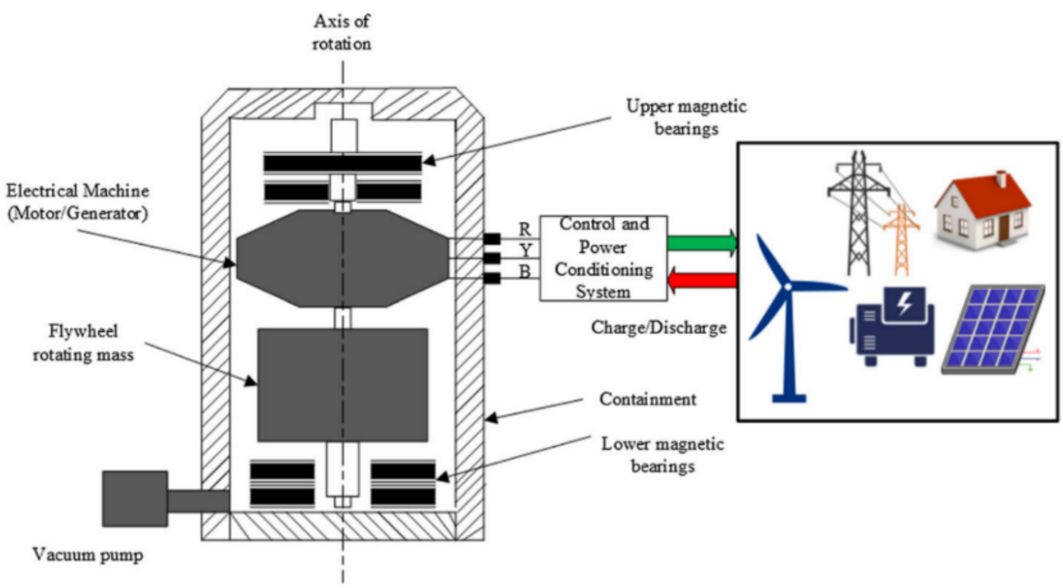

Figure 3: High-speed FES system (Krishan & Suhag, 2019).

2.2 Chemical

One of the most prominent systems for storing chemical energy is the hydrogen energy storage system (HESS), releasing only water as a reaction product. In addition to hydrogen, it is also possible to use methane or ammonia.

Hydrogen storage is a promising technology for long-term energy storage (days - months), since its self-discharge is limited, creating opportunities for grid-balancing purposes. The main process consists of two steps:

1. Hydrogen can be produced and stored when there is an excess of power available. This process is referred to as **Power-to-Gas (P2G)**, specifically power-to-hydrogen for HESS.

2. The stored hydrogen can be used to generate electricity using **fuel cells**, in case the power available is in shortage.

These two steps will now be discussed separately.

POWER-TO-GAS FOR "CHARGING"

Power-to-Gas (P2G) is, as the name implies, the conversion of electricity into gas. The most common process to achieve this is *electrolysis*, in which water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) with the help of electricity. As mentioned, it is intended that this electricity would be provided by surpluses of decentralized energy production (such as wind or solar). The efficiency of this process is about 80% (Abdalla, et al., 2018).

P2G distinguishes itself from other energy storage systems because it can fulfill *other functions* in addition to energy storage, which makes the business cases for P2G more diverse. Globally, approximately 70 Mt of hydrogen was consumed in industrial processing in 2019. However, currently over 90% of hydrogen is produced by steam methane reforming (a process that also releases carbon dioxide) due to the relative lower costs (Younus, et al., 2018). Hydrogen produced from electrolysis is currently about twice as expensive as fossil hydrogen production (Kayfeci, et al., 2019).

As can be seen in Figure 4, displaying both resources (left) and applications (right) of hydrogen, the main application area of hydrogen is **chemistry**, where it is used as a raw material in refinery processes as well as to create ammonia or methanol.

Besides a raw material in chemistry, hydrogen is also used for storage. Hydrogen can be stored under pressure in gas cylinders or tanks for practically an unlimited period of time. For stationary applications, gaseous storage under high pressure is the most popular choice. Large amounts of hydrogen can be stored in underground salt caverns and pipe systems. Smaller quantities are stored in above-ground tanks or bottles under pressure. For an overview of different storage possibilities see (Abdalla, et al., 2018). To turn the stored hydrogen back into electricity, fuel cells can be applied.

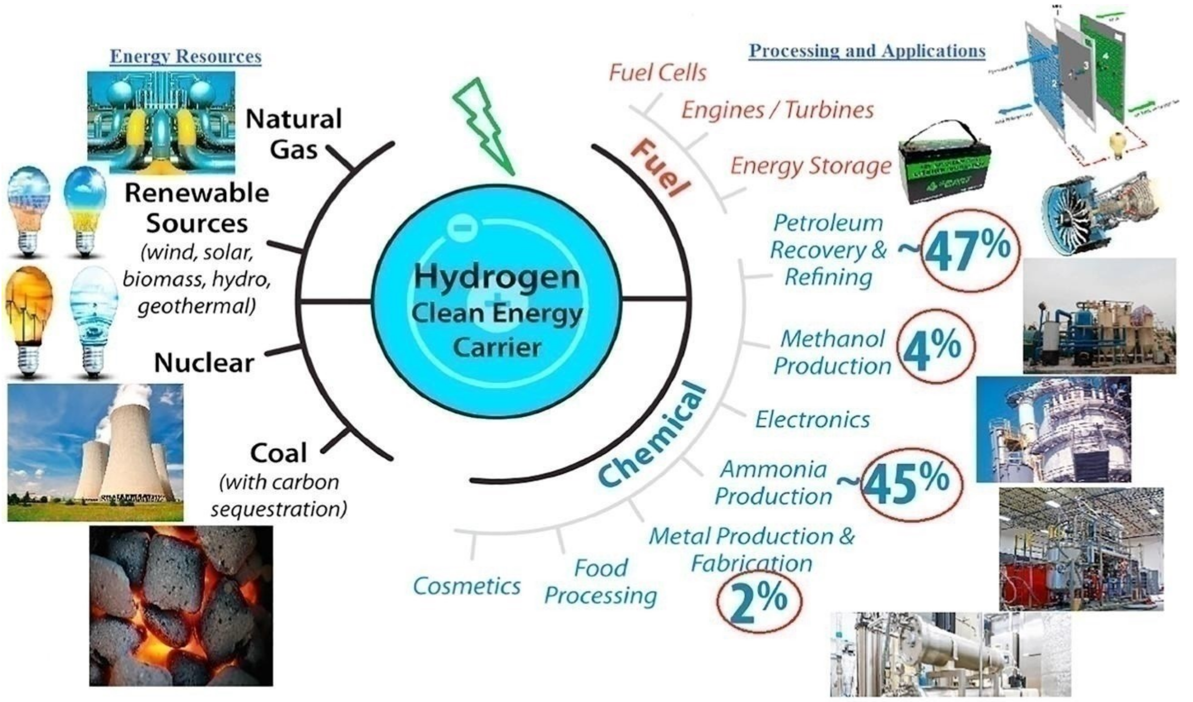

Figure 4: Hydrogen resources and applications (Abdalla, et al., 2018)

FUEL CELLS FOR "DISCHARGING"

Fuel cells, like batteries, consist of individual electrochemical cells. However, unlike batteries, this technology uses a fuel (usually hydrogen or natural gas). The fuel cells require a continuous supply of fuel to maintain a chemical reaction to produce electrical energy, and a fuel cell is therefore, as opposed to a battery cell, not a closed medium. Fuel cells have found their use in medium-term to long-term storage applications with energy storage capacities ranging from 1 kWh to tens of MWh (Krishan & Suhag, 2019).

Fuel cells consist of four main parts: an anode, a cathode, an electrolyte and the external circuit. The operating principle is shown schematically in Figure 5. An ion-conducting electrolyte is located between two electrodes. Hydrogen is sent along the cathode, oxygen along the anode. A chemical reaction occurs at the cathode in which electrons and ions are produced. These

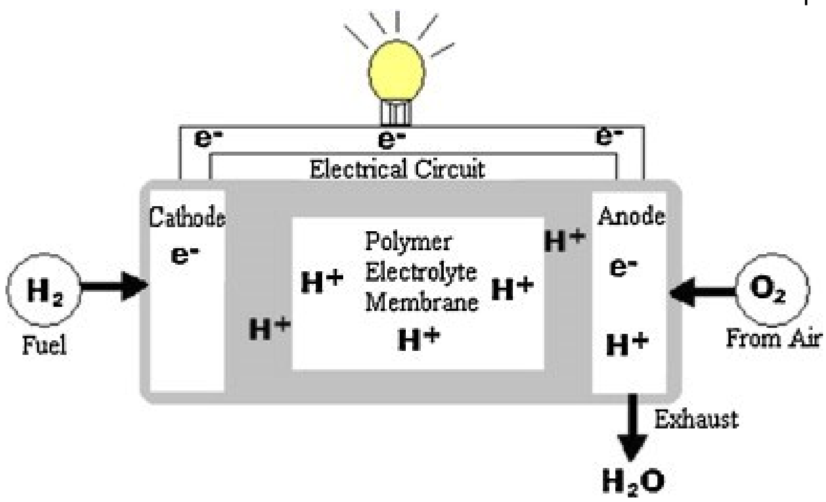

Figure 5: Fuel cell basic working principle (Mekhilef, et al., 2012)

electrons move along an external circuit to the anode and in the meantime drive a load. The ions migrate through the electrolyte to the anode, where together with the electrons and oxygen a new chemical reaction takes place and water is formed (Mekhilef, et al., 2012).

Fuel cells generate direct current, which may be converted into alternating current with inverter systems. According to (Krishan & Suhag, 2019) fuel cells can be classified into six groups. These six groups differ in their efficiency, type of fuel, operating temperature, and chemical reaction. An overview of the group properties can be found in the same work.

1. Proton exchange membrane fuel cell (PEMFC)
2. Alkaline fuel cell (AFC)
3. Phosphoric acid fuel cell (PAFC)
4. Molten carbonate fuel cell (MCFC)
5. Solid oxide fuel cell (SOFC)
6. Direct methanol fuel cell (DMFC)

HYDROGEN AND MOBILITY

Hydrogen can be used as fuel in transportation. As already introduced, hydrogen is converted into electricity via a fuel cell. In addition, it is also possible to use methane, which can be produced via P2G, as a car fuel. Though several automakers worldwide have predicted that fuel cell vehicles (FCVs) will be commercialized, they still require auxiliary power sources to overcome their high-power load needs (Huang, et al., 2016). Today the market is not yet sufficiently developed and further research is required. We conclude with an overview of the (dis)advantages of fuel cells in Table 3. An overview of the properties of fuel cells can be found in Table 12.

Table 3: Advantages and disadvantages of fuel cells (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Negligible self-discharge ➢ Environmentally friendly if hydrogen is used and not methane ➢ Low maintenance required	➢ Low maturity level ➢ High cost ➢ Low efficiency ➢ Safety issues due to flammability of hydrogen

2.3 Electrical

SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

In Superconducting Magnetic Energy Storage (SMES) units, electricity is stored in a magnetic field. This magnetic field is created by a direct current (DC) flowing in a superconducting coil. SMES must be operated under cryogenic temperatures, since superconducting materials only have zero resistance under a certain critical temperature about 20 K (Donnellan, et al., 2015). Obtaining these extremely low temperatures is cost intensive. In addition, the SMES system is rather complex. Advantages of the system on the other hand comprise its fast response time and high-power density, making SMES suitable for applications in which the fast, and short-term supply of power is central (e.g. service network interruption) (Pinnangudi, et al., 2017). An overview of the (dis)advantages of SMES are presented in Table 4. An overview of the properties of SMES can be found in Table 12.

Table 4: Advantages and disadvantages of SMES (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Long cycle life ➢ High %DoD ➢ High power density	➢ High cost ➢ Electromagnetic interference to nearby communication ➢ Low energy density

SUPERCAPACITOR ENERGY STORAGE (SES OR SCES)

A supercapacitor stores energy in an electric field. Supercapacitors can be charged very quickly and quite efficiently. However, supercapacitors have small energy densities. Supercapacitors consist of two carbon-based electrodes that are located in close distance, an electrolyte and a separator that electrically separates the two electrodes from each other. When a certain voltage is applied (during charging), the ions in the electrolyte are attracted to the electrode with the opposite sign to their charge. These opposite charges produce an electric field between the electrodes, in which energy is stored (Afif, et al., 2019).

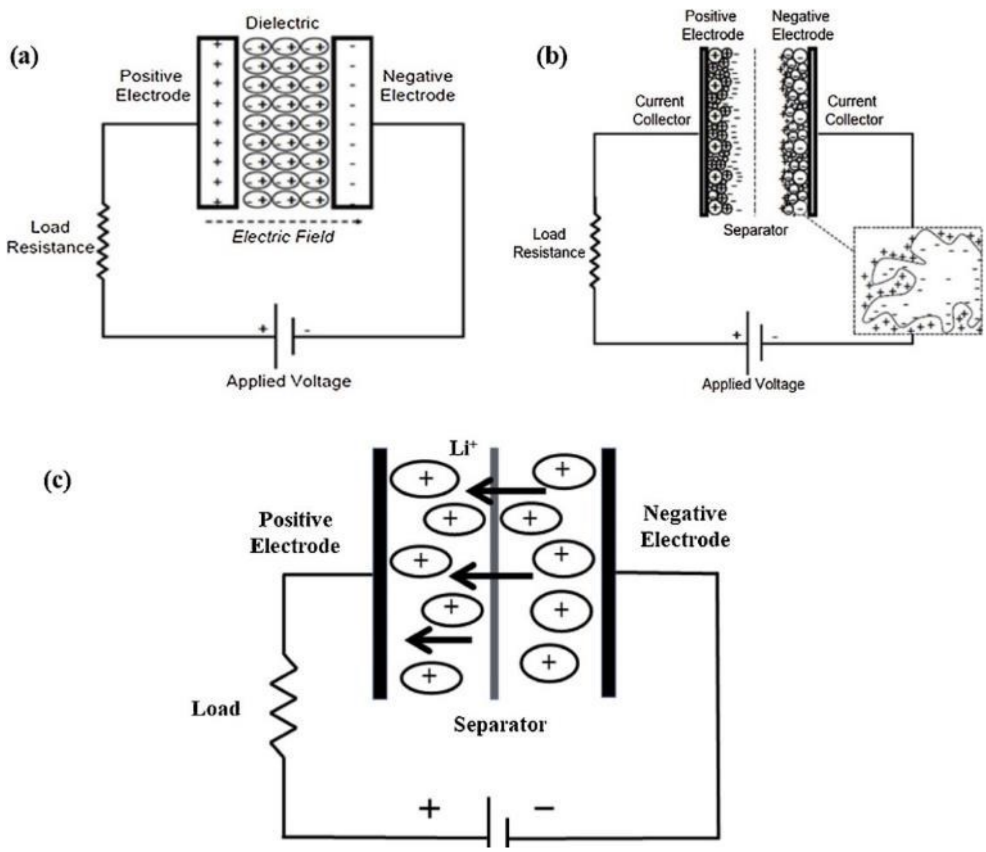

Figure 6: (a) Schematic of conventional capacitor, (b) Schematic of an electrochemical double layer capacitor (supercapacitor) and (c) Schematic of conventional discharging battery (Afif, et al., 2019).

The capacitance of a parallel plate capacitor with electrode surface A, separation d and dielectric constant ε, is given by

$$C = \frac{\varepsilon A}{d}.$$

The capacitance of a supercapacitor is 100 to 1000 times larger than that of a conventional capacitor, thanks to the very large surface area of the electrodes (A) obtained with porous materials (Krishan & Suhag, 2019). The amount of energy (E) stored in SES is given by

$$E = \frac{CV^2}{2},$$

with V the voltage between the two electrodes. We conclude with an overview of the (dis)advantages of SES in Table 5. An overview of the properties of SES can be found in Table 12.

Table 5: Advantages and disadvantages of SES (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Very fast response time ➢ Long cycle life and high efficiency ➢ Good alternative for batteries ➢ Easily used in strings	➢ Poor energy density ➢ Limited applications ➢ Relatively high cost

2.4 Electrochemical

Battery energy storage systems (BESS) are available in different sizes, ranging from tens of watts to megawatts. Batteries are made up of a number of cells with each cell consisting of two electrodes immersed in an electrolyte medium.

Batteries can be divided into primary (or non-rechargeable) and secondary (or rechargeable) cells. However, we will only consider secondary cells since primary batteries are not used in power applications.

Within the secondary BESS we can distinguish two broad categories: the *solid-state* batteries, where the chemically active components do not move, and the *flow batteries*, where the chemical active components circulate.

LEAD-ACID (LA) BATTERIES

Lead-acid batteries are the oldest and one of the most common type of batteries.

The electrodes are made of metallic lead and lead oxide and are immersed in an electrolyte consisting of a mixture of sulfuric acid and distilled water. During discharge, lead sulfate is formed on both electrodes and the electrolyte loses its sulfuric acid since this is converted into water. The lead-acid battery can be described as robust, reliable and cheap.

However, the lead-acid battery also has some drawbacks. Their biggest operational drawback is that their battery life decreases drastically if the battery is discharged deeply, limiting their Depth of Discharge (DOD) (Pinnangudi, et al., 2017). Despite the low cost of lead-acid batteries, they are characterized by a high cost per cycle. Furthermore, they typically have a low energy density, which means that they take up a lot of space (Nikolaidis & Poullikkas, 2017). Lead-acid batteries can be recycled quite easily, but not all batteries are recycled. If the batteries are disposed improperly, this has a significant environmental impact: lead is poisonous to humans and the environment (Guney & Tepe, 2017).

