Tampere University of Applied Sciences

Energy Storage: Technologies and Trends

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ABSTRACT

Tampereen ammattikorkeakoulu
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NIILO MÖNKKÖNEN:
Energy Storage: Technologies and Trends

Bachelor's thesis, 65 pages
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The environmental threat of man-made global warming has prompted the global community to push for the energy transition from fossil fuel sources to low-carbon emitting alternatives. Environmentally sustainable wind and solar power systems have made a significant progress to become more cost-efficient during the last decade and have reached the price parity with fossil fuel incumbents on some energy applications. But neither of the technologies can provide flexible, on demand power that is require by modern electricity-intensive societies and their existing grid infrastructure. Energy storage systems can assist in integrating additional renewable energy capacity into the power system.

The purpose of this study was to provide an overview of the energy storage systems, major energy storage technologies and energy storage market trends. The overview will be part of a more comprehensive market entry strategy of a global asset management company. A special focus was given to lithium-ion battery energy storage systems, where the study discussed the raw materials, environmental impact, and hazard and safety of lithium-ion systems. The study was an applied research project.

The research showed that pumped hydro energy storage is the most used system to store electricity, but in the long-term, the geographical constraints and the potential emergence of other long-term storage technologies will diminish the new installations of pumped hydro energy storage. Lithium-ion battery energy storage systems have benefited from the rise of lithium-ion electric vehicle market and are becoming more commonplace in stationary energy storage systems. Both of these technologies have their weaknesses, enabling market opportunities for other energy storage technologies.

Key words: energy storage, lithium-ion batteries, energy markets

ABSTRAKTI

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Opinnäytetyö, 65 sivua
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Sähköntuotanto on muutoksessa kun fossiilisista polttoaineista pyritään nopeasti eroon ilmastonmuutoksen hillitsemiseksi. Fossiilinen sähkötuotanto voitaisiin ainakin osittain korvata tuuli- ja aurinkoenergialla, jotka ovat päästöttömiä ja uusiutuvia tuotantomuotoja. Kuitenkin ne ovat sähköjärjestelmän kannalta haastavia, koska ne eivät pysty tuottamaan sähköä tasaisella teholla. Energian varastointi on yksi keinoista mahdollistaa tuuli- ja aurinkoenergian lisääntyvän kapasiteetin käyttö sähköverkossa.

Tämä opinnäytetyö tehtiin eurooppalaiselle finanssiryhmälle. Työn tavoite oli muodostaa yleiskatsaus sähkövarastojärjestelmiin ja sähkövarastomarkkinoiden tulevaisuuteen. Työ keskittyi erityisesti litiumioniakkujen tuotannon, ympäristohaittojen ja käyttöturvallisuuden tutkimiseen. Tietoa kerättiin soveltavan tutkimuksen metodilla, aineistoina käytettiin tiedejulkaisuja ja laadukkaita alan lehtiä ja nettijulkaisuja.

Aineistotutkimus osoitti että vesipumppuvoimalaitokset ovat yleisimmin käytetty energian varastoinnin muoto. Uusia laitoksia tullaan myös rakentamaan tulevaisuudessa, mutta sopivien maa-alueiden vähyys rajoittaa uusien projektien käyttöönottoa. Myös litiumioniakkujärjestelmät ovat viimeisien vuosien aikana yleistyneet pienemmissä energiavarastojärjestelmissä ja sähköautoissa. Nopeasti kasvava sähköautoteollisuus alentaa litiumioniakkujen hintoja ja parantaa toimitusketjuja. Energian varastointiin voidaan käyttää myös muita järjestelmiä, mutta monet niistä ovat vasta kehitysasteella.

Jotta fossiiliset polttoaineet voidaan korvata tuuli- ja aurinkoenergialla sähköntuotannossa, tarvitaan halpa, turvallinen, modulaarinen ja ympäristöystävällinen tapa varastoida sähköä. Vesipumppuvoimalaitoksilla ja litiumioniakuilla on omat heikkoutensa, esimerkiksi mikään nykyisistä sähkövarastojärjestelmistä ei pysty varastoimaan sähköä yli viikkoa. Koska energiavarastoinnin tarve on verrattain uusi, uudet innovaatiot voivat muuttaa sähkönvarastointimarkkinoita nopeasti.

Avainsanat: energian varastointi, litiumioniakut, energiamarkkinat

CONTENTS

GLOSSARY

°C	degrees Celsius
BESS	battery energy storage system
BMS	battery management system
CAES	compressed air energy storage system
DOD	depth of discharge
FES	flywheel energy storage
cf.	compare to
CO_2	carbon dioxide
EV	electric vehicle
GDP	gross domestic product
GW	gigawatts
GWh	gigawatt-hours
ICE	internal combustion engine
IPCC	The Intergovernmental Panel on Climate Change
kW	kilowatts
LCO	lithium cobalt oxide cathode
LFP	lithium-iron phosphate cathode
LMC	lithium manganese oxide cathode
Mt	mega tonne, 1,000,000 kg
MW	megawatts
MWh	megawatt-hours
n.d.	not dated
NCA	lithium nickel cobalt aluminium oxide cathode
NMC	nickel manganese cobalt oxide cathode
p.a.	per year
PHES	pumped hydro energy storage system
PV	photovoltaic
R&D	research and development
The U.S.	The United States of America
The UK	The United Kingdom of Great Britain and Northern Ireland

1 INTRODUCTION

The environmental threat of man-made global warming has prompted the global community to push for an energy transition from fossil fuel sources to low-carbon emitting alternatives. The alternative low-carbon energy system should not only be environmentally sustainable, but also affordable and reliable. Low emission wind and solar power systems have made a significant progress to become more cost-efficient during the last decade, reaching the price parity with fossil fuel incumbents on some energy applications. But neither of the technologies can provide flexible, on-demand power that is required by modern electricity-intensive societies and their existing grid infrastructure.