Because of the disadvantages listed above, lead-acid batteries are used in applications like peak shaving and uninterruptible power supplies (Khan, et al., 2019). Another "standby application" is the starting battery of a vehicle. An overview of the (dis)advantages of lead-acid batteries is given in Table 6 and their properties are summarized in Table 10.

Table 6: Advantages and disadvantages of lead-acid batteries

Advantages	Disadvantages
➢ Low capital cost ➢ Low maintenance required ➢ Proven technology	➢ Low energy and power density ➢ Long charging time ➢ Short cycle life ➢ Low %DOD ➢ Low cycle efficiency ➢ High energy cost of manufacture

Since lead-acid batteries were the only type of battery widely used for storage for many years, there have been many developments to tackle their disadvantages. We briefly discuss four different lead-acid based batteries below: deep cycle LA, starter LA, FLA and VRLA.

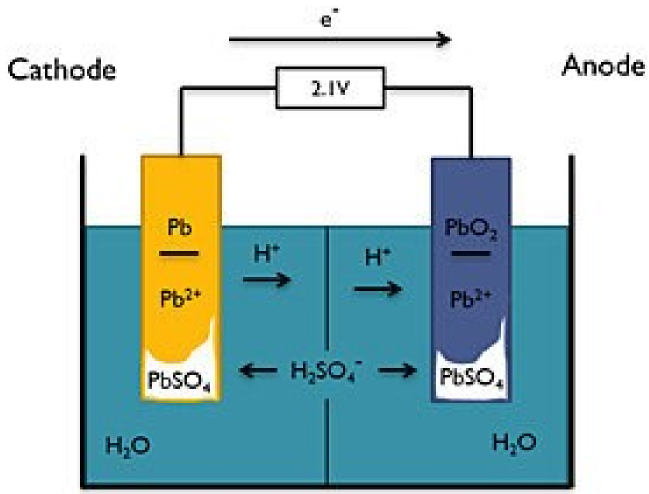

Figure 7: Schematic illustration of the lead–acid battery chemical reaction (Huang, et al., 2016)

- **LEAD-ACID BATTERIES: DEEP CYCLE BATTERIES AND START BATTERIES**

The **dimensions of the electrodes** of the lead-acid battery roughly determine two types: traction batteries, also called deep cycle batteries, and start batteries. The **traction battery** (deep cycle battery) to be seen in Figure 8 left has thicker electrodes, decreasing corrosive effects which may occur when charging the battery too deep. This battery type is therefore superior for energy capacity applications. On the other hand, the **starter battery** as depicted in Figure 8 on the right has many thin electrodes in parallel to achieve low resistivity and a large active surface. While this battery doesn't allow deep discharge, it has a superior power density.

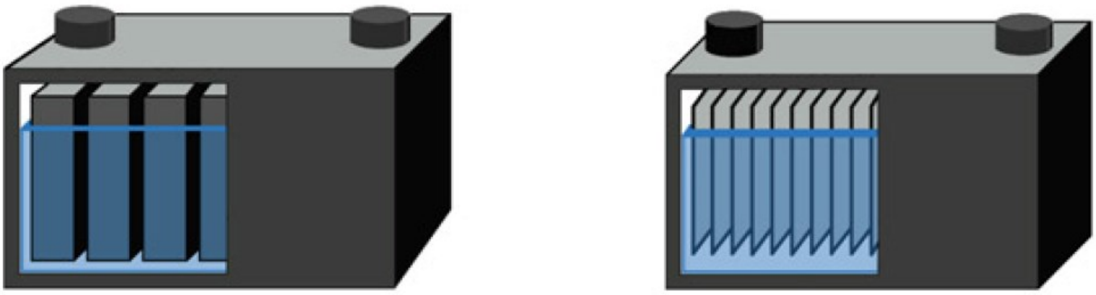

Figure 8: Illustration of traction (left) and starter (right) LA battery (Source: EverExceed Industrial Co., Ltd)

- **FLOODED LEAD-ACID (FLA) BATTERIES**

The term flooded is used because the *electrodes* are *completely immersed* in the *electrolyte*. When charging the FLA battery, the electrolyte level must always be above the electrodes to avoid damage to the cell. This requires regular replenishment of the cells with distilled water, since electrolysis (water splits into ions that escape the cell as gaseous H_2 and O_2) occurs when the battery is recharged.

- **VALVE REGULATED LEAD-ACID (VRLA) BATTERIES**

These batteries were developed to *eliminate the need for distilled water replenishment* and allowing the lead-acid cell to be used in *any orientation*. They were designed in such a way that during charging, the oxygen produced at the positive electrode is reduced back to water at the negative electrode. This process largely compensates for water loss. However, the process is not an ideal process, which means that the *surplus* of oxygen and hydrogen must be *ventilated*. That is why a pressure control valve is provided. The sealed design of the VRLA battery reduces many environmental health and safety risks such as acid spillage and release of acid fumes (Enos, 2015).

Despite the limitations, FLA batteries are still widely used for reserve power applications. This because the dense packing of the VRLA batteries causes a need for careful thermal control and additional requirements when charging (Enos, 2015). VRLA batteries on the other hand find their application in more environment friendly and maintenance free systems. An overview of different projects where Lead-acid batteries were used for medium- and large-scale energy storage can be found in (Enos, 2015).

NICKEL-CADMIUM (NI-CD) BATTERIES

Ni-Cd batteries have been available since 1980 with their first application in aerospace because of their high energy density and long lifetime. The negative electrode is made of Cd/Cd $(OH)_2$, the positive electrode of OH/Ni(O)(OH) and KOH servers as an electrolyte.

This battery differs from the lead-acid battery because of its *longer life* and the *greatly increased energy density*. Due to these advantages, the Ni-Cd battery was widely used in power applications, portable devices, mobile phones, generator starting, emergency light and in UPS systems (Khan, et al., 2019).

However, compared to lead-acid batteries, Ni-Cd batteries have a higher cost per kWh and a reduced cycle life. Another drawback is the toxicity of nickel and cadmium. These drawbacks have reduced the popularity of the Ni-Cd battery, in favor of the Nickel-metal hydride batteries (NiMH) battery (Krishan & Suhag, 2019). Advantages and disadvantages of the Ni-Cd battery are listed in Table 7. Their properties are summarized in Table 10.

Table 7: Advantages and disadvantages of Ni-Cd batteries (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ High energy density ➢ Long life span ➢ Low maintenance required ➢ High power density	➢ High costs ➢ High self-discharge ➢ Complicated battery management system required ➢ Low cycle efficiency ➢ Not environmentally friendly

LITHIUM-ION BATTERIES

Lithium-ion batteries are mainly found in the transportation sector (electric mobility), mobile applications (GSM, laptop, etc.) and the medical sector. However, they can also serve as stationary storage, for example as home batteries. Lithium-ion batteries are characterized by a high energy density, making them more compact than lead acid batteries.

Main drawbacks are the high investment costs and the sensitivity to high temperatures. The battery can ignite if overheated due to overcharging or if the battery case leaks.

Lithium-ion batteries exist in different chemical compositions, most often in combination with cobalt, nickel and manganese or lithium iron phosphate (LFP) in the cathode. A more elaborate description of both technologies is given in chapter *Lithium-ion cells with NMC or LFP in the cathode*. In Table 8 some (dis)advantages are presented. Properties are summarized in Table 10.

Table 8: Advantages and disadvantages of Li-ion batteries (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Very high energy density ➢ High cycle lifetime ➢ Low maintenance required ➢ High cycle efficiency	➢ Expensive to manufacture ➢ Safety issues leading to more complex management systems and environmental controls

SALT WATER BATTERIES

Salt water is a relatively new technology in the medium capacity range. It is the *safest and most environmentally friendly* way to store electrical energy, since saltwater batteries are non-toxic, non-flammable, non-explosive, safe to touch and completely maintenance-free (Park, et al., 2016). They are particularly suitable for durable stationary applications such as residential houses, commercial storage installations or grid independent stand-alone solutions. Unlike lead-acid and lithium batteries, deep discharging does not affect their battery life.

The biggest drawback is their low energy density. Another major drawback is the low discharge capacity. If you nevertheless discharge the salt water battery at high power, this will be at the expense of the available capacity. For private individuals, the availability of salt water batteries is still quite limited. Nevertheless, there are already some suppliers that offer this environmentally friendly battery.

Table 9: Advantages and disadvantages of salt water batteries (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Safe ➢ Environmentally friendly	➢ Low energy density ➢ Low power density ➢ Low efficiency

FLOW BATTERIES

Flow batteries are rechargeable batteries where the energy is stored in two soluble liquid electrolytes (catholyte and anolyte). These electrolytes are stored in two externally separable tanks, as shown in Figure 9. When the electrolytes are pumped through the electrochemical cells the chemical energy is converted into electrical energy.

Energy and power density are independent for flow batteries: the *energy density* of the flow battery is determined by the size of the tanks, while the *power density* is determined by the design of the electrochemical cell. This allows for a flexible power/energy combination, and is a large advantage compared to solid state batteries.

We distinguish two types of flow batteries:

1. **reduction oxidation (redox) flow batteries**: these batteries have all of the electroactive materials dissolved in a liquid electrolyte.
2. **hybrid flow batteries**: these batteries have one or more solid electroactive component deposited on the electrode.

The three most important types of flow batteries for electrical power applications are vanadium redox (VRB), zinc bromine (ZnBr) and poly sulfide bromine (PSB). Their properties are summarized in Table 10. Advantages and disadvantages for BESS are listed in Table 11.

Table 10: General properties of BESS (Krishan & Suhag, 2019)

Technology	Specific Energy [Wh/kg]	Specific Power [W/kg]	Lifetime: Number of cycles	Round Trip Efficiency [%]	Energy cost [€/kWh]
LA	50-75	150-300	1000-2000	75-80	240-960
Ni-Cd	60-90	150-230	3000-4000	60-65	1200-2000
Li-ion	100-200	1000-2000	1000-1500	85-95	560-2000
VRB	35-60	75-150	>15000	75-85	800-12000
ZnBr	75-85	90-110	2000-3500	65-75	560-2000
PSB	15-30	-	15000-20000	65-75	560-2000

Table 11: General advantages and disadvantages of BESS (Krishan & Suhag, 2019)

Advantages	Disadvantages
➢ Very portable ➢ Fast response time ➢ Flexibility in operation ➢ Flow BESS has almost unlimited lifetime	➢ Some batteries are not environmentally friendly ➢ Safety and health issues ➢ Suffer from memory effect

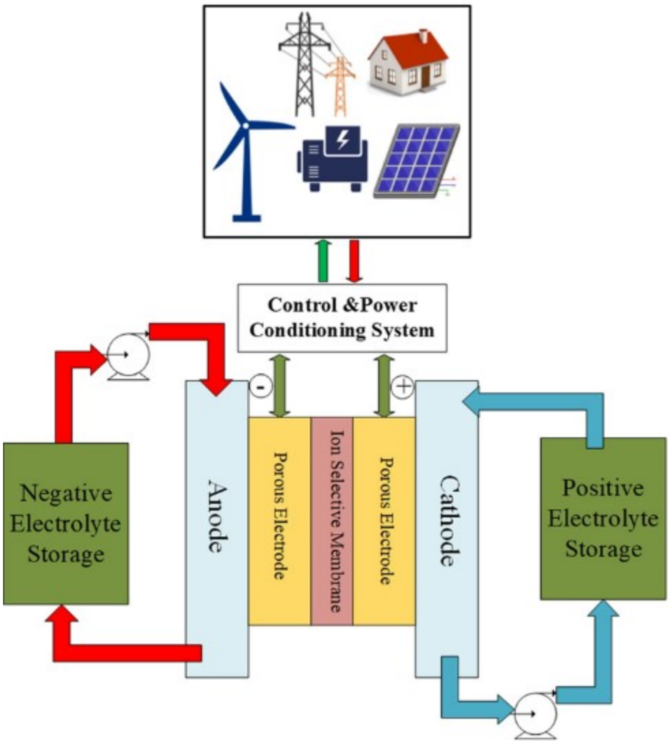

Figure 9: Flow batteries (Krishan & Suhag, 2019)

2.5 Guidelines for the selection of storage technologies

The properties of the technologies discussed in the previous sections are summarized in Table 12, whose information may be visualized in many different ways. Four different representations are shown in Figure 10. These figures already give a **first idea about a suitable technology for a certain application**. For example, if an application requires large power output, it is clear form Figure 10 a) that SMES is probably the most economic choice, since SMES has the lowest cost per kW. However, if this application would require both large power output and high energy storage, thermal energy storage (TES) (which was not discussed in this report) seems more suited, since it minimalizes both cost per kWh and kW. Another example: if an application requires long-time storage Figure 10 d) clarifies that hydrogen storage is the most suited solution.

Table 12: Comparison of technical and economical characteristics of ESSs (Krishan & Suhag, 2019)

Technology	Power Rating [MW]	Discharge duration	Response Time	Specific Power [W/kg]	Specific Energy [Wh/kg]	Cyle efficiency [%]	Lifetime: Number of years	Lifetime: Number of cycles	Power cost [$/kW]	Energy cost [$/kWh]	Technological maturity level (on a scale from 1 to 5)	Influence on the environment
FES	0-1	s-15 min	<ms	400-500	10-30	80-99	20	10^5-10^7	250-350	1000-5000	4	Negligible
Fuel cell	0-50	s-24h	<1s	5-500	800 -10 000	20-50	5-15	20 000	10 000	-	2	Small
SMES	0.001-5	s	ms	500-2000	3-25	85-99	20+	10^5-10^7	1000-10 000	1000-10000	3	Benign
SES	0.001-1	s	ms	2000-5000	3-5	97+	20+	10^5-10^7	100-300	500-1000	3	Small
BESS	0-50	s-h	s	0-5000	15-200	60-95	3-20	1000-20000	300-2500	10-1500	4	Negative

The **most appropriate storage solutions for various applications** are presented in Table 13.

In Table 13 the following symbols are used:

- ● signifies recommended/most often used in practice
- ◑ signifies less recommended/less used in practice, research is needed
- ○ signifies not recommended/almost never used in practice

Table 13: Appropriate technologies for most common storage applications (Pierie & van Someren, 2015)

	Frequency control	Hourly regulation	Daily regulation	Seasonal regulation	Decongestion transmission & distribution networks	Black start	Off-grid	Peak demand regulation	Self-consumption and self-sufficiency regulation	Tariff based regulation	Reactive power	Un-interruptible power supply	Transport
PHES	●	●	●	○	○	◐	○	◐	○	●	●	○	○
CAES	●	●	●	○	○	◐	○	◐	○	●	◐	○	○
FES	●	○	○	○	○	○	○	○	○	○	●	◐	○
SMES	●	○	○	○	○	○	○	○	○	○	○	●	○
SES	●	○	○	○	○	○	○	○	○	○	○	○	◐
LA BESS	○	●	○	○	◐	●	●	◐	●	○	○	●	●
Li-ion BESS	○	●	○	○	◐	●	●	◐	●	○	○	●	●
VR BESS	○	●	○	○	◐	●	●	●	●	○	○	●	●
HESS	●	●	●	●	●	○	○	◐	○	●	◐	○	◐
TESS (warm water)	○	○	●	●	◐	○	●	○	●	○	○	○	○

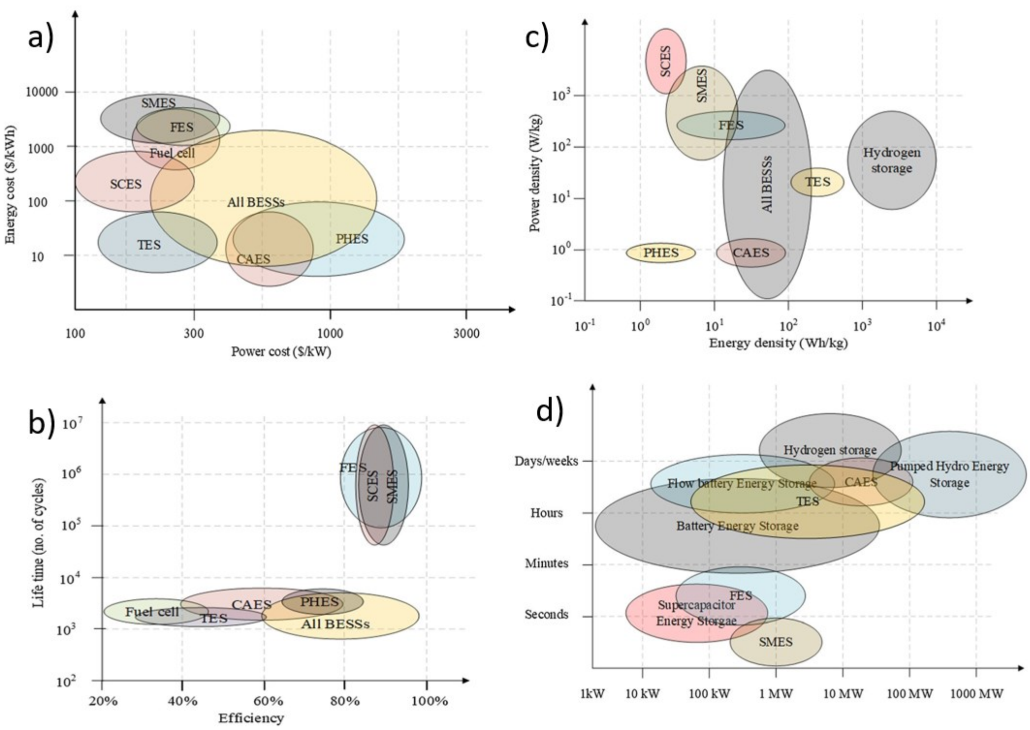

Figure 10: Comparison of technical and economic characteristics of ESSs. a) Energy cost versus power cost, b) life expectancy (no. of cycles) versus efficiency c) power density versus energy density, d) comparison of power rating with discharge time duration (Krishan & Suhag, 2019).

It should be noted that Table 13 gives a general indication but does not consider all details. For example, while low-speed FES is indeed not suited for hourly regulation because of the large self-discharge, high-speed FES has lower self-discharge and may therefore be used to save energy for hours without significant losses. For a more detailed overview with a broader range of applications see (Luo, et al., 2015).

If the requirements for a certain application are more complicated, for example long term-storage, response time and the influence on the environment are both equally important, using "simple" figures won't suffice, and the overview in Table 13 is not specific enough. Therefore, a **broader approach to find a suitable technology for a certain application** is required. A possible strategy is illustrated in Table 14. This strategy consists of three steps.

STEP 1: Draw up a *selection matrix*. In this matrix a score, e.g. on a scale from 1 to 5, based on the parameter values given in Table 12, is given to each criterion (property) for each technology.

STEP 2: Assign a *weight* to each criterion. In order to do this, the question: "*what do I want to do with my storage system?"* is asked as well as an assessment of what is important to the enterprise. In this way, the assigned weights depend on the specific needs of the enterprise. Note that the list of criteria is not exhaustive, additional criteria could be fire safety, environmental impact, occupied surface, etc. Table 14 illustrates only a subset of them.

STEP 3: Finally, the score of each criterion is multiplied with the weight, yielding the final result. The technology with the highest score is the most suited for the specific application.

Table 14: Assigning the appropriate technology to your application.

Criteria (ESS-E)	Specific energy	Specific power	Energy efficiency	Response time	Durability	Cost per kWh	Ease of implementation	Total Point
Criterion weight	20	10	10	10	10	20	20	
Lead acid	4	3	4	4	2	4	5	390
Li-ion	5	4	4	4	3	3	5	410
NaS	5	3	4	4	3	3	2	340
Flow batteries	5	1	5	4	4	3	3	360
HSS	5	2	2	3	3	1	3	280
SC	2	5	5	5	5	2	4	360
SMES	2	5	5	5	5	2	3	340
Flywheel	3	5	4	5	5	2	2	330

STEP 2 STEP 1 STEP 3

3. Applications of energy storage systems

Energy storage technologies find diverse applications in everyday life, from small energetic capacities like mobile phones and watches to high capacities like pumped hydro power plants. This report concerns applications in the capacity range between 5 kWh and 2 MWh. Applications in the aforementioned capacity range can be divided into two main categories, i.e. transportation and stationary. The attempted classification of energy storage applications is oriented towards the market, investor and user perspectives.

Stationary applications of energy storage systems include but are not limited to:

- **households** by increasing the self-consumption of mainly solar generated electricity
- **industrial and commercial** by increasing the self-consumption of electricity generation, buffering fast charging of electric vehicles, peak shifting, integrating uninterruptible power supplies for sensible applications like datacenters and hospitals
- **utilities** by offering grid services

Transportation applications of energy storage systems can be further segmented in:

- **private transportation**, e.g. private cars
- **short range public transportation**, e.g. buses in the city center
- **commercial vehicles,** e.g. trucks and vans
- **marine**, e.g. boats and vessels

3.1 Households

Dr. Martin Knipper, House of Energy e. V.

The main home storage application is a solar storage system. These systems for storing electricity are typically used to store energy from locally installed PV to increase self-consumption of the installed PV-system. Lithium-ion batteries are predominantly used today due to their high energy density. Due to the higher energy density, lithium-ion solar storage systems require significantly less space than the lead-acid or lead-gel storage systems used before. In addition, lithium-ion technology has the advantage that it is less maintenance-intensive. One of the disadvantages of lithium-ion technology is the sensitivity to deep discharge and also to overvoltage.

For a solar storage system to store and deliver electricity, depending on the technology, it consists of a battery management system (BMS) that controls loading and unloading in addition to the large battery packs. For lithium-ion batteries a BMS is necessary. A charge regulator optimizes the charging of the batteries. A battery inverter converts the voltage so that the energy can be used in the household. The energy management system (EMS) optimizes storage operations depending on the dynamic energy balance in the household. Similar to the battery status display on a smartphone, the solar storage system also requires a monitoring system with a screen and graphics that show the battery status and charge level.

Solar storage systems are available in different topologies (BVES, 2019):

- **AC-coupled** solar storage systems as illustrated in Figure 11 on the left: These systems have their own battery inverter and are connected to the house network. An electric meter shows when electricity is used and when it is stored. AC solar storage systems are often used to retrofit PV systems. There is no change in the PV system needed. The electricity goes into direct use or the grid feed-in (PV2AC). The battery is charged (AC2BAT) and discharged (BAT2AC) from/into AC.
- Solar storage system with **hybrid inverter** as shown in Figure 11 in the middle: These solar storage systems are connected directly to the PV system. They draw electricity from the system and pass it on to the desired consumer when required. The integrated inverter regulates the power supply via the PV system as well as the power consumption (BAT2PV and PV2AC or direct PV2AC).
- **DC-coupled** electricity storage as depicted in Figure 11 on the right: These solar storage systems are connected to the DC side of the PV MPP-Tracker (PV2BAT). One advantage over hybrid inverter systems is, that these systems can also be retrofitted if the inverter does not facilitate this. The PV system (PV2AC) then supplies the direct current, which is converted directly via an inverter. It is also possible to use the stored energy via a converter and an inverter (BAT2AC).
- **DC / AC system** as featured in Figure 11 on the right: There are now DC-coupled systems that can charge the battery not only on the DC side, but also on the AC side (AC2BAT). This means that they can be used more flexibly than AC systems, but in principle they can also offer the advantages of DC systems with appropriate interconnection.

Ideally, the energy storage will last for many years. In addition to longevity, there are other criteria that are decisive when choosing a solar energy storage system for a private home. Basically, the storage should of course be large enough to supply the household with electricity for some hours - i.e. during the time when the sun is not shining and solar power is not available for direct use. It also should be able to increase the self-consumption of the PV generated electricity. Typically, the capacity of batteries for solar home systems is in the range from 5 kWh to 15 kWh and the trend is to go higher in capacity. Freeware calculators helping private users to optimal size the battery storage depending on the installed PV power and the personal framework are widespread.

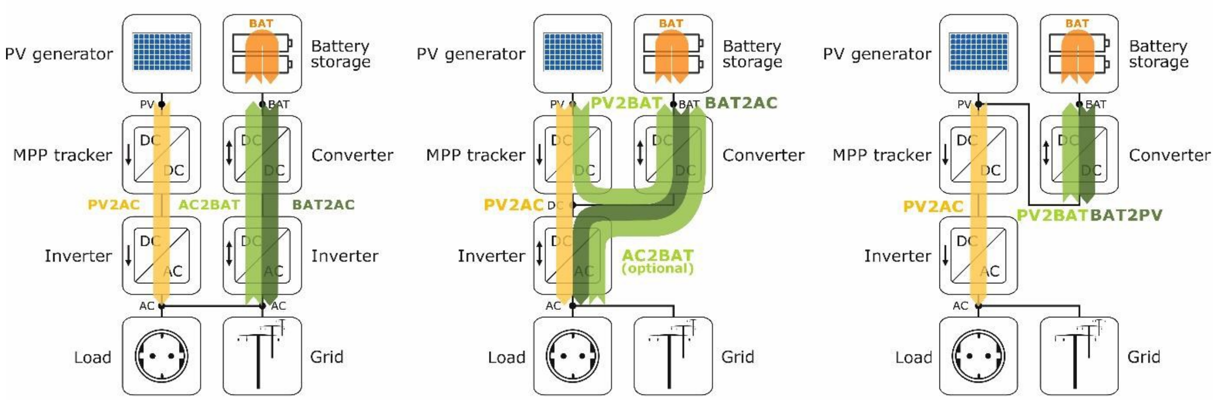

Figure 11: Energy conversion pathways of the individual topologies of PV storage systems.
(Source: Hochschule für Technik und Wirtschaft Berlin)

3.2 Industrial and commercial

Panagiotis Mouratidis, Technical University of Darmstadt

Commercial and industrial energy storage installations vary in uses and magnitudes depending on the enterprise size. According to a combined database maintained by Forschungszentrum Jülich and RWTH Aachen University, the majority of industrial and commercial projects in Germany lie between 10 kWh and 100 kWh (Figgener, et al., 2020). The projects registered in the database mainly target to **increase the self-consumption of electricity generation** and **offer buffer for fast vehicle charging**.

The terms **peak shaving or peak shifting** imply the limitation of the maximum power consumption of an installation by moving electricity load from peak to off peak hours. Consumers being able to flexibly schedule their activities could apply peak shifting. Rather industries can schedule their production plan for peak shifting than home installations, where consumer needs are spontaneous. Besides rescheduling production plans, energy storage facilitates peak shifting with only minor changes in the production activities. The incentives for industries to apply peak shifting strongly depend on the pricing rewards received. Since pricing policies may vary significantly between different energy suppliers, it is not easy to quantify the cost savings that industries potentially achieve by applying peak shaving.

Uninterruptible Power Supply (UPS) is also included in this report inside the category of industrial storage. Datacenters are nowadays in high demand to support the digitization of many means of today's activities. Consequently, there is an increased need for storage systems to supply the interruptions sensitive electronic devices of datacenters. Usually uninterruptible power supplies are only used in case of power failure and not to offer additional services. Sometimes the UPS should only bridge the time until an auxiliary emergency unit, e.g. a diesel generator, starts to bear the load. Since storage systems for UPSs are not meant to be actively used but stay in standby modus, the desired properties comprise low self-discharge, low calendrical aging as well as low failure risks.

3.3 Utilities

Panagiotis Mouratidis, Technical University of Darmstadt

Generally, utilities may store surplus energy generated by power units that also belong to them. In this way, utilities can take advantage of the flexibility arising from energy storage systems and offer energy during peak hours, which is better rewarded. Moreover, utilities may target at offering grid balancing services to the local transmission system operators according to the European regulation (EC, 2017). The most usually offered balancing service is **Frequency Containment Reserve (FCR)**. Additionally, other kinds of grid services, e.g. those presented in Table 13, may be also offered. A detailed overview of grid services with indications about the arising costs of the appointed storage technologies is given in (IRENA, 2020).

According to the database maintained by the Forschungszentrum Jülich, 59 large-scale storage systems were installed between 2012 and 2018 in the German power grid. In line with the

Forschungszentrum Jülich, energetic capacities higher than 1 MWh and nominal output higher than 1 MW classifies the systems as large scale. The cumulative installed capacity of these projects' in Germany as of 2018 accounts for 0.55 GWh. The applied technology is electrochemical storage with lithium-ion batteries being dominant (Figgener, et al., 2020).

With the aid of a database research regarding the whole EU region, the large-scale energy storage facilities in operation as of 2019 were captured (EC, 2020). A subset of the aforementioned database for the installed capacity of electrochemical storages in northwest Europe is presented in Figure 12. It is obvious that as of 2019 Great Britain and Germany are in the lead of large-scale electrochemical storage installations. That is well reasonable due to their higher population. Worth to be mentioned that as of 2019 about 1.3 GWh and 5 GWh large-scale electrochemical storage projects are projected in Ireland and United Kingdom respectively (EC, 2020). This kind of projects enable the provision of ancillary services to the electricity grid and consequently facilitate a higher penetration of wind power.

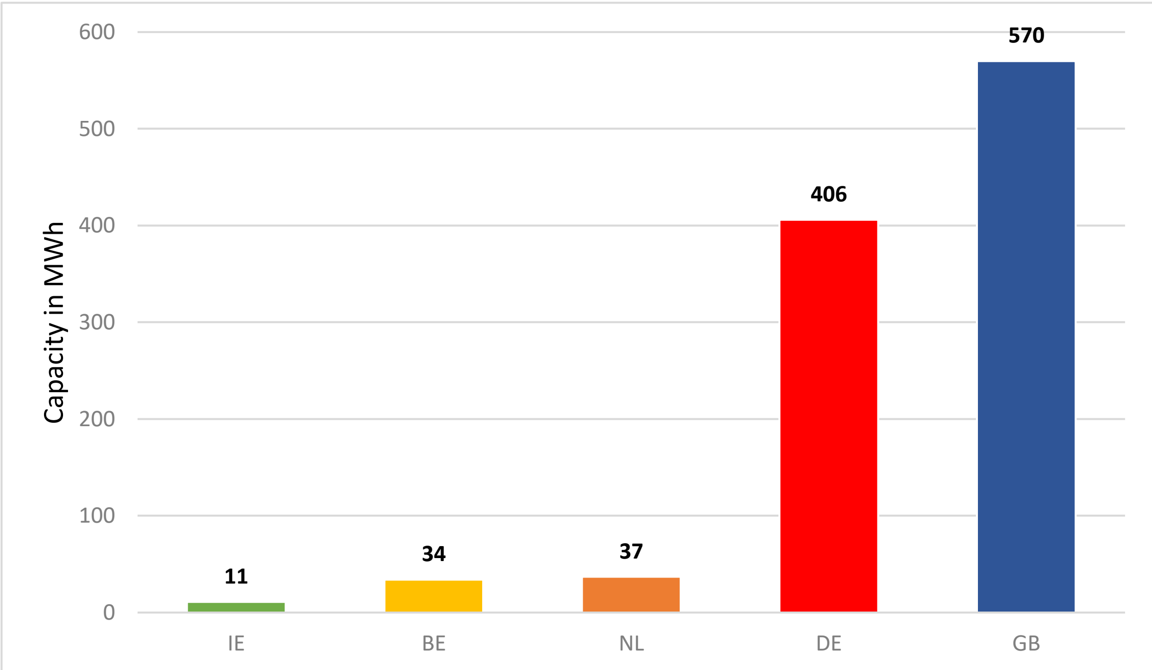

Figure 12: Installed capacity of large-scale electrochemical energy storage units in northwest Europe as of 2019 (EC, 2020)

Although utilities increasingly invest in storage systems, the installed capacity of home storages in Germany turns out to be higher. A database of installed home storage systems is maintained by the RWTH Aachen University. This database gathered the data of the public funded program of the German Federal Ministry for Economic Affairs and Energy (BMWi) for home storages between 2013 and 2018. Using this database as well as other sources, the RWTH Aachen University estimates that as of 2018 about 125,000 households in Germany installed energy storages that correspond to an approximate capacity of 0.93 GWh (Figgener, et al., 2020). Furthermore, according to a study concerning the European residential battery storage market, the installed capacity of households in Germany added up to 1.33 GWh inside 2019 (SolarPower Europe, 2020). In line with the same study the estimated residential battery capacity in United

Kingdom amounts to 0.14 GWh. The high deviation in market breakthrough between Germany and United Kingdom is disproportional to their populations. The different weather conditions, by means of lower solar power generation in United Kingdom, could be the main reason for this fact. It is noteworthy that the varying technology acceptance for battery storage among the populations may play a secondary role to this development. Belgium seems to lag in household storage, according to the Flemish parliament as of 2020, 337 household batteries were registered by the Distribution Network Operator *Flevius* that account for a total capacity of 1.3 MWh (FlemParl, 2021). The Sustainable Energy Authority of Ireland (SEAI) launched from 2018 onwards the so-called Solar Electricity Grant to support the installation of battery storages alongside solar PV panels in households. According to a short communication of SEAI at the time of this report, the grants funded amount to 2688 batteries with an average battery size of 4.3 kW.

3.4 Transportation

Panagiotis Mouratidis, Technical University of Darmstadt

In contrast to stationary applications, transportation is a sector that is always dependent on energy storage. Conventional internal combustion engines use fossil fuels, which are generally classified as chemical storage. Fossil fuels have a high energy content making them ideal for transportation applications, where lightweight design and long range have high importance. However, fossil fuels are not a renewable source of energy and their combustion is one of the main causes of CO_2 emissions.

In order to act upon the climate agreements on the reduction of greenhouse gas emissions, governments and industries plan to increasingly facilitate the use of the so-called carbon-neutral fuels. Carbon-neutral fuels include but are not limited to methane, ammonia and hydrogen. The production of carbon-neutral fuels is meant to be done by the excess of renewable energy generation (P2G) as well as other processes that are not related to greenhouse gas emissions. Carbon-neutral fuels as well as technologies concerning their production and combustion are relevant for future transportation systems.

Electrochemical storage technologies constitute the main fuel alternative for transportation applications. Despite their major drawback of having lower specific energy than fuels, the advances in battery technologies such as in lithium-ion cells, outpaced the development of combustion engines fed by carbon-neutral fuels. Hence, battery driven passenger cars comprise nowadays a considerable market. Battery powered electric buses are increasingly introduced in short range public transportation, already exhibiting air quality improvements in dense urban areas.

PRIVATE TRANSPORTATION

Electromobility has increasingly won ground in the private car market over the last years. Although the prices for pure electric vehicles are still higher in comparison to cars based on conventional combustion engines, a downward trend in prices becomes obvious. The decreasing prices are mainly driven from economies of scale, especially in the production of the energy storage units. Today lithium-ion batteries for electric traction dominate the market in the private car segment. The capacity range of batteries for purely electric cars extends between 20 kWh and 100 kWh, with the higher limit being relevant for premium and thus cost intensive implementations. Up until now, the private car sector seems to be rather reluctant for alternative energy storage systems based on hydrogen or carbon-neutral fuels.