Energy storage systems, such as stationary batteries, can provide grid security by storing electricity when it exceeds the grid system's demand, and then supplying it when the electricity generation is short of supply. They can also provide power quality services to ensure reliable flow of electricity. There are different energy storage technologies with distinct attributes, strengths, and weaknesses. Currently the most deployed technology is pumped hydro energy storage system (PHES), which accounts for 97% of total energy storage deployments. But geographical issues limit the deployment of PHES, and the technology cannot be relied on to become the sole energy storage technology. Another form of energy storage system, lithium-ion battery energy storage system (BESS), has seen rapid cost-reductions and technological innovations in the recent years.

The purpose of this study is to provide an overview of the energy storage systems. The overview will be part of a more comprehensive market entry strategy for the global asset management company. This study aims to answer the following questions:

1. how energy storage systems fit in and can accelerate the energy transition;
2. what are most used energy storage technologies;
3. what are the battery storage technologies and their strengths and weaknesses; and

4. what is the energy storage market landscape in the decade of 2020.

The study is an applied research project, where a literature research will be conducted to compare and assess the viability of major energy storage systems, and the storage systems' strengths and weaknesses. The literature research materials will be sourced from scientific articles, and high-quality websites and news sources that focus on the energy sector. The sponsor of the thesis has provided materials from professional sources, which are under a non-disclosure agreement.

This study is divided into 6 chapters. Chapter 2 provides information on the need for the energy transition, the current and historical transitions, the challenges facing the current energy transition and the role of energy storage for the energy transition. Chapter 3 gives a short overview of energy storage technologies other than battery energy storage systems. Chapter 4 provides information on battery energy storage systems, with a special focus on lithium-ion batteries. Chapter 5 presents the current energy storage markets and the future trends. Chapter 6 provides a discussion on the energy storage systems and chapter 7 provides a summary of the study and further research objectives.

2 ENERGY SYSTEM IN TRANSITION

2.1 Climate change presents one of the world's most pressing issues

Climate change, due to the use of fossil fuels and other human activities, present one of the world's most pressing issues. Since the discovery of fossil fuels precipitated the industrial revolution in the 18th century, the atmospheric carbon dioxide (CO_2), methane and nitrous oxide concentrations have increased to the levels not seen on earth for the last 800,000 years. There is a consensus among scientists on the relationship between atmospheric greenhouse gas concentrations and global temperatures, and the increased concentrations have led to the increase of 1.1 degrees Celsius (°C) of global average temperature compared to the baseline year of 1850. (IPCC, 2019.) With current policies and decarbonisation efforts researchers estimate that the world will warm around 3°C above pre-industrial levels by the end of the century (Hausfather & Peters 2020).

The increase in global temperatures induces potentially unprecedented risks for natural and human systems, including species loss and extinction, food insecurity, both droughts and floods, and diminishing economic growth, among other risks. The Intergovernmental Panel on Climate Change (IPCC) estimated that the biggest risks associated with the climate change are borne by already threatened ecosystems, warm-water corals, the Arctic region, and flood-prone coastal areas. Globally, the Arctic region experiences the highest winter warming, while the strongest warming during summer is located within the tropics surrounding the Equator. (IPCC 2019.) In human populations, small developing island states and the least developed countries in Africa and Asia bear a disproportionately higher risk of adverse consequences of the climate change (Buis 2019).

To mitigate and minimise the effects of climate change, nearly all countries have set out individual targets to collectively prevent "dangerous anthropogenic interference with the climate system" by cutting greenhouse gas emissions as rapidly as possible (Victor, Geels & Sharpe 2019). The Paris Agreement in 2015 set a goal of limiting the increase of global temperatures 2°C above the pre-industrial levels, while pursuing the means to limit the increase to 1.5°C (Denchak 2018). Limiting the global warming under 2°C from the pre-industrial levels would require dramatic and concerted actions by all countries and across all sectors, and currently seems more aspirational than realistic (Cembalest 2020).

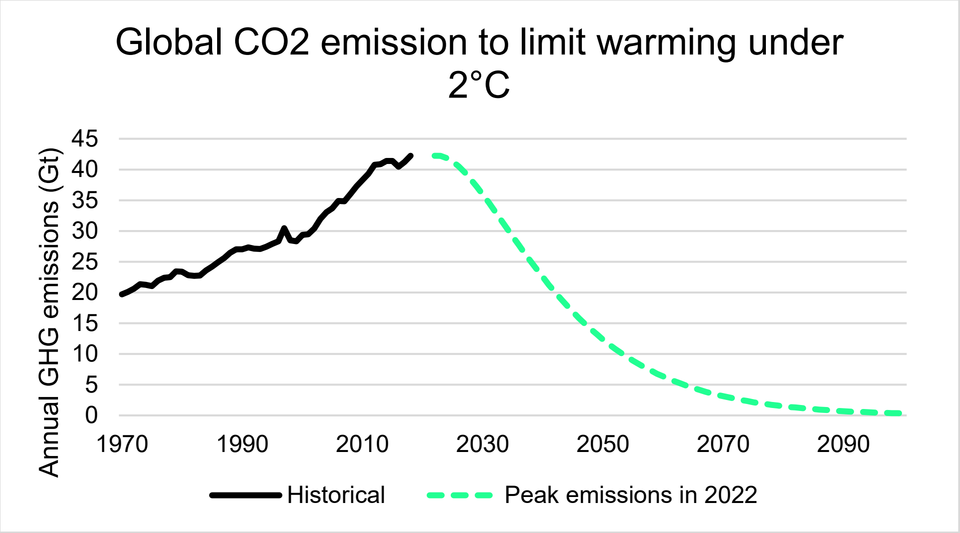


FIGURE 1. Decarbonisation pathway to keep global temperature rise under 2°C (Our World in Data 2020)