SHORT RANGE PUBLIC TRANSPORTATION

Electric buses are nowadays increasingly observed in busy city centers of metropolitan regions. Following the technological developments in the private car segment, electric buses in short range public transportation mainly use lithium-ion batteries. The capacity range for pure electric buses vary significantly depending on the charging strategy. Buses designed for overnight charging have the highest capacity needs, whereas buses targeted at end-terminus or opportunity charging exhibit significantly lower battery capacities. Considering that, the capacity range may extend from 50 kWh for small buses to 400 kWh for large articulated buses.

COMMERCIAL VEHICLES

The electrifications of light duty vehicles like small trucks and vans for urban deliveries seem to develop faster than heavy duty vehicles targeted at long distance deliveries. The reason is simple: long distances require larger energy storage units and additional charging stations along the route. Charging facilities and carbon-neutral fuel filling networks for heavy duty vehicles are in most areas, including northwest Europe, still underdeveloped. Additionally, the specific energy of diesel alternative technologies is still comparatively low, increasing the total cost of ownership of long-distance heavy-duty vehicles. In contrast, short range, frequently stopping and depot-based charging makes the total cost of ownership of fully electric light-duty commercial vehicles attractive in comparison to conventional diesel-based vehicles.

Battery-based commercial vehicles exhibit low noise and zero CO_2 emissions, which turns to be advantageous for inner-city areas. In case of regulatory changes for the inner-city traffic towards low emissions, purely electric vehicles would certainly be favored by several means. Most of the established commercial vehicle manufacturers are already well prepared and adapted their powertrains for the forthcoming electrification. However, the market is still reluctant to replace the diesel-based commercial vehicle fleets and is likely waiting for further cost reductions, which are mainly expected in the energy storage technology part of the vehicles.

Delivery vans are vehicles used for post and courier services. This kind of vehicles carry moderate load and start-stop frequently in city centers to deliver mail and packages. The short range and low power needs of delivery vehicles makes a purely electrical implementation based on battery storage expedient. An application example is the company *Deutsche Post AG*, the largest German package delivery enterprise, which managed to produce its own vehicle intended for mail delivery through the acquisition of the enterprise *StreetScooter GmbH* (Kampker, et al., 2017). According to the German *Federal Motor Transport Authority* 10,000 pure electric vehicles manufactured by StreetScooter were registered by 2019. The main model of StreetScooter named *Work* exhibits a peak power of 68 kW and can be configured with 20 kWh or 40 kWh lithium-ion battery modules.

The electrification of commercial vehicles is ongoing in the Netherlands. A promising use case arises in food deliveries, the Netherlands' largest supermarket *Albert Heijn* plans to deliver more of its groceries with electric vans. According to a press release of the German manufacturer *ORTEN Electric-Trucks GmbH*, the supermarket plans to convert 25 of the existing 400 VW-Craftern from diesel to electric. The converted pure electric vehicles should carry a useful load of 1300 kg and enable a range of 130 km. Since 2019 the consumer electronic oriented Dutch online store *CoolBlue* delivers, according to its own statement, 80% of all the TVs ordered in Rotterdam and Amsterdam in pure electric vans and plans to expand this service to Belgium. Furthermore, the Dutch Postal service *PostNL* set the goal in its annual report to improve its CO_2 efficiency from 249 g/km into 205 g/km inside 2021 and reach 45 g/km until 2030. Among other measures these goals are to be met through the introduction of renewable fuels and scaling up the share of electric vehicles in its fleet (PostNL, 2021).

Plans to replace commercial fleets with electrified vehicles exist also in other countries. According to the Belgian authorities, starting in 2026 onwards, all new registered commercial vehicles like take-home and leasing vehicles should be emission free (FedRegBE, 2020). The Irish authorities established the Low Emission Vehicle (LEV) task force to look for the range of measures available to accelerate the take-up of low carbon technologies in the transport sector. Among other recommendations, the task force concluded that the establishment of a purchase grant for commercial vehicles powered by batteries and alternative fuels is expedient (LEV, 2019). Similar measures are also planned by other countries worldwide (SLOCAT, 2020). The annual report of the non-profit organization *The Climate Group*, which provides up to date information about the ongoing electrification of commercial fleets, is worth to be mentioned here (EV100, 2021).

MARINE BOATS AND VESSELS

The shipping industry is already looking upon fossil fuel alternatives (DNV GL, 2019). Pure battery driven vessels are currently feasible only for small-scale implementations, like ferries and boats. However, the hybridization of chemical and electrochemical storage exhibits the advantage that the battery system can stay active at low load, whereas the combustion engine mainly covers the marine propulsion. Nevertheless, according to a recent analysis, the costs of carbon-neutral-based propulsion systems are still higher than diesel-based systems (NOW GmbH, 2019).

The large amount of energy as well as the high power needed for long distance freight shipping enforces the use of fuels. As already mentioned, electrochemical storage technologies are still far from reaching the energy density requirements for long distance marine applications. Considering the so-called well-to-propeller unitization path, hydrogen exhibits a lower energy expenditure than other carbon-neutral fuels (NOW GmbH, 2019). However, hydrogen comes at the cost of additional installation space for the fuel tank, which greatly limits its application range.

4. Technological developments

The increasing demand for energy storage solutions triggered lots of technological innovations the last years. Improvements on energy density, lifetime, efficiency etc. are constantly announced in the scientific and technical community. Over the course of time, established energy technologies turn to be inefficient compared to novel technologies and therefore seek for upgrades. Technological developments also concern complementary technologies to energy storage such as electronics for the monitoring system as well as energy management algorithms.

4.1 Lithium-ion cells with NMC or LFP in the cathode

Dr. Peter Eckerle, StoREgio e. V.

Lithium-ion batteries exist in different chemical compositions, usually classified by the active cathode material. The typical structure of a lithium-ion cell including a short annotation of the commonly used materials can be seen in Figure 13. Among the various types of cathode materials, the so-called Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP) claim the largest market share.

The properties of NMC and LFP based batteries are intensively discussed with respect to performance and safety. Despite some intrinsic technical differences between the two systems, it is important to note, that the overall performance and safety of a lithium-ion battery is additionally determined by the quality of the manufacturing and assembly process as well as active and passive safety mechanisms. The electrolyte used in both systems is largely the same and responsible for most safety issues.

NMC and LFP materials crystallize in different structures. This leads to a theoretical difference in the volume-density of lithium-ions embedded in these structures. The lithium-ion density in NMC materials is about 60% higher than in LFP materials. Additionally, open circuit voltage of NMC is slightly higher than that of LFP, i.e. 3.7 V against 3.4 V, both against graphite (Korthauer,

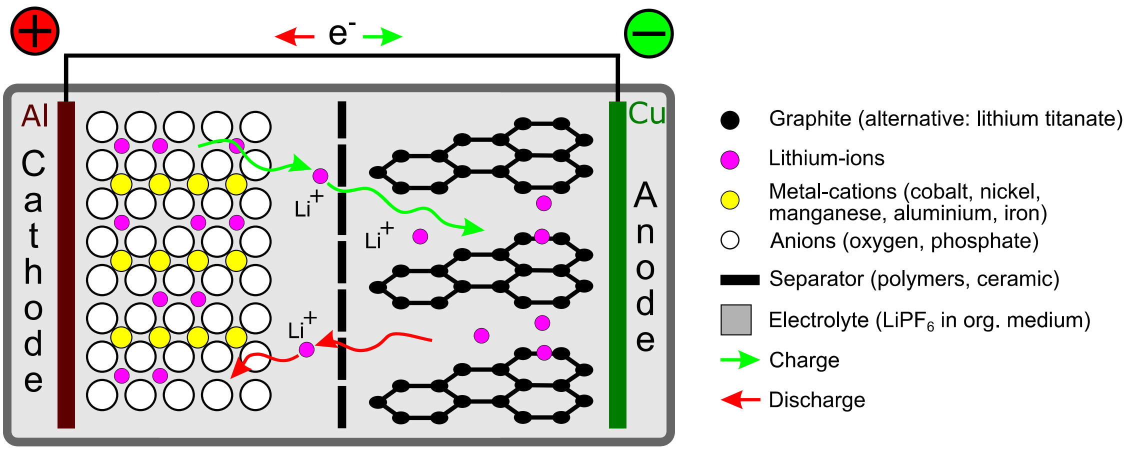

Figure 13: Schematic of a lithium-ion cell structure; cathode, anode and electrolyte materials vary depending on the applied chemistry. (Source: *schematic of* a *lithium-ion cell structure with $LiCoO_2$ anode and Li-graphite cathode*, licensed under CC BY-SA 2.0 de, modified by StoREgio)

2013). This leads to a theoretical energy density of NMC cells of about 1000 Wh/kg, compared to 580 Wh/kg for LFP. However, in order to avoid misleading information, these values are to be comprehended as theoretical limits, which are not met in practical cell implementations today.

Other effects, however, decrease the usable difference in energy density of the two systems. NMC materials show a significantly higher volume change during the charging/discharging process (i.e. the transport of Li-ions embedded in the material) than LFP. This mechanical stress can lead to microcracks and hotspots within the cathode material. In order to limit the mechanical stress, usually only about two thirds of the lithium-ion content of an NMC cell is used, decreasing the energy density.

Oxide cathode materials such as NMC tend to decompose at high current densities and SOC values, releasing oxygen. In order to limit this effect. charging rates are decreased at higher SOC values.

LFP, in contrast, shows an intrinsically lower electrical and lithium-ion conductivity than NMC. Using nano-scaled LFP particles and adding carbon black to increase electrical conductivity improves the properties of LFP cells and leads to a usable energy density close to that of NMC (Korthauer, 2013).

Summarizing, NMC still shows a higher energy density compared to LFP, while LFP can tolerate higher charging/discharging rates than NMC. Both systems are intrinsically flammable and would release toxic substances in case of fire. While LFP exhibits a higher chemical stability than NMC at high SOC and charging rates, this advantage can be compensated in case of NMC by the battery management system leading – in both cases – to battery systems with a high degree of safety when manufactured well.

4.2 State of Charge and State of Health estimation for lithium-ion batteries

Seyedreza Azizighalehsari, University of Twente

Because of the vital role of the battery in energy storage applications, it is important to give special attention to the battery pack which acts as the heart of the energy storage system. Nowadays, lithium-ion batteries are the most promising technology as energy storage systems and the closest to commercial use, in order to satisfy the quickly growing request of the market. Unfortunately, there is a lot of shortcomings in this technology: these batteries are the most expensive and sometimes the weakest part of the system. For example, in the solar system the overall lifetime of the product is relatively short due to the relatively low number of cycles per battery which defines the weakest part of the product components while solar panels can live up to 10-20 years. For this reason, using the proper procedure to evaluate the battery lifetime is a big challenge and as lithium ion batteries become mainstream, a standardized testing method that can reveal battery capacity and long-term health is essential.

The key characteristics of a battery are the specific energy, specific power, durability, safety and cost. The specific energy for lithium-ion batteries is mostly dependent on the used cathode and anode materials. Available commercial Li-ion batteries according to Table 10 cover a wide range of specific energy from 100 up to 200 Wh/kg. All Li-ion batteries remain far above the modest specific energy of lead-acid batteries, which is typically around 50 Wh/kg. The specific energy is one of the central development criteria in Li-ion batteries for use in electric vehicles as part of the approach to increase the driving range. This has resulted in a general upwards tendency to use these batteries. Figure 14 illustrates a comparison between various energy storage systems demonstrating that lithium ion cells have higher specific power and energy.

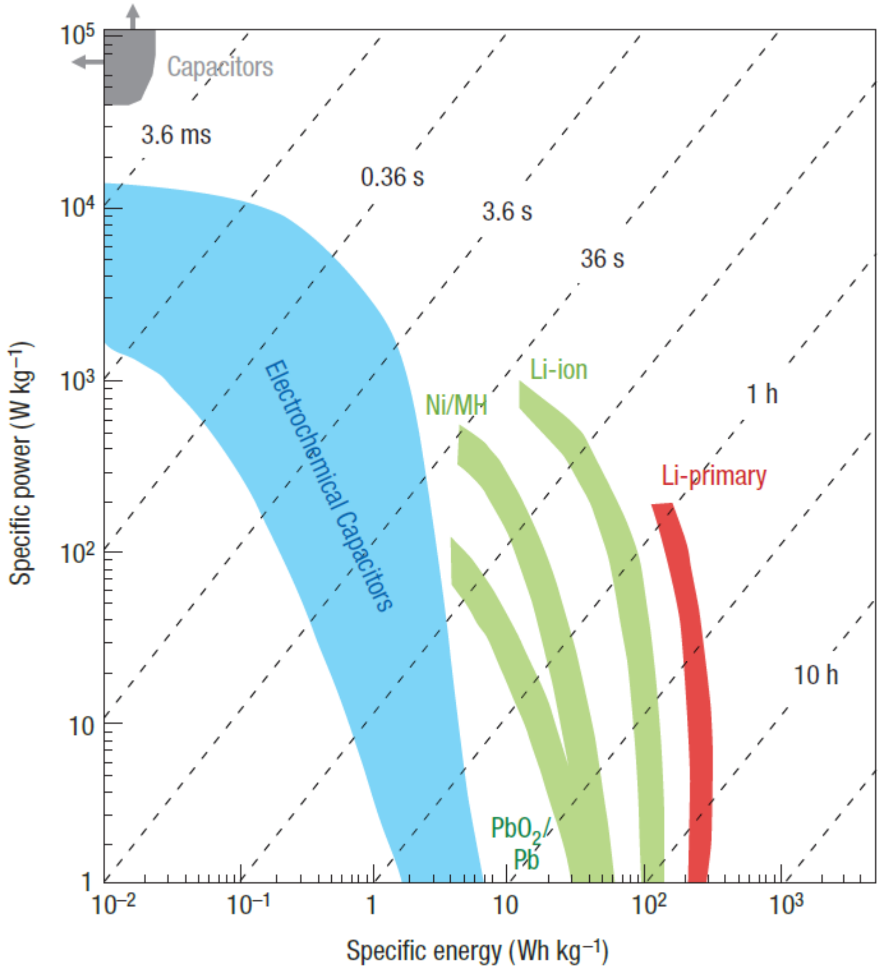

Figure 14: Ragone plot to compare various energy storage systems with time constants by division of energy density with power density (Simon & Gogotsi, 2008)

Some advantages that increase the market tendency to use lithium-ion batteries are their high specific energy, high specific power, low self-discharge rate, no memory effect and the ability to drain high current for high power application. This type of batteries is the most favorable for different electric vehicles and recently their utilization in green energy and industry is growing.

A detailed understanding of the ageing mechanisms of a battery chemistry paves the way for advanced battery designs with longer cycle life. Thereby, improvements could take place both on the cell and BMS (Battery Management System) level. Li-ion batteries have improved notably in terms of durability and there is a widely held expectation that this tendency will continue. An interesting overview of Li-ion cells used in the automotive sector can be found in (Wang, et al., 2016).

To guarantee a safe and reliable operating condition for a battery pack each pack must be tailored with a Battery Management System (BMS). BMS can protect the battery pack against abnormal situation also by controlling the charge and discharge cycle and in that way, increase the battery durability. The main functions of a BMS are cell and pack monitoring, charge and discharge control, cell balancing, thermal management, cell and pack protection, and battery state estimation.

Battery State of Charge (SOC) and State of Health (SOH) because of their importance in battery performance are two key states that should be estimated in BMS. SOC is a quantity that describes the stored charge capability of the battery and SOH is a quantity describing the aging level of the battery. Unfortunately, battery SOC and SOH cannot be measured directly and for each battery pack, these parameters should be accurately estimated. The accuracy in SOC estimation is important to make the best effective use of the battery system by protecting the battery from over-charge or high DOD enhancing battery lifetime and safety. Also, SOH is an indication that illustrates the battery capability to store energy as a result of battery degradation during over time. There is no general agreement about the exact definition of the SOH but it can be defined as a comparison between the battery capability at the start of its life and the current situation.

Due to the battery performance decrement during the battery lifetime a battery diagnostic and prognostic system should be considered to enhance the effective use of the battery system. SOC and SOH are two important parameters in battery diagnostics and battery lifetime expectation so that the remaining useful life of the battery (RUL) can be investigated in battery prognostics.

The directly measurable parameters that can be employed for SOC and SOH estimation are battery terminal voltage, cell current, and temperature, etc. An overly optimistic or pessimistic estimation can set the battery in abusive operating condition. To use the battery in a good safety level with high reliability an accurate estimation of battery SOC and SOH is necessary. A key issue for both SOC and SOH estimation is nonlinearity and time varying nature. It is almost unfeasible to perceive the battery's chemical process and its performance that is really dependent on the dynamic battery operation conditions (Rezvanizaniani, et al., 2014). Even a simple charging/discharging cycle of the battery depends on the battery operation condition. As a consequence, it is obvious that the estimation of the battery states like SOC and SOH are challenging and so many parameters can have an effect on estimation accuracy.

BATTERY STATE OF CHARGE ESTIMATION

Generally, the percentage of the remaining charge in the battery or the battery SOC is defined as the ratio of the amount of charge extractable from the battery to the total charged stored in the battery. An accurate estimation for battery SOC will prevent the battery from overcharging or high DOD and improve the battery lifetime by reducing the battery ageing effects during the battery operation. In recent years, many researchers from different points of view proposed different methods for battery SOC estimation. As mentioned before, one of the key challenges to accurately estimate the SOC is the inherent nonlinearity of the battery chemistry. In addition, all parameters that affect the battery aging process will affect the SOC estimation. Some of these parameters that can be important in the battery ageing process are temperature (over temperature, under temperature), over voltage, under voltage, over current, under current, etc. Various types of SOC estimation methods have been proposed in literature and most of them employ different battery electrochemical or electrical models by using mathematical and estimation tools. This section gives a brief overview of different battery SOC estimation methods.

In general, the methods that have been used for the estimation can be categorized as direct approaches and indirect approaches. Typical estimation methods measure parameters like battery open-circuit voltage (OCV), current (coulomb counting) or battery impedance, so that the battery SOC can be estimated. These methods are easy to implement and have a low computational effort but unfortunately suffer from low accuracy and cannot be used for batteries with a flat OCV-SOC curve. On the other hand, indirect methods are more complicated and more accurate with a higher computational effort. Indirect methods are categorized in two approaches, model-based methods and machine learning methods. The former approaches can be further divided according to the applied model and the estimation algorithm.

Using the right method completely depends on the battery type and the application that the battery will be used for. Figure 15 illustrates a simple classification of different methods of SOC estimation.

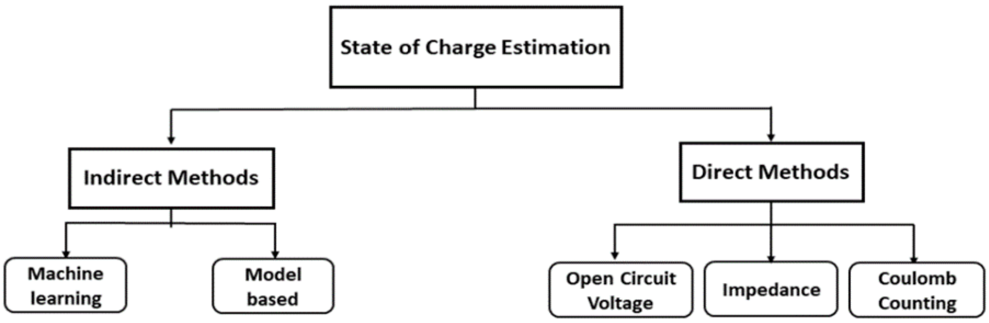

Figure 15: Classification of the different battery SOC estimation approaches

- **DIRECT METHODS**

In these type of battery SOC estimation approaches the battery SOC will be estimated by evaluating one of the battery measurable parameters like voltage, current, impedance, or temperature and then the battery SOC will be estimated according to a relationship that will be considered between these measurable parameters and battery SOC.

○ Open Circuit Voltage Method

There is an approximate relationship between battery SOC and OCV, this relationship can be fitted as a linear function with a good approximation. In this method, the battery OCV will be measured at each SOC. The OCV-SOC relationship can be defined as a linear function. A problem with this method is that the relationship can be different even for the cells with the same material and same fabrication method in the same operation condition as depicted in Figure 16.

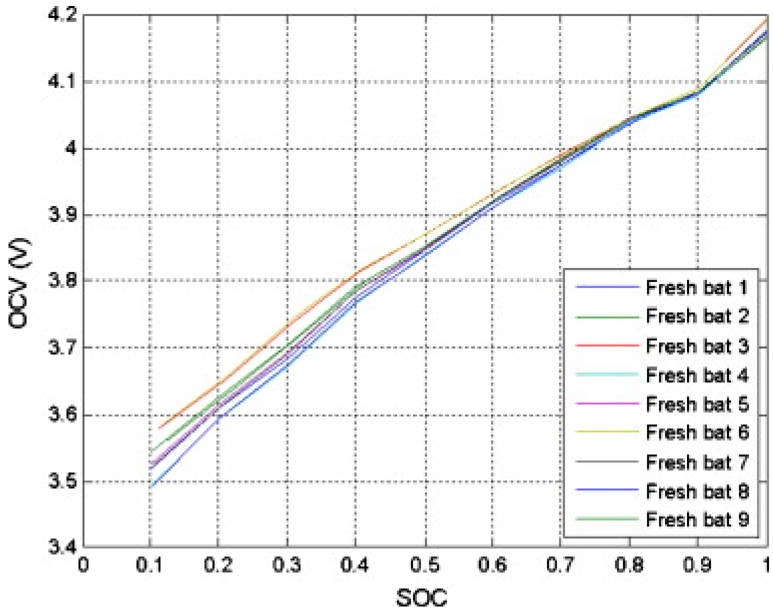

Figure 16: OCV-SOC relationship for nine fresh battery under the same conditions (Lee, et al., 2008)

The accuracy of this method is completely dependent on the measurement accuracy of the OCV and requires a long period of time for the battery to reach its steady state so the battery should be disconnected from the application and usually it takes a long time, so this method cannot be used for onboard applications (Truchot, et al., 2014). Also, for some types of batteries, especially LiFePO4 cells this relationship is almost like a flat curve so a small error in battery OCV measurement will result in a large SOC estimation inaccuracy (Dang, et al., 2017). The OCV-SOC relationship is completely dependent on the battery operation, environment and the battery ageing so for robust and accurate estimation the battery OCV-SOC should be gathered in different temperature and operating conditions.

In general, the open circuit voltage method can be used as a tool for other feasible methods to increase the accuracy. Also, in some approaches, this method is employed to determine the battery parameter to be used in model-based approaches (Nejad, et al., 2015).

○ Impedance Measurement Method

The basis of this method is the change of the battery impedance in relation to the battery SOC, SOH and temperature. This method is more suitable for lead-acid and Nickel Cadmium batteries than for Li-ion batteries, where the battery impedance will not change significantly while charging. This method is not accurate and feasible due to this huge shortcoming in DC internal resistance for Li-ion batteries.

○ Coulomb-counting method

This method is the most common method for battery SOC estimation due to its basic and simple manner for battery SOC estimation. Coulomb- counting or Ampere-hour integral method uses the following equation for SOC value during the time:

$$SOC(t) = SOC(t_0) + \frac{\eta \int_{t_0}^{t_0+t} I(t)dt}{C_N}$$

That *SOC*(*t*) is the value of the SOC at time *t* and $SOC(t_0)$ is the initial value of the SOC, *I*(*t*) is the battery charging/discharging current, C_N is the battery nominal capacity and η is the battery coulombic efficiency. This method has been used in a lot of different applications due to ease of implementation and low computational effort. The estimation accuracy depends on two important factors, $SOC(t_0)$ and the accuracy of the measured charging or discharging current. The initial $SOC(t_0)$ should be known or be estimated and it is necessary to have an estimation for this initial SOC and any small value error in the first SOC estimation directly has a negative impact on the final estimation. Any error in battery current measurement will be accumulated for SOC estimation so especially after a long period of time the estimation will be inaccurate. It is clear that this method needs a tool to calibrate the initial estimated value. Also, according to the nominal capacity that has been employed in the equation there are two important factors that should be considered. The first one is that the battery nominal capacity value is dependent on temperature and the battery discharge current rate (Stefanopoulou & Y. Kim, 2015), C-rate is an important parameter to battery capacity measurement and higher discharge rate will lead to lower capacity and vice versa. The second factor is that the battery nominal capacity is not a fixed value and it will change due to chemical degradation. In consequence, the coulomb-counting method is very efficient regarding computation time and implementation but suffers from inaccuracy. This is the reason why this method normally will be used in combination with another method to increase accuracy (Li, et al., 2019). In Table 15 a brief comparison between the different direct methods for battery SOC estimation is summarized.

Table 15: Comparison of direct SOC estimation methods

Methods	Advantage	Disadvantage
Open Circuit Voltage	The simplest method for SOC estimation, Linear relationship between battery SOC and OCV	Low accuracy, not suitable for batteries with flat OCV-SOC curve, not suitable for onboard SOC estimation
Impedance Measurement	Low complexity	Low accuracy, not suitable for batteries without significant change in their impedance with SOC, not suitable for onboard SOC estimation
Coulomb-Counting	Straightforward implementation, Onboard method	Low accuracy especially after a long period of time, cannot estimate the initial value, needs highly accurate current sensor

- **INDIRECT METHODS**

In these methods, the estimation will be done according to the measurable values like voltage, current and temperature by employing an appropriate and accurate battery model. The main idea in these methods is to set up a relationship between the measurable properties of the battery as an input and the SOC by using a battery model (Li, et al., 2019).

- **MODEL-BASED METHODS**

This type of estimator uses an electrochemical or electrical model combined with algorithms or computer methods that are used to infer or to estimate the hidden and internal states of a dynamic system, which in this case is the battery system. In Figure 17 a schematic of a battery model SOC estimation is shown. The inputs in this model are the battery current and temperature and the true battery measurement output is the battery terminal voltage that changes as a response to the input current and temperature. The basis of this method is that by comparing the measured output voltage and the predicted output voltage of the battery model the difference measured by an observer or filter will go through the model and update the battery model parameter and battery state. By using a high accurate model, the residual voltage will be lower and it will be zero if the battery model parameters be exactly the real battery system parameters. As a result, the estimation accuracy in this method is highly dependent on the battery model.

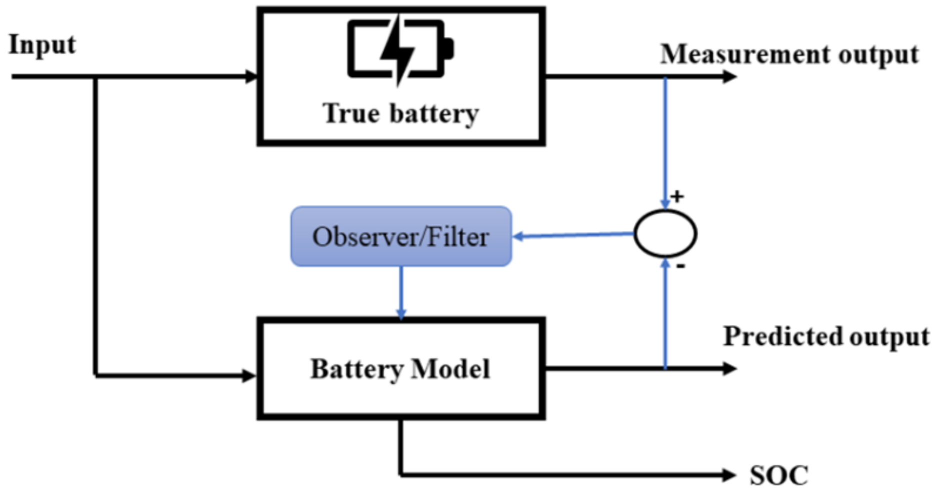

Figure 17: Simple schematic of a model-based SOC estimation method

The electrochemical model can describe the electrochemical reactions inside the lithium-ion battery. This model is comprised of partial differential equations to describe the diffusion, migration, and reaction kinetics inside the battery (He, et al., 2018). The key advantage of electrochemical models used for battery states estimation is the validity of the battery model but considering a full order model increases the battery model complexity and decreases computational efficiency of the method (Xi, et al., 2019).

Electrical circuit models (ECM) are the most prominent type of experimental models for Li-ion batteries. In comparison with battery electrochemical models, electrical circuit models are less complicated and have a very high computational efficiency. Unfortunately, circuit models suffer from accuracy issues under various charge/discharge conditions as well as challenges in considering the temperature reducing estimation accuracy. Several ECMs for Li-ion batteries have been proposed in different research approaches (Plett, 2015).

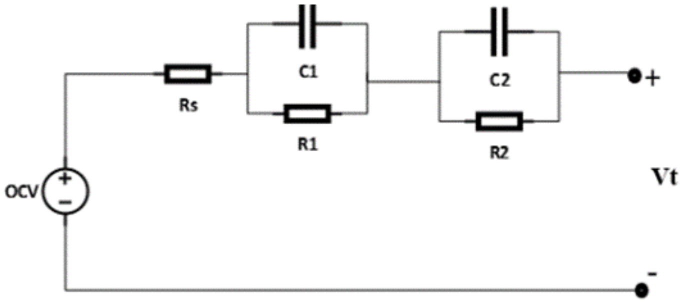

Figure 18: Battery equivalent circuit model

Figure 18 illustrates a second-order ECM. In ECMs there are often three important elements, the OCV, the series resistance *R*s, the internal battery resistance and the *R*C network that models diffusion voltages. As the number of parallel RC networks gets higher it can improve the accuracy of dynamic battery response prediction (Xia, et al., 2016). Considering the battery model known, the so-called Kalman Filter (KF) can be used to estimate its parameters. The Kalman filter is an optimized autoregressive data filtering algorithm that can be used to estimate the inner aspects of any complex dynamic systems according to the concept of minimizing the mean of the square error.

- **MACHINE LEARNING METHODS**

In spite of a lot of research on battery electrochemical model and ECM due to the complex chemical reaction inside the battery, the dynamic behavior of the battery system is intricate and still, there is a shortcoming about physical and chemical knowledge of the battery system.

In this method without any knowledge about the chemistry and physics of the battery and only with the training data, an approximate relationship between input and output of the battery system can be extracted (Chemali, et al., 2018). Recently this method has been used in different applications such Electric Vehicles (EVs) to have an accurate SOC and SOH estimation. With a proper amount of training data and similarity between the training data and the real-world operation conditions of the battery system, this method can be an interesting approach to have a highly accurate estimation. As mentioned, the quality of this method is completely dependent on the training data and the quality and amount of data is critical for this method. As a result, if the battery operation condition is outside of the training data region the result in estimation would not be accurate (Xi, et al., 2019).

Artificial Neural Network (ANN), Support Vector Machine (SVM) and Fuzzy Logic (FL) are the commonly used machine learning methods for SOC estimation. In (Hu, et al., 2019) a Long-Short Term Memory (LSTM) was proposed to estimate SOC of a lithium iron phosphate battery and the result shows a maximum absolute error within 2% to capture the non-linear correlation between SOC and measurable signals. In Table 16 a brief comparison between the different indirect methods for battery SOC estimation is summarized.

Table 16: Comparison of indirect battery SOC estimation methods

Methods	Advantage	Disadvantage
Model based	High accuracy, robust to unknown initial SOC value and measurement noise, suitable for real-time application,	Accuracy completely depends on the battery model, high complexity with electrochemical model
Machine Learning	High accuracy suitable for real-time application,	Accuracy completely depend on the quality and amount of the training data, High complexity and high computational time

BATTERY STATE OF HEALTH ESTIMATION

Battery SOH normally is defined as the battery's maximum capability to store and deliver electrical energy compared with a fresh new battery. Battery SOH is one of the key parameters of a battery and was selected as diagnostic measure that like SOC is not a directly measurable parameter and should be estimated with the help of the measurable battery parameters.

Like SOC estimation, a lot of methods have been proposed for battery SOH estimation. Substantially, battery SOH methods can be categorized in four categories, i.e., physics-based models, empirical models, data-driven methods and Incremental Capacity Analysis (ICA) based methods (Hu, et al., 2019).

Physics-based models comprised of partial differential equations (PDEs) are used to describe the diffusion, migration, and reaction kinetics inside the battery. These models need a comprehensive knowledge about the physics and chemistry of the battery and have a high accuracy regarding battery state estimation. By fitting experimental data gathered under predefined experimental conditions, battery empirical models will be obtained (Waag & Sauer, 2013). As a result, this model completely depends on the experimental data and the accuracy of this model depends on how well the experimental test represents the real battery operation conditions. This means that to have an accurate SOH estimation, a comprehensive ageing test should be conducted under different conditions.

Data-driven methods for battery health estimation are becoming one of the most leading approaches to battery SOH estimation due to the important factor that they do not involve the complex battery physics model in their estimation and flexibility. Like SOC estimation here the methods need a large set of ageing data and the method effectiveness is completely dependent to the amount and quality of the data.

The incremental Capacity Analysis method is a powerful tool for online SOH. This method is based on the differentiation of the battery capacity over the battery voltage, estimation in this method can be easy to implement by monitoring only two parameters, i.e. voltage and charge/discharge capacity (Kalogiannis, et al., 2017).

Three main degradation modes that are considered as the primary causes of battery capacity fade in Li-ion batteries are loss of lithium inventory, loss of active anode material, and loss of active cathode material. The main factors in battery degradation during the battery ageing are, time, high temperature, low temperature, battery charge/discharge current rate, over charge or over voltage, high DOD or under voltage and etc. Table 17 illustrates a comparison between available SOH estimation methods.

Table 17: Comparison of different SOH estimation methods adapted from (Li, et al., 2019; Hu, et al., 2019)

Methods	Advantage	Disadvantage
Physics based models	High accuracy	High complexity, high computational effort
Empirical models	Simple structure, easy implementation	Low accuracy and robustness
Data-driven methods	Model-free approach, good estimation accuracy, applicable in dynamic operation condition	Dependent on the quality and amount of the data, high computational effort
Incremental Capacity Analysis	Usable for batteries of different type, size and chemistry, easy to implement, easy to monitor (only voltage and capacity)	High requirement of voltage and current measurement, sensitive regarding the operation temperature

4.3 Emerging technologies and their technology readiness level

Ian Ellerington, The Faraday Institution

Although well-established energy storage technologies are available, there is still potential for improvements and innovations considering most of the technologies categorized in Figure 1. Technological developments in energy storage systems emerge steadily. Especially chemical and electrochemical storage is intensively researched by plenty of private as well as public funded institutions worldwide. Emerging technologies which are still in validation phase or inadequately long in operation may be classified in the so-called technology readiness levels (TRLs), which are widely used in the space industry (ISO 16290, 2013).

DEVELOPMENTS IN MECHANICAL STORAGE

With the exception of flywheels, innovations in mechanical storage technologies are likely to be at a large scale and outside of the scope of this report although it may be feasible to design compressed air energy storage at a small scale but previous attempts have led to unacceptably low cycle efficiencies and high costs. The innovations required would be in cost effective low capacity machinery, low cost pressure containers and heat management and transfer during the compression and expansion. Investigation has not established any concepts beyond TRL 3.