2.2 Energy transition to limit the impacts of climate change

The global CO_2 emissions can be simplified into a product of four fundamentals: population, gross domestic product (GDP), energy intensity and carbon intensity. Energy intensity is composed of energy generation per GDP unit and carbon intensity is emissions per energy unit generated. This relationship of the four fundamentals is called Kaya identity:

$$Emissions = Population \cdot GDP \cdot \frac{Energy}{GDP} \cdot \frac{CO_2}{Energy} \qquad (1)$$

While the energy intensity and the carbon intensity have decreased, the emissions have continued to grow, as the decreases have not been able to offset the growth in global population and affluence (Cembalest 2020). Even when the developed countries have been partially successful in decoupling their energy use from the economic growth, there are no simple pathways for rapid decoupling (Moreau & Vuille 2018). For limiting emissions, the energy transition from fossil fuels to low CO_2 emitting renewable energy is therefore vital.

The previous energy transitions have happened slowly, usually in a time of hundreds of years. For example, coal become a dominant fuel in the UK already by the mid-17th century, but it only reached to supply 50% of the world's primary energy by start of the 20th-century. Even in decline, coal still provides around 25% of the total energy supply. For natural gas, it took 60 years to grow from 5% to 25% of the global primary supply. Existing conventions, infrastructure, and know-how favour the incumbent energy technologies. The energy transition from fossil fuels to low carbon solutions needs to be unprecedented, both in its scale and speed. (Smil 2016.)

For the benefit of global carbon emission reductions, the technological advancements of renewables have been unprecedented: the solar photovoltaic (PV) technology reached a technological maturity with increased solar cell efficiencies and a 91% cost reduction between the years of 2009 and 2020. Wind power technology saw similar technological advancements with a cost reduction of 70% at the same timeframe. (Lazard 2020.) Currently wind and solar PV are the cheapest forms of electricity generation in most countries, with both projected to become significantly cheaper over time. Cheap and abundant renewables offer solutions for decarbonisation beyond the power sector - which amounted only to 25% of total greenhouses gases - through electrification. For the other, harder to abate sectors, such as transportation and heating, electrification and increased use of renewables can diminish the sectors' carbon intensity (Puglielli 2019.)

With over 50% of the global population and swift pace of economic expansion, advancements in low-carbon technologies in Asia are necessary for global success of limiting the effects of climate change. As seen in the figure 3, the electricity demand in Asia-Pacific (APAC) will rapidly grow with the compound annual growth rate (CAGR) of 2.5% while the rise in demand is much more modest in Europe with the CAGR of 0.5%. In 2019, the electricity demand was three times higher in Asia than in Europe; in 2050, it will be over 5 times higher. Especially the electricity need for air conditioning (AC) will rapidly grow in Asia, and in 2050 the AC demand will nearly top the Europe's total electricity demand (BloombergNEF 2020c).

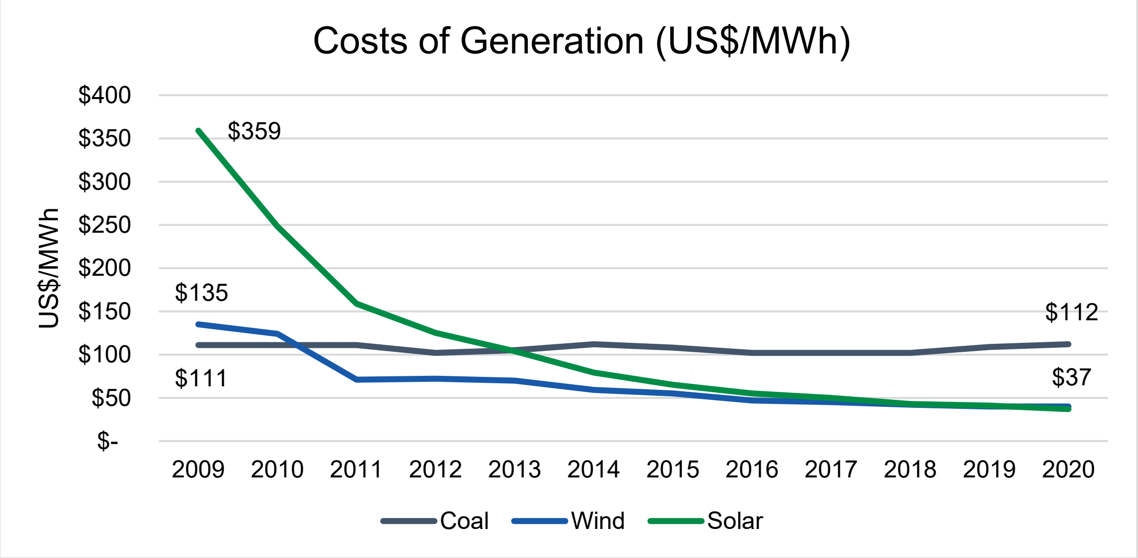


FIGURE 2. Rapid price reductions have made wind and solar power the cheapest sources of electricity generation (Lazard 2020)

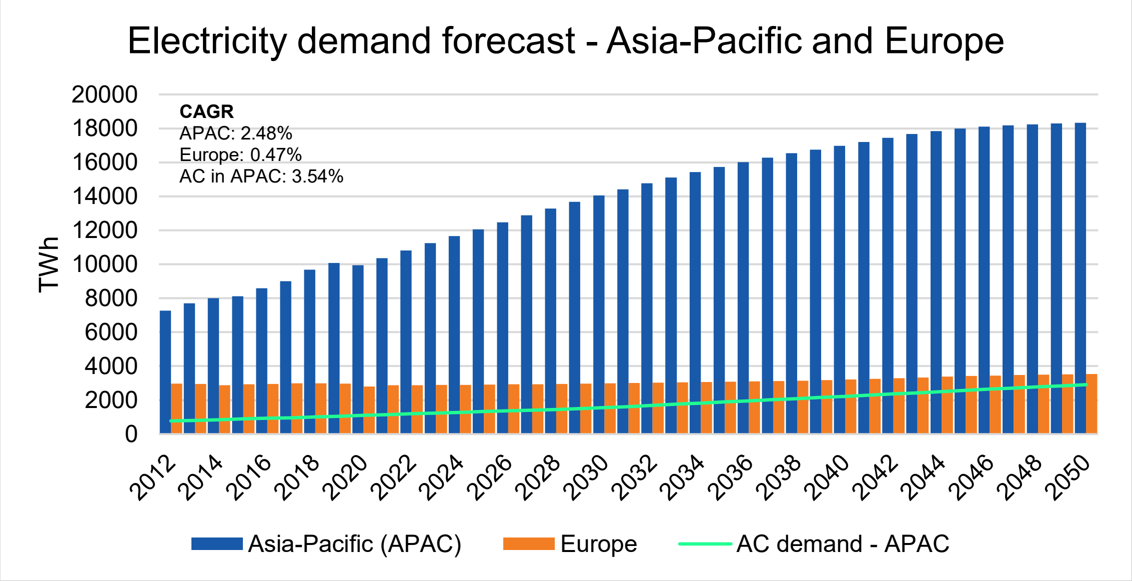


FIGURE 3. Electricity demand between 2012 and 2050 in Asia-Pacific and Europe and the air conditioning demand between 2012 and 2050 in Asia-Pacific (BloombergNEF 2020c)

2.3 Ensuring grid stability in energy transition

For the countries that have a low share of renewables in their electricity mix, the energy transition to low-carbon renewables requires not only cheaper renewables but innovations in systems' market design, business models and grid infrastructure and operations. For the countries with increasingly high levels of renewables, the main challenge will be to incorporate variable renewable energy generation while ensuring grid reliability and security. Renewables can provide cheaper electricity for end users, but they cannot provide similar stability services compared to the conventional fossil fuel thermal production. Without the necessary grid systems planning and innovations on grid strength services, the push for decarbonisation will result in an unpredictability in the supply of electricity. (Beard 2019.)

For the stable grid, electricity supply needs to meet demand on any given moment. To ensure this, intricate grid architecture has been built, which is, according to The National Academy of Engineering, "the greatest engineering achievement of the 20th century" (Schewe 2007). The stability of the grid relies on two fundamental principles: the modelling of energy demand is reasonably accurate, and the supply is predictable, and, to an extent, controllable. This system has been robust, built with limited competition and market disruption, small variability in supply and demand, and centralised, linear flows of electricity. The grid architecture is not only designed to meet the electricity demand, but also reliably maintain frequency and voltage. Additional generation is maintained in case of disruptive events, such as unexpected loss in supply. If supply does not meet demand, the result can be a 'brownout', where lower voltage electricity sluggishly keeps the lights on, but can damage sensitive electrical appliances, or a 'blackout', where the electrical service stops entirely, either from a certain area or from the whole grid. (Beard 2019.)

There is a real challenge to integrate intermittent and decentralised renewable technologies of wind and solar power into the grid that thrives on predictability and stability. Unlike more conventional electricity sources of coal, natural gas, hydro power and nuclear power, the power output of those renewable sources is neither predictable, nor controllable. Solar power has predictable seasonal variance between the winter and summer months but experiences unpredictable and swift power output fluctuations during cloudy days. Wind power supply has large variations occurring on both short (of seconds) and long (of years) timeframes. High penetration of these intermittent renewable technologies, especially solar, reduces the profitability of baseload power generation, leading to their retirement. The decrease of baseload power generation increases the potential risk of grid instability. (EPRI 2019.) Globally, solar and wind power still have a limited impact on grid operations, but as the share of variable power generation rises, the grid systems will need more energy balancing systems, such as energy storage. (Beard 2019.)

Figure 4 provides an example of a market with a high share of renewables in its electricity generation. In South Australia, the renewables produce over 50% of the state's electricity. In between October 2019 and 2020, the daily renewables generation in South Australia varied from 3.88 gigawatt-hours (GWh) (9% of total demand) to 39.59 GWh (85% of total demand) (OpenNEM 2020).