Flywheel systems are well understood, further developments will likely be in control systems and innovations reducing manufacturing costs. Flywheels are typically well developed and at TRL 7-9.

DEVELOPMENTS IN CHEMICAL (POWER-TO-GAS) STORAGE

The conversion of renewable energies into gas, which can be long-term stored, gained increasing interest from the technical and scientific community the last years. Especially the conversion of electrical energy into hydrogen by means of electrolysis attracted lots of attention, since its reverse conversion to electricity is not connected with CO_2 emissions.

There are a number of different technologies for hydrogen production by electrolysis but most developments are one of three main types:

- Low Temperature Polymer Electrolyte Membrane
- Mid temperature Alkaline Electrolysis 100 °C
- High Temperature Solid Oxide Electrolysis usually operates at 500 °C or higher

All three are available commercially and so TRL9 albeit various new configurations are being developed. The least developed and possibly the most potential for improved performance and high efficiency is the Solid Oxide Electrolyzer.

In summary, for power to gas technologies, electrolyzer technology is typically at TRL 7-9 and there is high interest in Europe both politically and commercially in developing commercial offerings. There may be other approaches to power-gas technologies beyond these types of electrolyzer at early stages of development but these are likely to be for larger scale systems.

DEVELOPMENTS IN ELECTRICAL AND MAGNETIC STORAGE

Energy can be stored in magnetic fields and research is ongoing on into this technology but the author is not aware of any devices close to practical application so it is assessed as TRL 1-3.

Energy storage in electrical fields is a very active area of development with commercial examples of supercapacitors from companies such as Skeleton in Europe and Maxwell in the USA. More recently, hybrids of cells with some of the characteristics of electrochemical cells and some of supercapacitors have been announced. An example is *Shenzhen Toomen New Energy* who are developing a commercial device in partnership with Kurt Energy, a division of Belgian energy research company *Altreonic NV*.

Further details for high-density hybrid power capacitors can be found in the article (Blain, 2020). The TRL level of this technology is difficult to estimate accurately since development is ongoing.

DEVELOPMENTS IN ELECTROCHEMICAL STORAGE

Electrochemical Energy Storage is today the leading contender for small-mid scale energy storage systems and will continue to develop a market position alongside storage of heat and cold to balance electricity supply and demand. Among the commercially available electrochemical storage technologies, lithium-ion cells have attracted many billions of Euros of research effort and there is evidence that this has led to steady increases in energy density and reductions in cost as materials are used more efficiently. The current commercialized cell designs are however within sight of their maximum theoretical limit of performance. Clearly lithium ion-based energy storage is currently being marketed and is TRL 9 but system design and control algorithms for better performance and commercial advantage are still being developed so it would be reasonable to assess these in the range TRL 7-9. An overview of the energy density over the technology maturity level for diverse electrochemical storage technologies is given in Figure 19.

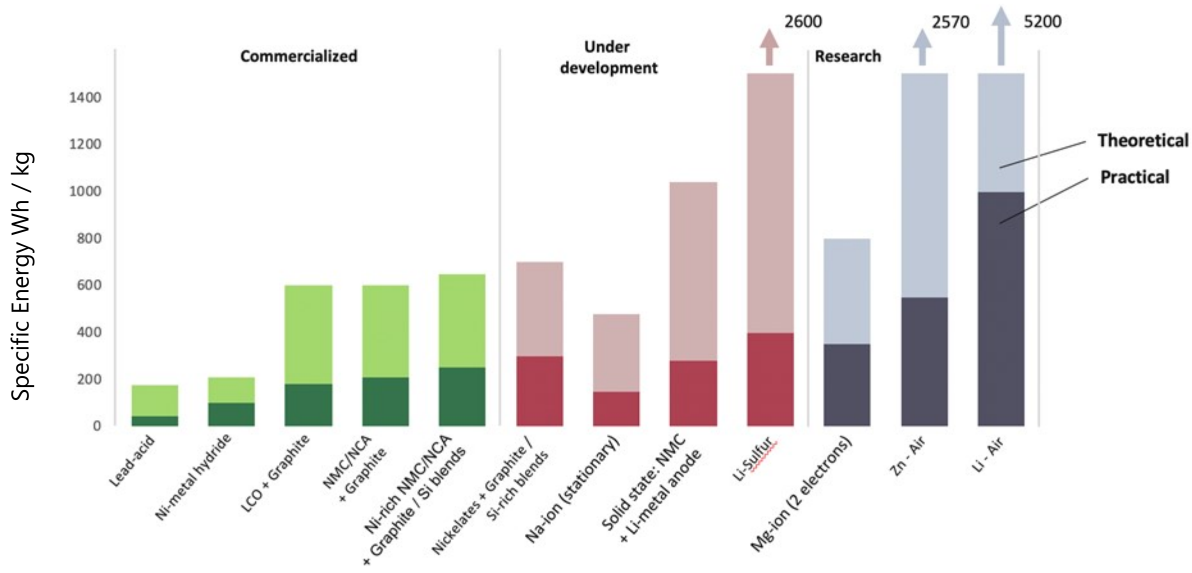

Figure 19: Energy density over technology maturity for various electrochemical storage technologies (Source: Faraday Institution)

As an indication of future developments in lithium-ion technology, Tesla announced during their battery day that they expect performance to double and costs to approximately half in the foreseeable future. This is only one example of many improvements making progress from lab demonstration to commercial application (TRL 5-9). The performance of this cell will be better than 60% of the theoretical maximum so the headroom for further performance improvement is becoming limited.

The continued research is leading to increased understanding of performance limitations and degradation mechanisms of the lithium-ion cell. Whereas a decade ago, it would be expected for cells to have a life of only a few hundred cycles, todays cells routinely have a life of many thousands of cycles and in the high life designs, many tens of thousands of cycles is common. The reduction of cost (levelized cost of storage) due to enhanced cycle life in energy storage applications has been driven as much by this performance improvement as by other reductions.

The above performance improvements have been achieved in parallel with the explosion in manufacturing capacity and the continual improvement in manufacturing techniques. These volume increases have enabled a continual reduction in cell costs. As a result, the market entry for new technologies is increasingly difficult because of the high performance, low cost, proven lithium batteries.

Alternative battery chemistries are however being developed. Some are incremental changes on the now widely available lithium-ion such as “Solid State Batteries” whereby the liquid electrolyte is replaced with either a ceramic or organic alternative. This may ultimately enable higher energy density and lower costs but in the short-term these next generation cells are likely to find uses in niche applications which will accept higher costs for performance benefit. An exception is *Blue Solutions SA* in northern France who are currently offering their LMP (Lithium Metal Polymer) battery as a potential energy storage solution.

A further example of a solid-state battery which the developer claims is close to marked is *24M Technologies Inc.* a semi-solid-state battery technology designed specifically for non-transport energy storage applications with a novel electrode design and a high proportion of active components. Plans have been announced for manufacture of these batteries in North West Europe by *FreyR AS* at their Norwegian facility so we assess the development stage as TRL 8-9.

Potentially the most cost effective and high-performance battery would in theory be metal-air batteries but there are significant scientific challenges to obtain sufficient life and most experts view that the air handling and purification challenges will outweigh the potential benefits in the foreseeable future. Metal-air secondary batteries using various metals have been demonstrated in laboratory environments and there is at least one, *NantEnergy Inc.* of Arizona (formerly called Fluidic) with a commercially available battery system based on zinc-air technology. To the authors knowledge deployment has to date been limited to controlled test installations. Most metal air systems are very early stage so we assess them as TRL 3-8.

A potential stepping-stone to metal air is other cells with metal anodes. An example is US based *Eos Energy Enterprises Inc.*, makers of a novel zinc hybrid battery technology. They have supplied multiple systems at the 100 kWh scale and partnered with a UK utility, *Bryt Energy* and system engineer, *Connected Energy* to demonstrate the system performance in a European environment.

A further late-stage metal battery currently under development is the liquid metal battery currently being developed by *Ambri Inc.* of the US and *NEC Corporation* in Japan. Ambri is a spin-out from MIT funded by private investors and *TOTAL SE*. The technology is based on Calcium and Antimony and avoids the common degradation mechanisms by keeping the active materials in a liquid state. The company claims a 20-year life with negligible degradation at a significantly lower cost than alternatives. At the end of 2020, after many years of lab-based development and proving, the company announced a large-scale deployment in Nevada. We assess the TRL as 7-8 although this technology may after many years of testing shortly achieve full commercial status.

Finally, on traditional cells, there is potential to replace the Lithium in a battery with cheaper, more abundant Sodium or Potassium. Faraday Institution analysis has confirmed that there is likely to be significant economic benefit from Sodium ion batteries in applications less sensitive to energy density. These technologies are at a far earlier stage of development than sodium ion but the first generation are starting to become commercially available. Companies such as *Tiamat SAS* in France, *Faradion/AMTE* in the UK and *Natron Energy Inc.* in the USA have products ready for commercial applications but there is scope for continued optimization and development. These technology examples are at TRL 7-8 but other sodium ion batteries have developed novel concepts and are at earlier development such as *LiNa Energy Ltd* in the UK.

DEVELOPMENTS IN THERMAL STORAGE

Storing heat, either at high temperature in rocks or metals or at lower temperatures in water may be a very cost-effective store of energy. Most such schemes promoting full round-trip conversion are at early stage TRL and are typically very large scale. Siemens *Gamesa Renewable Energy SA* for example have their Electric Thermal Energy Storage (ETES) system which is being demonstrated at MW scale since 2019 in Hamburg-Altenwerder. Nottingham University spinout, *Cheesecake Energy Ltd* is another early stage example of this approach.

Liquid Air energy storage has now been demonstrated so is at TRL 8-9 but again is likely to remain large scale so beyond our scope.

At the smaller scale though, *Caldera* in England, *Mixergy Ltd* and *Sunamp Ltd* in Scotland are among companies storing heat with the aim of managing electrical supply variability. While these technologies do not offer full round-trip storage of electricity, they may offer much of the benefit in some applications. Heat storage is at TRL 5-9. A similar approach can be applied to "storing cold". Industrial or domestic refrigeration or air-conditioning can take advantage of cold stores to manage power demand. Cold stores are at a similar TRL.

5. Production industry

The growing demand for energy storage in northwest Europe would be ideally covered by suppliers based in the region. This not only creates jobs in the region but also eventually decreases the carbon footprint of the storage products, since the distance to end customer is decreased. Due to the worldwide competitive environment a large percentage of the energy storage systems installed in NWE are neither designed nor produced in the region. SMEs based in NWE could improve their market position tailoring their products to meet the local market requirements.

5.1 Business models of energy storage solution providers

Niall Ó Brolcháin, National University of Ireland, Galway

Energy storage enterprises include both well-established companies as well as smaller new entries, e.g. SMEs and startups. Independently of the company size, a well-structured business model is required to be sustainable in the worldwide competitive environment.

According to the fortune magazine (Fortune Business Insights, 2020) the main players in the global battery energy storage market set to hit $19.74 billion in value by 2027 include the following companies:

- Siemens Energy (Germany)
- LG Chem (South Korea)
- VRB Energy (Canada)
- Fluence (United States)
- Total (France)
- Black & Veatch (United States)
- ABB (Switzerland)
- Eve Energy Co. Ltd. (China)
- GE Renewable Energy (France)
- Hitachi Chemical Co., Ltd. (China)
- Hitachi ABB Power Grids (Switzerland)
- Samsung SDI (South Korea)
- Kokam (South Korea)

Furthermore, according to (Fortune Business Insights, 2020) "The global battery energy storage market size stood at USD 7.06 billion in 2019 and is anticipated to attain USD 19.74 billion by 2027, exhibiting a CAGR of 20.4% during the forecast period". In 2019 44.5% of the Global battery energy storage market was on grid while the remainder was off grid.

While this list includes a number of European companies it is clear that there is stiff competition from Asia and the Americas. Hence, an expedient goal for European projects would be to uplift the energy storage market in a European context by working with SMEs directly and creating a network linking SMEs, testbeds, knowledge partners, business support partners, Government and Government agencies at all levels.

Although the current business focus and the main focus of this report is on battery storage, there are many other established methods of energy storage including hydrogen, compressed air and pump storage. These are not specifically reflected in the list above.

BUSINESS MODELS USED BY THE MAIN PLAYERS

The main players in the global energy storage market are driven by a number of factors. These factors are clearly outlined in the Fortune Business Insights Report (Fortune Business Insights, 2020). This report examines Battery Energy Storage Systems (BESS) in detail.

- **INCREASING UTILIZATION OF OFF GRID ENERGY STORAGE BATTERIES**

Based on connectivity this market can be broadly split into an on-grid segment and an off-grid segment. The off-grid segment is likely to observe substantial expansion owing to the growing deployment of behind the meter units especially in emerging economies. On the other hand, favorable feed in tariff policies by governments to provide energy backup to grids coupled with significant opportunities for electricity storage integration across transmission and distribution networks, will complement the on-grid segment outlook (Fortune Business Insights, 2020).

- **DEVELOPMENT OF ADVANCED BESS BY KEY PLAYERS**

Many of the participants in the market are focusing on expanding their portfolios with innovative product lines having dedicated applications. These companies are also concentrating on introducing products and components with the ability to integrate next generation technologies to provide customers with safe and easy installations and operations. For instance, in March 2019 Siemens launched a new lithium-ion battery storage unit specifically designed for residential applications, the *Junelight* smart battery system is equipped with enhanced energy management features and is embedded with a mobile application to manage the device in real-time effectively.

- **DEPLOYMENT OF RENEWABLE ENERGY TECHNOLOGIES**

The growing installation of low-carbon technologies such as wind and solar is set to become a long-term driver and open up new possibilities for stationary storage units in the market. Different administrations and organizations have observed a steep increase in renewable power deployment as a result of their plans and investments to significantly increase clean energy contribution in the primary energy mix. For example, as per a report published by the international renewable Energy Agency (IRENA) total solar energy installed capacity across the globe equated to 584.8 GW by the end of 2019 as compared to 486.7 GW in 2018 observing an annual increment of over 20.2%.

- **EFFORTS TO CREATE COST EFFECTIVE BESS TECHNOLOGIES**

Various government agencies are increasingly focusing on reducing installation and operational costs associated with different solid-state batteries, including lithium-ion batteries propelling the global energy storage market. Additionally, numerous private organizations are also joining forces to incorporate new electrochemical solutions to fight climate change problems. For example, in September 2019 the Faraday Institution an independent energy storage research facility located in the UK, allocated around €55 million to five national consortia to conduct research for modifications in battery systems chemistries and production procedures for improved costs and applications in grid storage and transport use.

- **GROWING ENERGY DEMAND WORLDWIDE**

Rapidly rising energy demand across developing and developed economies owing to the transforming residential, commercial and industrial infrastructures is set to propel market growth. In September 2019 for instance the International Energy Agency (IEA) projected that global energy demand is set to grow by about 50% by 2050 from 2018 levels. Additionally, encouraging a regulatory framework to support low carbon technologies along with a positive outlook for the electrification of distant areas is likely to augment the industry outlook further. For instance, the European Union has enforced a 2030 climate and energy framework from 2021 to 2030 with a target to diminish greenhouse gas emissions by about 40% by 2030.

- **EXTENSIVE ADOPTION OF LITHIUM ION BATTERIES FOR ENERGY STORAGE**

Based on battery type, the global market is divided into lithium ion batteries, lead acid batteries, flow batteries and others. The lithium ion battery segment is projected to account for the major market share owing to the declining installation costs coupled with quick response time and high energy density of these batteries. The lead acid batteries segment is also anticipated to observe substantial growth due to their high specific power and easy operations in variable temperatures. Long working life versatile functions, less electrolyte degradation and improved safety are the key features complementing the expansion of flow batteries.

As a summary, an overview of the current market trends and drivers is illustrated in Figure 20.

Figure 20: Overview of current market trends and drivers in energy storage technologies

BASICS OF BUSINESS MODELLING FOR NEWLY ESTABLISHED COMPANIES (SMES) & START-UPS

Extracts below are principally from a paper entitled "Bringing innovation to market: business models for battery storage" (Li, et al., 2019). *It was presented at the Applied Energy Symposium and Forum, Renewable Energy Integration with Mini/Microgrids, REM 2018, 29–30 September 2018, Rhodes, Greece.*

> (Osterwalder & Pigneur, 2010) indicate that a successful business model consists of nine building blocks, including customer segments, value proposition, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure. The nine building blocks are the basics of a Business Model Canvas (Teece, 2010), which is widely used to design business models. In essence, it covers four key areas in a business: customers, suppliers, infrastructure and financial capabilities. In another study, (Johnson, et al., 2008) introduce four main components in a successful business model: a customer value proposition, a profit formula, key resources and key processes. These components can explain how the company addresses customer needs through value proposition, which in turn generate revenues for delivering the product or service. It is also important to address key resources and processes, which are fundamentals for the company to deliver what customers need. In fact, the four main elements are very similar to the main elements in (Osterwalder & Pigneur, 2010) nine building blocks but are categorized into different groups. (Li, 2019, p. 328)
>
> (Shafera, et al., 2005) conduct a review on the components covered in business models. Given that differences among industries, over 40 different components are listed. These components vary from branding and strategy to economic logic and sustainability. In addition, the design of a business model is closely linked to the potential of the innovation itself. The potential of an innovation is determined by five factors. Three factors are internal to the innovation, including market, function and adaptability; the other two factors are external to the innovation, including skilled management team and support. (Li, 2019, p. 328)
>
> Nevertheless, for early innovations when a market does not exist or is too small to allow the penetration of a new product, a business model might require governmental support to succeed (Zafirakis, et al., 2013). (Li, 2019, p. 329).
>
> (Pollitt, 2016) addresses three main components in the business models of battery storage, including value proposition, value creation and value capture. Battery storage delivers tens of services. Each service is associated with one revenue stream (in other words the payments that providing these services could earn). (Li, 2019, p. 329)

BASIC BUSINESS MODEL FOR ENERGY STORAGE SMES OR START-UP COMPANIES

In his work (Pollitt, 2016) expands on the three key components of a basic energy storage business model. These are described below. This business model exists within the context of a market and a policy and regulatory framework.