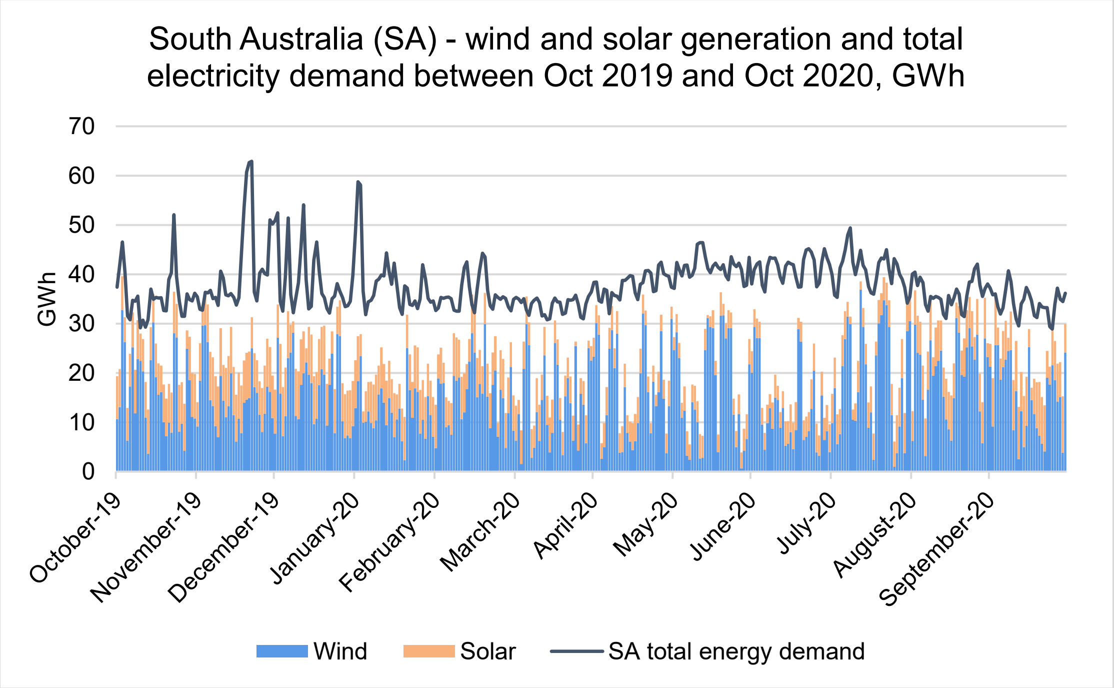


FIGURE 4. Wind and solar generation, and total electricity demand in South Australia between October 2019 and October 2020 (OpenNEM 2020)

2.4 Energy storage can accelerate the energy transition

The large-scale integration of energy storage systems can accelerate renewables deployment and enhance grid stability and security, while reducing electricity costs. Energy storage solutions can:

- integrate distributed and intermittent renewables into the grid, providing low-carbon, predictable, and dispatchable power;
- efficiently respond to changes in peak electricity demand;
- provide grid ancillary services critical to the stable and efficient electricity supply;
- alleviate increasing congestion and pressure in transmission and distribution systems; and
- decrease the voltage and frequency fluctuations that can be detrimental to the sophisticated consumer power electronics and information and communication systems. (Carnegie, Gotham, Nderitu & Preckel 2013.)

Complementing variable renewables, energy storage systems can provide grid reliability and security. Combination of cheap renewables with abundant decentralised storage can create a new energy system that is cheaper, more secure, and sustainable.

3 ENERGY STORAGE SYSTEMS

Electricity is flux of electric charges, it cannot be stored as it is (ADB 2018). But electric energy can be converted into another form, such as mechanical, potential, and electrochemical energy, and then re-electrified in time of demand. The backbone of conventional grid has been the dispatchable and controllable generation, and there has not been a major need for the energy storage to date. For example, in 2019 less than 1% of the U.S. electricity generation was stored (Cembalest 2020). Pumped hydro energy storage system (PHES) has been the major energy storage technology in the grid: starting from the second half of the 20th century, PHES deployments have complemented the nuclear or coal power plants' production. The power plants have provided the baseload power, and the PHES has matched the daily variable power demand cycles, charging during the low demand (usually at night), and discharging during the peak times (usually at morning and evening). (Rufer 2018.)

3.1 Energy storage services

Fundamentally, a grid-scale energy storage can provide energy for the consumption and power services for the grid. Power is the rate at which electricity is transferred, and energy is the capacity of electricity to do work. Energy can be thought as a quantity or volume, whereas power can be thought as a rate at which the volume changes. Mathematically these concepts can be defined as

$$E = \int_{t_1}^{t_2} P(t) \cdot dt \tag{2}$$

$$P(t) = \frac{dE}{dt} \tag{3}$$

where energy *E* is the integral of exchanged power *P* per unit in time *t* (Rufer 2018). In large-scale energy storage systems, rated power is measured in megawatts (MW), and energy capacity is measured either in megawatt-hours (MWh) or the duration of time that the system can provide the rated power. For example, the proposed Dungowan Dam pumped hydro energy storage in New South Wales, Australia, could provide 500 MW of power for eight hours, meaning that the storage capacity would be 4,000 MWh (Power Technology).