Value Proposition: relates to the energy storage services that are being sold and who the services are being sold to. They are often based on intermittency of energy supply and inflexibility of energy demand.

Value Creation: relates to how the energy storage service can be created and provided and whether new technologies can facilitate supply and demand matching in power, transport and heat.

Value Capture: relates to how the energy storage service can be monetized and how future energy investments will be able to earn a return.

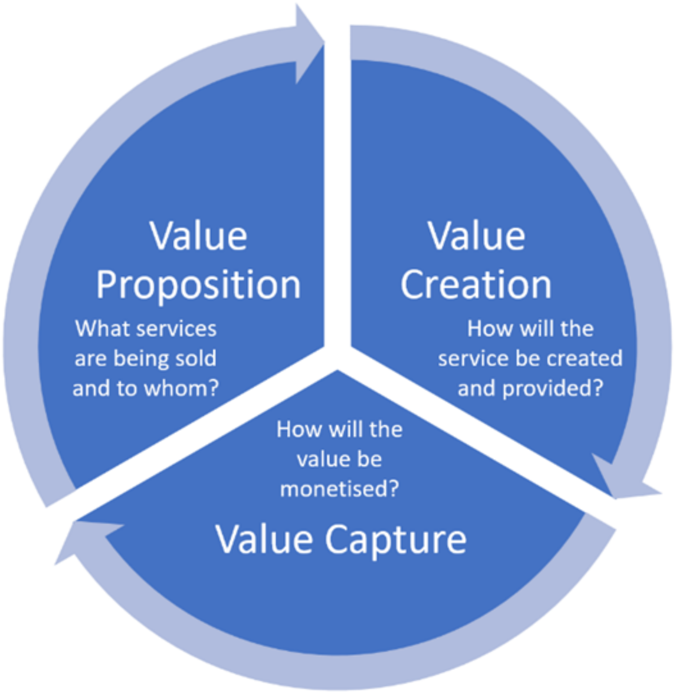

Figure 21: The three key components of a basic energy storage business model according to (Pollitt, 2016)

- **BASIC ECONOMICS OF ENERGY STORAGE (POLLITT, 2016)**
  - High frequency of use storage is more profitable than seasonal storage, given high capital costs.
  - Storage which relies on multiple sources of value faces higher transaction costs.
  - More storage reduces the value of each additional unit of storage, meaning that non-integrated storage is likely to be less than globally optimal.

- The value of storage will depend on what else is on the energy system in terms of storage, demand and generation.
- If storage is not about energy then residual fossil fuel systems will compete strongly with advanced forms of storage, in a so-called sailing ship effect

- **REGULATORY BARRIERS TO BE ADDRESSED FOR ENERGY STORAGE**
  - Definition of Energy Storage – Is it generation or retail or something else?
  - Regulated incumbent network companies may be able to include storage in their asset base, reducing the scope for non-regulated storage.
  - Unbundling rules may mean that if network companies own storage they cannot dispatch it and must work through a third party.
  - Existing network charging methodologies may over- or under-incentivize new investments.

- **SUMMARY FOR ENERGY STORAGE BUSINESS MODELS**
  - The fundamental economics of the smart, low carbon, renewable energy future still looks challenging.
  - Regulatory and market design changes will be necessary to support new business models in energy.
  - Good business models should focus on creating value for customers, not satisfying 'system' requirements.

5.2 Value chain of lithium-ion batteries in Europe

An De Schryver, Provinciale Ontwikkelingsmaatschappij Oost-Vlaanderen

Although the production of lithium-ion batteries in Europe was behind most of the other continents, the announcement of investments mainly from the automotive industry change the landscape. The value chain of electrochemical storage in general is composed of:

- Extraction of raw materials
- Production of components of cells e.g. cathodes, electrolytes, separators and electrodes
- Cell manufacturing
- Battery pack and BMS/EMS
- Recycle/reuse

EXTRACTION AND REFINEMENT OF RAW MATERIALS

In order to produce batteries, extracted minerals are needed depending on the battery-technology. Depending on the type of battery, different mineral resources are necessary. Six main battery minerals can be identified: lithium, cobalt, graphite, rare earths, nickel and vanadium. For lithium Australia is the dominant producer (58%). The Democratic Republic of Congo provides 61% of cobalt. China is the dominant producer of three of the six battery minerals (graphite 70%, rare earths 80% and vanadium 56%). Only in nickel there are several supplying countries, each accounting for 5 to 15 % of global production (FBI-CRC, 2020). After mining, most minerals undergo chemical refinement/extraction. The geographic link between mining and manufacturing has largely disappeared. For example, most lithium is refined in China. Refinement is mainly located outside the EU in Asia.

PRODUCTION OF COMPONENTS

Production of components for battery cells such as cathodes, electrodes, separators is mainly done by big chemical companies. Two European multinationals, *BASF* and *Umicore*, are important producers of cathodes. Both companies are investing in production capacity: BASF in Finland and Germany, and Umicore in Finland and Poland. Umicore's cathode materials are made for NMC and NCA batteries. Additionally, Umicore has a long-term supply agreement with LG Chem and Samsung. BASF produces both NMC and NCA cathode materials.

CELL ASSEMBLY

Creating a battery cell is a complex process which requires a strict control of the production environment. Although China still accounts for 83 percent of world cell manufacture overall, a closer look provides us with more insight on its target market. For smaller consumer products such as phones, computers and e-bikes China remains overwhelmingly dominant. For more technologically sophisticated applications with stringent performance requirements, production is much more global. The market is evenly shared between US, EU and China (each about 30%) and Japan (5-15%) (FBI-CRC, 2020). With electric vehicles and energy storage systems gaining popularity, this is an opportunity for non-Chinese producers to capture a greater share of the market.

The production itself remains in the hands of five companies with production sites spread around the globe. The number of cell assembly factories is increasing yearly. Even though most new production sites are located in China, Europe has announced the construction of an additional 14 over the next years. An overview of the worldwide significant lithium-ion cell

Table 18: Significant lithium-ion cell manufacturers, key factories and clients (SOMO, 2020)

Company	Forecast capacity in GWh end of 2020	Key factories	Key clients
LG CHEM (Republic of Korea) including joint ventures	93	Wroclaw, Poland Holland, Michigan, US Nanjing, China Ochang, Korea	Volkswagen, General Motors, Ford, Geely (Volvo), Renault, Nissan, Hyundai, Kia, Tesla and others
CATL (China) including joint ventures	110,1	Ningde, China Thuringia, Germany (announced) Guangzhou (announced) Jiansu, China	Geely (Volvo), BMW, Daimler, Volkswagen, Toyota, Honda, Nissan, other Chinese manufacturers
BYD (China)	60	Qinghai, China Shaanxi, China (announced) Chongqing, China (announced) Shenzhen, China Huizhou, China	BYD, Toyota
Panasonic (Japan)[ii]	69	Nevada, US Various locations, Japan Dalian, China	Tesla, BMW, Toyota
Samsung (South Korea)	62	Xian, China Ulsan, South Korea Göd, Hungary	BMW

manufacturers including existing and announced key factories as well as their key clients is given in Table 18.

BATTERY PACK AND MANAGEMENT SYSTEM

A battery pack is a set of interconnected cells. A management system is needed to make the battery cell work properly. Most car manufacturers keep the design and assembly in-house and have contracts with one or more cell suppliers.

For EV, there is a trend to produce battery packs in the proximity of car assembly plants in order to reduce transportation costs and have greater certainty about the supply chain. Top international battery manufacturers are also investing in production facilities in Europe. It is estimated that the total European battery capacity production will reach 207 GWh by 2023 (SOMO, 2020).

For household and standard use, the market offers commercially available standard battery packs. These batteries are mostly installed by companies also offering PV panels. Most of these companies are in fact resellers of ready-to-install products. Some bigger PV-companies also offer storage systems under the company's name.

For bigger storage solutions, several battery packs are combined into one. This type of storage requires tailored solutions and control. Most companies buy battery packs as building blocks from a third-party supplier. The general management software is provided/developed by the company itself. Since this is still quite a recent and new market, the installers are companies specialized in installation and development of electrical installations.

RECYCLE/REUSE

Nowadays, the availability of end-of-use batteries is still limited. Due to higher volumes of EV's being sold every year, this market will grow steadily.

There are several options for recycle or reuse as presented in Figure 22 and elaborated below:

- Remanufacturing allows the battery to be re-used in EV's
- Repurposing is also gaining importance: batteries which don't meet stringent requirements for use in EV's, can be used as second life batteries for other storage applications.
- Recycling is nowadays mainly focused on recovery of precious minerals. In a circular economy, recovery of materials is very important to limit the use of new materials. However, recycling of lithium-ion batteries is still in its infancy. Complex recycling processes need to be developed to enable multi-component recycling. Only specialized big companies are active in this market.

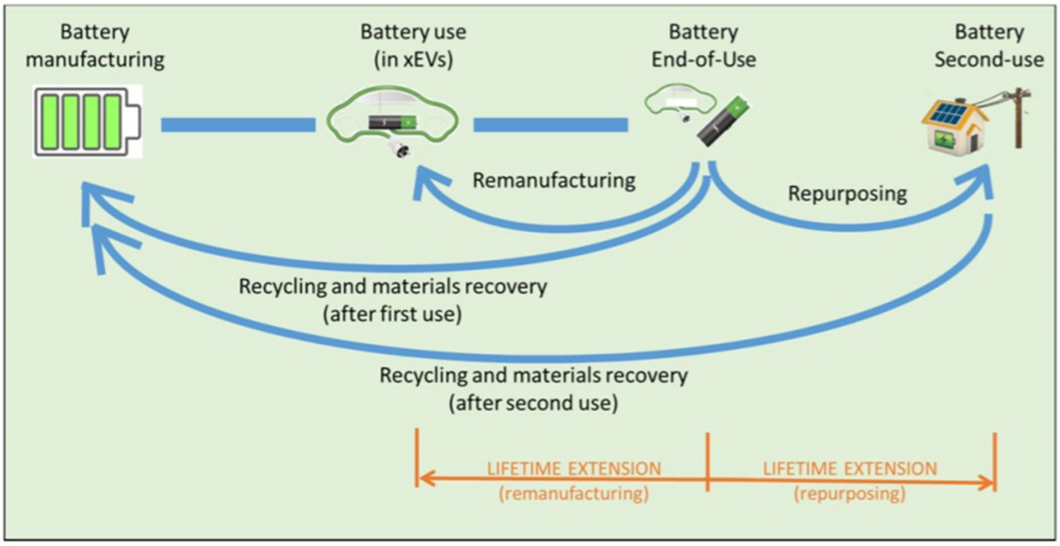

Figure 22: Repurposing, remanufacturing and recycling of batteries (Bobba, et al., 2019)

5.3 European policy

An De Schryver, Provinciale Ontwikkelingsmaatschappij Oost-Vlaanderen

Launched in 2008, the European Union's Raw Materials Initiative was the first government policy to recognize the need to develop new and more secure materials value chains to meet industry demand. It consists of three strategies: improving supply sustainability, better developing mining and processing industries within Europe, and promoting efficiency and recycling within value chains.

The Integrated Strategic Energy Technology (SET) Plan sets out ten priority actions to accelerate the transformation of the EU's energy system through joint investments between European Countries, private stakeholders and the European Commission (EC) in research and innovation (R&I). Key Action seven of the SET Plan aims at fostering research and innovation in the European battery sector to promote e-mobility and to make EU industry more competitive (EU-SETIS, 2019). The implementation plan, also called the Battery Implementation Plan, defines three focus areas and has identified five Flagship R&I Initiatives:

- Materials flagship: advanced materials for batteries
- Manufacturing flagship: eco-efficient production
- Fast-charge flagship: development of batteries with fast charging capability
- Second-use flagship: second-use of EV batteries
- Recycling flagship: high yield recycling

This Implementation Plan is proposed as an input to the R&I dimension of the European Battery Alliance.

In October 2017 the European Battery Alliance was launched. This industry-led cooperative platform brings together the EC, EU countries, the European Investment Bank (EIB) and industrial and innovation actors. The mission of the European Battery Alliance (EBA) is to ensure an unbroken value chain in Europe that can supply the market with all the batteries it needs –

with the smallest environmental footprint possible. By doing so, the EBA is set to prevent Europe's technological dependence and to maintain industrial leadership, notably in automotive sector.

In its short life span, the EBA has become a true success story. It has attracted over 500 industrial and innovation actors and secured, thanks to the cooperation with the European Investment Bank, some €100 billion in investments along the entire value chain.

The support that the EC (including through the European Battery Alliance) is giving for the development of a battery value chain also marks important changes in European industrial policy. First, there is a change from the sectoral approach towards a focus on the value chain. Second, the EC has identified the battery value chain as strategic due to its market value potential, its importance for a competitive industry and its role in the clean energy transition. Declaring the Li-ion battery as 'strategic', opens the door to direct government support to industry or state targeted industrial policies.

RAW MATERIALS EXTRACTION AND REFINEMENT

Europe still relies heavily on import of refined minerals. If Europe wants to be less dependent on third countries, there are only two options: extraction and refining within Europe and more recycling. More efficient and better product development will also contribute to lower the need for primary minerals in the final product.

Several European countries have significant mineral resources of lithium, copper and other minerals/metals needed for battery production. Maps with identified lithium resources in the EU are available. There are even quite a lot of valid exploration licenses for lithium. The most promising projects are located in the Czech Republic, Finland, Portugal, Spain, France, Austria, Germany, UK and Serbia. Refining is not possible in Europe which means that all extracted lithium needs to be refined in China.

Recently, the European Lithium Institute *eLi* with headquarters in Brussels, Belgium and Würzburg, Germany was created. This non-profit organization brings partners together involved in the whole lithium value chain. The goal is to set up international cooperation and to pride policy and industry advice. Six thematical platforms treat several aspects. Four of those cover the material value chain whereas the two remaining platforms focus on business models and applications, circular economy and predictive modelling.

CIRCULARITY AND RECYCLING

The EBA also wants to accelerate the recycling of batteries. More and more companies look at possibilities on how to recycle batteries from EV's. Having both economic and environmental benefits, the recycling business is developing rapidly. Several big battery recycling projects have been announced by companies such as BASF, Eramet, SUEZ, Umicore, Northvolt, Solvay and Veolia.

Honda is partnering with the French recycling specialist SNAM to collect batteries from Honda dealers and authorized recycling facilities in 22 countries and test them for their suitability for recycling and further processing.

FACTORIES FOR CELL AND BATTERY PACK ASSEMBLY

The European effort to attract investors in production facilities has proven very successful. Figure 23 shows all planned production facilities. This, in turn, will attract new investments from other companies producing components for the cells and battery packs. Besides, Europe already has significant knowledge on engineering in the field of battery management systems, systems integration and manufacturing machinery development.

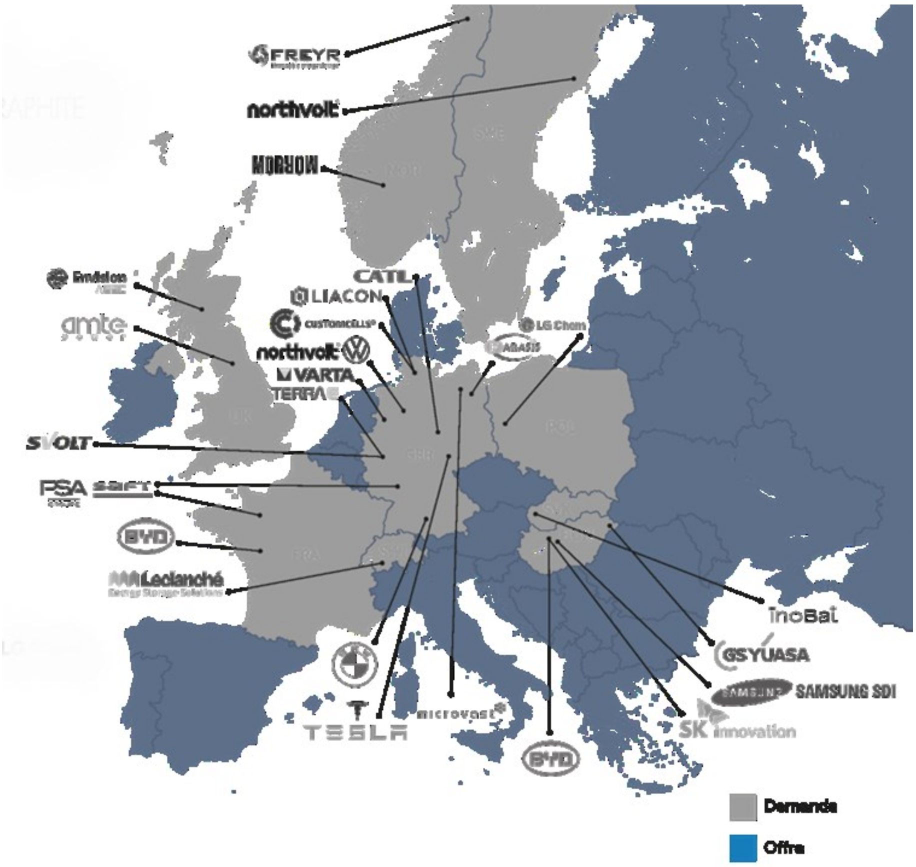

Figure 23: Map of announced production facilities within Europe. (Source: Nouveau Monde Graphite Inc.)