The power and energy services that energy storage provides can be broadly classified into three categories based on the electricity discharge time:

1. Instantaneous and short-term applications (discharge duration: milliseconds to minutes) provide ancillary services that help the grid operators to maintain a reliable electricity system by matching supply with demand, ensuring suitable power flow and providing contingency services in case of an adverse power system event. These services include voltage and frequency control, black start and spinning reserves;
2. Mid-term applications (discharge duration: minutes to under 5 hours) are usually utility-scale applications for intra-day energy shifting, where energy storage is charged during low energy demand, and then discharged during the peak demand; and
3. Long-term applications (discharge duration: days to weeks) are solutions that provide seasonal storage for grids with high penetration of intermittent renewable generation. Currently, all technologies are too costly to be used for long-term applications (Divya & Ostergaard 2009.)

For each of the categories, different attributes of energy storage are valued. Short-term energy solutions should have low cost per MW, high round-trip efficiency and be able to withstand multiple charge-discharge cycles per day. The long-term applications value low cost per MWh, low self-discharge rate and long lifecycle. The attributes of mid-term applications are a combination of the two.

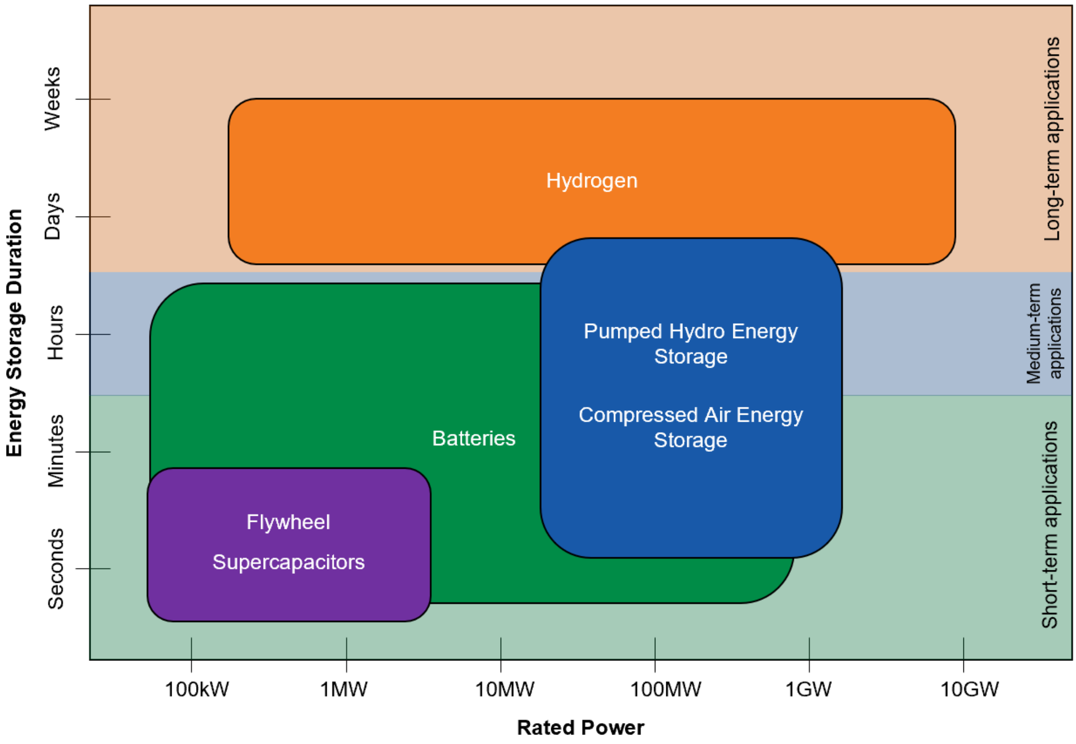


FIGURE 5. Comparison of storage technologies based on rated power and discharge time.

Figure 5 provides an illustration of the storage technologies based on their electricity discharge time. The observations include that:

- flywheels and supercapacitors can provide short-term burst of energy;
- batteries are flexible but cannot provide seasonal energy storage;
- pumped hydro energy storage and compressed air energy storage are best used for daily energy shifting needs; and
- hydrogen can be utilised for seasonal storage but is not yet cost-efficient. Note the non-linear scale in figure 5.

Modular mid-term applications, such as BESS, can provide energy storage services to stakeholders across the energy system, creating revenue from multiple sources. This ‘revenue stacking’ can be exemplified by the Hornsdale Power Reserve battery, developed by the French renewable energy developer Neoen. Located in South Australia, the Hornsdale Power Reserve provides contracted ancillary services to South Australian Government, sells power quality frequency control services in multiple spot markets, and sells energy to the wholesale market (Viaud 2018). Examples of energy storage services for the stakeholders is provided in table 1.

TABLE 1. Fast reacting mid-term storage, such as BESS, can provide variety of services to stakeholders (Everoze 2016, modified)

Stakeholder	**Role of energy storage**	**Energy storage services**
System operator	Ensure that the system runs reliably	Fast frequency response Fast reserve Short-term operating reserve Black start Capacity mechanism
Transmission/ distribution Operator	Reduce costs of reliable infrastructure	Capture congested energy Delaying high-capital investments
Connected generation	Maximise the value of energy and lower network costs	Capture congested energy Market arbitrage Improve forecasting accuracy Self-consumption
End-user	Reduce energy costs and ensure reliable supply	Provide back-up power Retail market arbitrage

3.2 Metrics and considerations for energy storage technologies

Energy storage systems can be used for wide range of applications in magnitude of scales, ranging from narrow power quality services of small-scale supercapacitors to broader power and energy projects using large-scale battery energy storage system (BESS), pumped hydro energy storage system (PHES) or compressed energy storage system (CAES). Depending on the use, an energy storage system must satisfy various criteria to be the best system economically, technically, and environmentally. Some of the main considerations to assess the suitability of an energy storage technology are:

- **Capacity**: both in power (MW) and energy (MWh);
- **Density**: in energy (Wh/L) and power (W/L) volume, and in specific energy (Wh/kg) and power (W/kg);
- **Efficiency**: as a return-trip efficiency;
- **Lifetime:** in lifetime (years), cycling times and throughput (MWh)

- **Costs:** in power ($/MW) and energy ($/MWh) capital costs and operating and maintenance ($/p.a.) costs; and
- **General considerations:** such as response time, technology risk and maturity, physical footprint, system weight, environmental impact, and safety. (BloombergNEF 2020a.)

Some of the attributes to differentiate energy storage technologies are outlined in the following sections of 3.2.1 - 3.2.3.

3.2.1 Energy density and physical footprint

For energy storage, energy density is not used as the most important parameter that distinguishes technology from each other. Stationary applications do not usually have very strict space and weight requirements. But it is important in the transportation sector, where the technology cannot be too big or too heavy without impeding the operational requirements of a vehicle. For example, the low energy density of battery technologies poses a significant barrier for electric long-distance flights (Crittenden 2020). Neither BESS nor any other energy storage technology can compete with fossil fuels on energy density (Schlachter 2012).

Even though BESS' energy density cannot compete with fossil fuels, its systems are still in order of magnitude smaller by area footprint compared to the technologies of PHES and CAES. An average Australian household consumes 40kWh per day (Mount Alexander Shire Council). To provide 24 hours of energy storage for a small hamlet of 350 households, BESS needs a space of less than one standard 20 feet shipping container (DSV). For that same energy need, CAES with air at 300 bar needs 8 containers and PHES with 500 m dam height needs 326 containers.

Hydrogen is an outlier technology on its energy density. It has the highest known energy content of any fuel by mass. But hydrogen also has very low volumetric density: there is over 3,000 times more energy in a litre of gasoline compared to a litre of hydrogen at a standard temperature and pressure. To be viable for use, hydrogen must be stored under great pressure or liquified - both of which incur significant costs. (Abe, Popoola & Ajenifuja 2019.)

3.2.2 Efficiency losses

If possible, it is better not to store energy and release it later, as all energy storage technologies incur energy losses. Round-trip efficiency quantifies energy losses of a storage system by measuring the difference between the amount of energy that is stored to the amount of energy discharged (Beard 2019). Battery energy storage system charged with 100 MWh but providing only 92 MWh when discharged translates into the round-trip efficiency of 92%. Electrochemical conversions used by BESS provide higher efficiencies (between 80-95%) compared to the efficiency of the incumbent thermodynamic engines. The engines have the upper limit on the efficiency (73%), which is called the Carnot cycle (Beard 2019). Kinetic energy conversions of PHES and CAES have a round-trip efficiency of 70-80% (ADB 2018.). Green hydrogen fuel cell power production has a low round trip efficiency between 20-30% (Bernier, Hamelin, Agbossou & Bose 2005). This has a major effect on total costs of hydrogen compared to batteries: hydrogen energy storage with a round-trip efficiency of 30% will have to charge 3 times as much energy than BESS with a round-trip efficiency of 90% for the same discharge.

Another form of efficiency loss is self-discharge: internal discharges that reduce the stored charge. All energy storage technologies are affected by self-discharge to a degree, but in some technologies, such as PHES and CAES that rely on kinetic conversions, the self-discharge can be minimal. Hypothetical and actual round-trip efficiency can differ: the actual round-trip efficiency depends on multiple variables, such as energy needs and losses in supporting balance of plant (such as cables and lights), type of charge-discharge cycle, and other environmental factors (Schimpe et al. 2017).

3.2.3 Lifetime and cycling

All open systems see their performance deteriorate over time. After repetitively performing charge-discharge cycles, energy storage system gradually loses its efficiency until it gets retired due to the performance or economic factors. Mechanical energy storages such as superconductors, flywheels, PHES and CAES can withstand much greater number of charge-discharge cycles (from 10,000 cycles to over 100,000 cycles) than electro-chemical BESS (from 1,000 to 10,000 cycles) (Rufer 2018).

It can be difficult to define a cycle in many applications where the energy storage only operates partial cycles with different states of charge. The global consultancy company DNV-GL prefers to compare battery systems' throughput - the MWh discharged per the installed MW capacity - than the cycles, which DNV-GL calls a “legacy metric” (Hill & Kleinberg 2019). Increasingly, the system providers are moving to warrant the systems based on energy throughput (Frith 2019). The performance degradation of energy storage depends on various factors, such as depth of discharge (DoD), rest periods between cycles, rate of charge/discharge, and environmental conditions, such as system temperatures (Haidl, Buchroithner, Schweighofer, Bader & Wegleiter 2019).

3.3 Description of energy storage technologies

Table 2 compares the characteristic of energy storage systems, followed by table 3 that provides short description of each technology. The list of technologies is not exhaustive - but a vignette to the diversity of energy storage technologies that are currently being considered. One segment of technologies that is not described is thermal storage technologies, which usually provide both heat and power.