5.4 SME landscape within northwest Europe

Gieles Kinget, Provinciale Ontwikkelingsmaatschappij Oost-Vlaanderen

There are definitely several enterprises based in northwest Europe that design and produce energy storage solutions. Since this industry is under development in the last years, it would be expedient to map the status of the present business environment.

The target group are SMEs based in northwest Europe active in energy storage which are not only resellers but also active in product development in the medium capacity range. Information about more than 180 SMEs was collected and analyzed through desk research. Large companies don't belong to the focus and were not included in the desk research. This research must however be considered as a snapshot of the SME-landscape and this for two reasons:

- SMEs with a big potential are prone to acquisition by big companies;
- Development of a product has a risk of failure or underperformance.

Based on three parameters a high-level analysis of the energy storage SMEs active in the NWE region was made and a classification of market, value chain and technologies are summarized in Table 19.

Table 19: High-level analysis of the energy storage SMEs active in the NWE region classified into target market, value chain and technology

Target market	Value chain	Technology
- Households - Commercial - Industrial - Ancillary services - Mobility	- Component - Cell - pack - module - Integration: storage system - EMS - Second life battery - Business Integrator - Vertically integrated	- Electrochemical - Chemical - Electrical - Mechanical - Thermal

Note that a combination of target markets and technologies is common. Before diving into the results, a few words about the categories for a better understanding:

- Commercial includes retail, offices, hospitals, data centers;
- Industrial target market entails the secondary sector of the economy, i.e. production of goods through the use of labor, machines, tools, and chemical or biological processing or formulation;
- EMS stands for energy management system, it includes intelligent load management, IoT applications and congestion management among others;
- Business integrators don't necessarily provide a physical storage system as such but provide their customers with their expertise in the field;
- Vertically integrated SMEs provide/cover two, but often more steps within the energy storage value chain.

TARGET MARKET

Over 100 SMEs offer services and products to the entities and companies falling under the commercial category. As it can be observed in Figure 24 this sector is more often targeted than the industrial sector (85) and household clients (55). The reason could lie in the higher profit margins, i.e. the need for both commercial and industrial clients for a tailored solution. Thus, the conceptualisation has to happen in close and intense dialogue between the client and the

SME. These solutions are not always offered by large companies aiming at mass and standardized production.

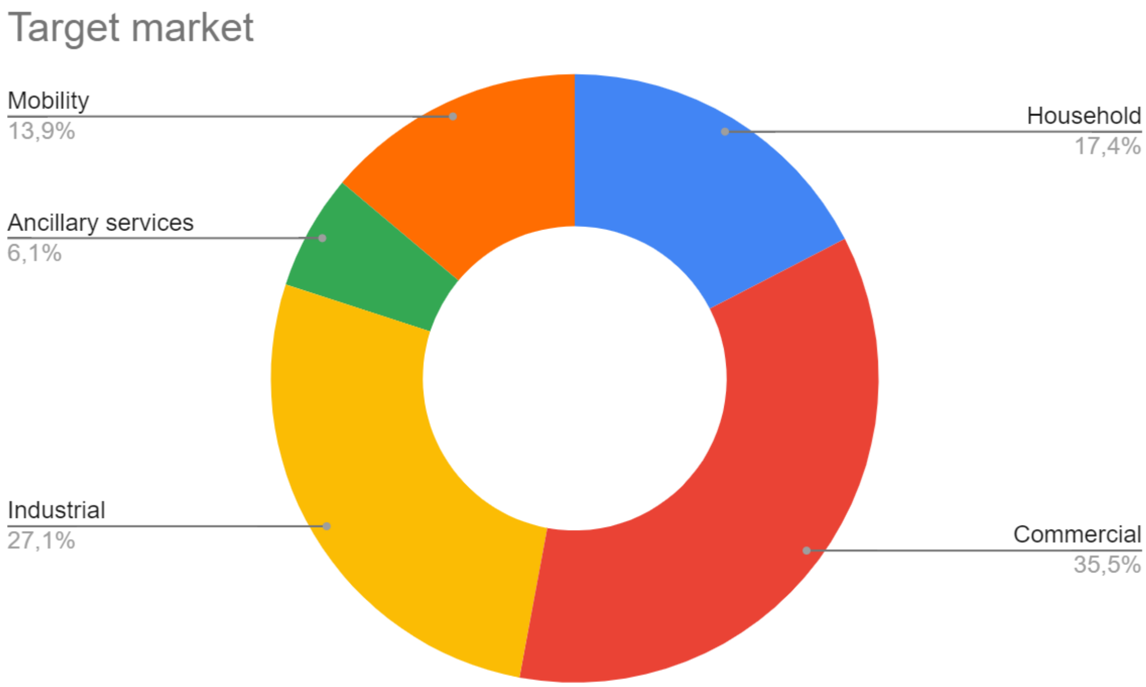

Figure 24: Target market of SMEs in the northwest Europe: most SMEs target the commercial and industrial market with their storage solutions

The combination of industrial and ancillary services is common since energy storage solutions often require the stacking of different applications to become profitable. For example, providing both UPS and net balancing services.

A lot of SMEs are in fact active in household market but a majority only acts as a reseller or installer because standard solutions are already available ("home batteries"). The market for household batteries will continue to grow in the different regions of NWE. The amount of growth will largely depend on the viability of the business cases.

Only a low percentage of SMEs is working on mobility applications. This is no surprise because this market is dominated by big companies. In most cases, mobility brands work exclusively with one or more of the five Asian cell suppliers of Table 18 to make their own battery packs.

Regional differences are few but two observations are worth mentioning:

- More SMEs offer ancillary services both in Belgium and Germany compared to the other NWE regions;
- Only a relatively small number of SMEs provide products or services for mobility applications in Ireland.

Both observations could be explained by regionally differing legislation and support mechanisms.

VALUE CHAIN

A first conclusion one could draw from Figure 25 is the limited prevalence of SMEs that manufacture components, cells, packs or modules used in energy storage systems. This is not surprising considering the high capital expenses associated with the setup of a production plant. Following the above, it comes as no surprise that most of the SME innovations lie in the later stages of the value chain. Using third party components, cells and battery packs or containers, they make their own configurations to offer clients a storage solution to meet their specific needs. About 35% works in this way, while 15% also includes one or more company-specific elements. These two groups are often offering their own BMS/EMS but only combined with their storage solution. 8% of the SMEs is specialized in developing management systems for storage solutions from other companies.

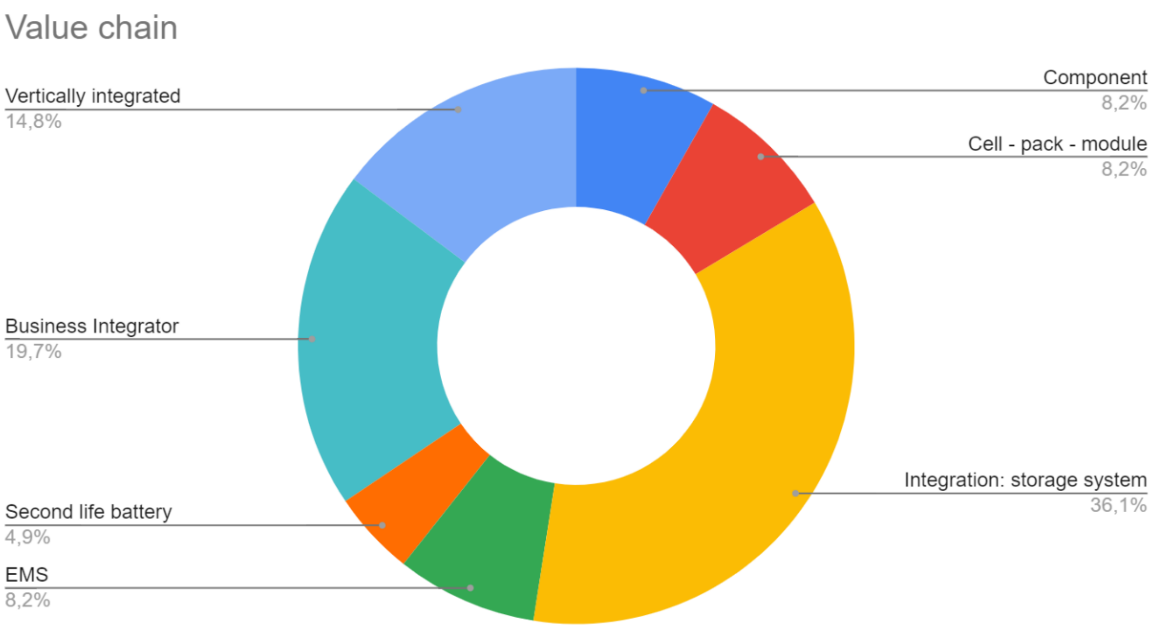

Figure 25: Value chain of SMEs in the northwest Europe: most SMEs offer an integrated storage product

Almost 20% of the SMEs only offer a service, business integration, without providing actual hardware. These companies help their clients – independently of a specific brand of manufacturer in choosing the right storage systems and dimensioning, adapted to the specific needs.

Almost 5% of the SMEs is actively working on already used batteries, mainly from EVs. These batteries can be given a second life in a stationary application. With electric mobility gaining popularity second life batteries will become more and more available during the next years. The higher interest in circularity is an important driver for this market. However, it is possible that this market will attract bigger companies when the EV-industry starts to recollect its own batteries.

As a conclusion it is clear that:

- very few SMEs are situated in the lower sections of the value chain i.e. working on component, cell or pack level. In the UK and the Netherlands, the highest number of those exceptions was encountered;
- second life batteries for stationary storage is still in a premature phase. In the Netherlands and Belgium there seems to be a higher uptake by SMEs.

TECHNOLOGY

The dominant role of the electrochemical technologies in the NWE SMEs can be clearly observed in Figure 26. Most of the SMEs focus on lithium-ion storage solutions, a small number of them on other technologies such as flow batteries and salt water batteries. Chemical applications are offered by more than 20 SMEs within the studied area. Because of the high interest in hydrogen storage, this market will grow exponentially over the coming decades. Chemical and electrochemical storage accounts for almost 90% of the storage solutions offered by SMEs. A limited number of SMEs are working on mechanical solutions such as flywheels. Electrostatic and magnetic storage is almost not taken up by SMEs probably because their application range is limited and a lot of R&D is still needed to become viable. Thermal storage even seems to be less of interest for SMEs. There are more SMEs working on thermal storage but only those with medium size storage capacities were considered.

Looking at the regional distribution of the storage technologies, they seem quite evenly distributed inside the NWE region. However chemical energy storage solution providers seem to be scarcer in both Belgium and northern France.

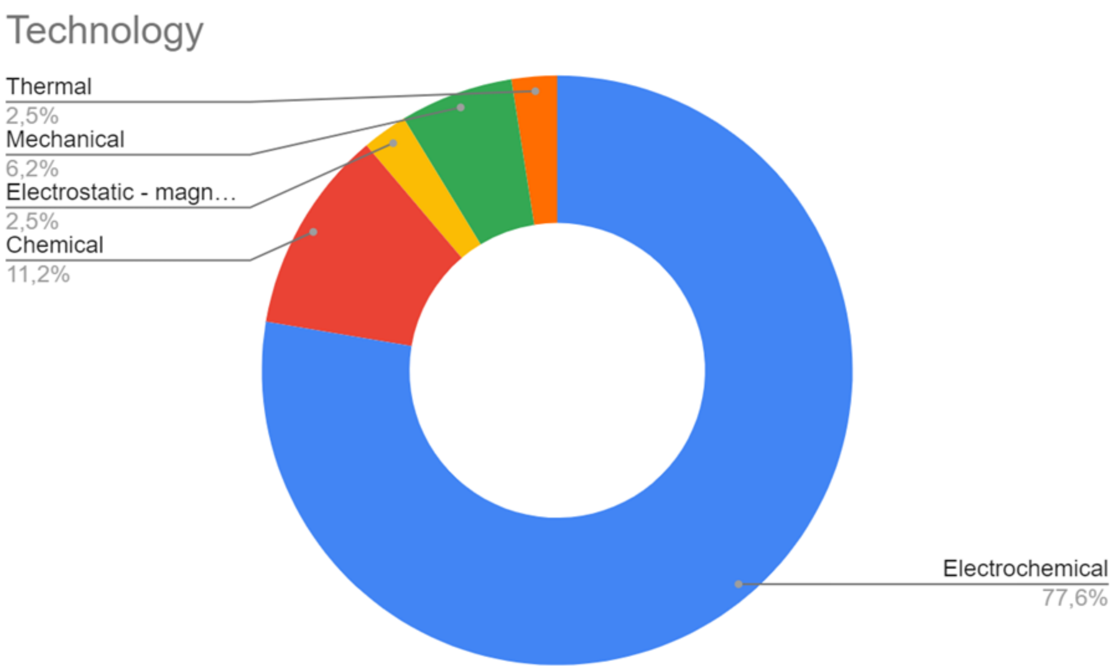

Figure 26: Offered storage technologies by SMEs in the northwest Europe: electrochemical storage makes up most of the offered solutions

6. Identification of opportunities and trends

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Observing the energy storage developments in northwest Europe, trends in the deployed technologies as well as in the appointed applications can be identified. Home storage systems in combination with solar power generation constitute a growing market and the decreasing prices of lithium-ion battery systems will probably encourage private investors to purchase such systems. Furthermore, industries and businesses willing to install energy storage systems in order to increase the self-consumption of electricity generation are expected to increase. The digitization and the associated need for datacenters with uninterruptible power supplies will further trigger the need for electrochemical energy storage systems.

Large scale battery systems aiming to provide balancing services, especially Frequency Containment Reserve, to the electricity grid represent a current practice. However, due to the increasing competition particularly in the German FCR market and the consequently decreasing reward prices, it seems that this market reached a saturation point (Figgener, et al., 2020).

Private, commercial and public electromobility applications have been constantly growing over the last decade. Especially in the private sector, a boost due to public subsidization is expected. Although private cars comprise a difficult sector for SMEs to win over, applications like commercial vehicles for deliveries or local public transportation compose a more appropriate target. Eventually, stricter emission regulation in the European metropolitan areas could accelerate electrification in public and commercial vehicles.

The expected electrification of the vehicle fleet would unavoidably increase the amount of electrochemical systems to be disposed or recycled within a time horizon of ten years. This fact in combination with possible reformations in disposal policies in the European Union generate opportunities for enterprises, which specialize in recycling and disposal. The possibility to extend the usage of battery systems originating from the automotive sector, the so-called second-life batteries, is also an opportunity where SMEs can focus. The estimation of the battery state of health, i.e. whether and to which extend the battery is appropriate for further use, is a field where additional expertise will be required. Enterprises could combine measurements and electrochemical models to provide qualified estimations for these purposes.

The manufacturing of battery cells is rather an inappropriate entry point for SMEs due to the high upfront investment costs. System integration of battery systems is already offered from various SMEs in northwest Europe. However, the absence of a unique selling point makes this kind of business model prone to competition from big system suppliers, which can take advantage of economies of scale to exert price pressure. The enhancement of the battery storage solution with in-house development of required system components such as the Battery Management System and monitoring equipment certainly adds value to the end-product.

Lithium-ion batteries currently dominate the energy storage market in almost every sector and segment for both stationary and mobile systems. A lot of research activities are presently focused on improving intrinsic properties such as energy density and lifetime of lithium ion cells. Electrolytes, separators as well as anode and cathode materials are thoroughly investigated for potential improvements. Forthcoming Li-ion cells envisage higher voltages (5 V) and higher capacities using among others silicon or tin-based anodes (Deng, 2015). Beyond lithium-ion batteries, sodium-ion cells represent a not yet commercially available alternative. Promises for sodium-ion batteries include lower manufacturing cost due to the much higher availability of sodium in comparison to lithium in the Earth crust (Slater, et al., 2013).

Investments driven by governmental policies, such as the German *National Hydrogen Strategy* introduced by the German Federal Ministry for Economic Affairs and Energy (BMWi, 2020) expect to trigger technological improvements and encourage facilities related to hydrogen and carbon-neutral fuel generation.

As a summary, trends in the energy storage research and applications as well as opportunities for the production industry are listed below.

TRENDS IN ENERGY STORAGE RESEARCH AND APPLICATIONS

- The amount of funds invested in electrochemical storage research will most probably trigger improvements in the intrinsic properties of forthcoming battery cells
- Lots of research efforts still concentrate on lithium-ion cells, however sodium-ion cells consist a research trend worth to be highlighted
- The use of lithium-ion batteries in households in combination with photovoltaic electricity generation is expected to grow further, especially in regions with relatively many sun-hours
- The electrification of light duty commercial vehicles for deliveries in urban areas is expected to extend further
- Furthermore, the gradual electrification of short-range public transportation fleets in various European cities also is also a trend to be highlighted

OPPORTUNITIES FOR ENTERPRISES FOCUSING IN ENERGY STORAGE TECHNOLOGIES

- Development of additional features for the energy management systems of home storage applications enhances the value proposition and creates new selling points
- Subsidies and policies focusing on the production, storage and use of carbon neutral fuels, especially hydrogen, give upwind to enterprises concentrating on this value chain
- Repurposing of lithium-ion batteries from the automotive sector give incentives for new business cases, which may lead to affordable second life batteries
- Additionally, the increased amount of automotive batteries to be recycled or disposed within the next years will inevitably increase the recycle and disposal effort creating at the same time new jobs in these industries

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