Table 2. Properties of commercial/emerging energy storage technologies (Dehghani-Sanij et al. 2019)

Technology	Type	Maturity	Discharge time	Capital costs, energy capacity US$/kWh	Lifetime, cycles	Return-trip efficiency	Specific energy, (Wh/kg)	Environmental impact
Li-ion	Electro-chemical	Emerging	Short, Medium	$400	1,000 - 10,000	75 - 90 %	120 - 240	High
Pb-a	Electro-chemical	Mature	Short, Medium	$400	1,500 - 5,000	75 - 80 %	35 - 40	Medium
Na-S	Electro-chemical	Emerging	Short, Medium	$500	2,500 - 4,500	75 - 95 %	150 - 250	Low
Flow	Electro-chemical	Early stage	Short, Medium	$500	10,000 - 12,500	65 - 80 %	15 - 30	Low
PHES	Mechanical	Mature	Short, Medium, Long	$100	10,000 - 30,000	70 - 85 %	1 - 2	Low
CAES	Mechanical	Emerging	Short, Medium, Long	$100	8,000 - 12,000	50 - 70 %	3 - 6	Medium
Flywheel	Mechanical	Mature	Short	$5,000	20,000+	90 - 95 %	20 - 80	Low
Super-capacitor	Electrical	Early stage	Short	$2,000	20,000+	90 - 97 %	10 -30	Low
Hydrogen Fuel Cell	Chemical	Early stage	Long	$500	20,000+	20 - 30 %	500 - 3,000	Medium

Table 3. Strengths and weaknesses of energy storage technologies (Arup 2015; WILTW 2020)

Technology	Strengths / Opportunities	Weaknesses / Threats
Li-ion Battery	+ Widely used in other applications + High energy density + Global supply chain already set up + High efficiency + The most deployed energy storage technology by installations	- Negative effects of overcharging/discharging - Fire safety issues - Environmental impacts of mining - Potential bottlenecks of raw materials - Limited potential for seasonal storage
Pb-a Battery	+ Low self-discharge rates cf. other batteries + Mature technology	- Lead is hazardous - Low energy density - Susceptible to high depths of discharge
Na-S Battery	+ Relatively long cycle life + Already deployed, mature technology	- Operates only in high temperatures (>300°C) - Pure sodium presents fire hazard - Projects in Japan faced multiple delays
Flow batteries	+ Tolerates high rate of cycles + Minimal self-discharge + Good fire safety cf. li-ion batteries	- Not technically mature - Lower R&D cf. li-ion
PHES	+ Widely deployed, mature technology + Long asset life + Potential for long-term storage + Large power and energy capacity	- Long typical total project timelines (>10 years) - Environmental and water safety impacts - Geographically constraints
CAES	+ Long asset life + Potential for long-term storage + Asset recycling potential	- Long typical total project timelines (>10 years) - Low round-trip efficiency - Geographical constraints
Flywheel	+ High rate of cycles + High efficiency	- High price - Low energy capacity
Supercapacitor	+ High rate of cycles + High efficiency	- High price - Low energy capacity - Self-discharge
Hydrogen Fuel Cell	+ Potential for seasonal storage + Widely used in other sectors + High gravimetric density + Energy carrier, like fossil fuels	- Low round-trip efficiency - High price - Low volumetric energy density - Needs global supply chain

3.3.1 Pumped hydro energy storage

Pumped hydro energy storage system (PHES) is the most established energy storage technology, with 97% of the energy storage power capacity deployed being PHES. PHES uses the potential energy stored in the differential of height between two water reservoirs. This potential energy is turned into mechanical energy by a turbine that runs on water released from the higher reservoir to the lower reservoir via a tunnel. PHES is a mature, large scale technology that is widely deployed around the world. It is well-suited into our conventional energy system with similar attributes to fossil fuel power plants and has a relatively good round-trip efficiency of 65% - 80%. The systems' lifetime is often considerably longer than the competitive technologies. While it has low annual operating cost, PHES has high capital costs. It is also geographically constrained, needing sites with an altitude difference of 200 - 900 metres between the reservoirs. (Blakers, Stocks & Lu 2020.)

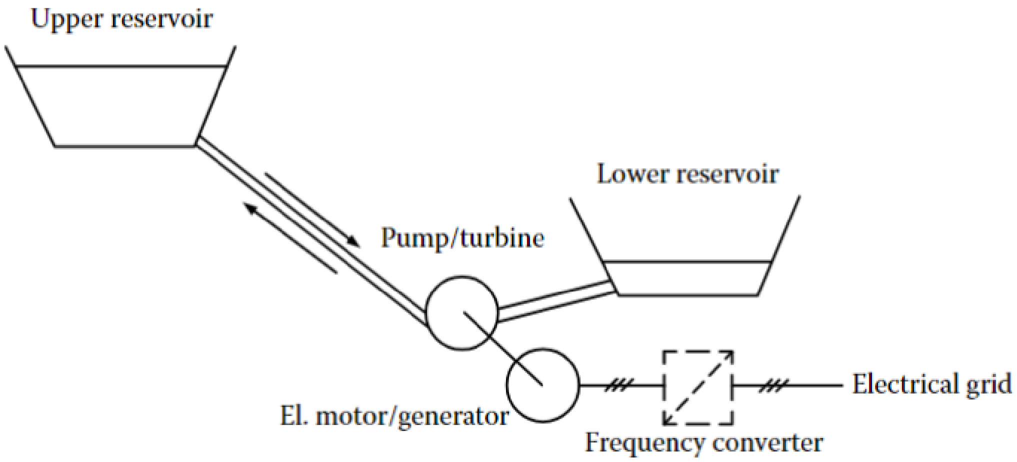


FIGURE 6. Schematic of a pumped hydro energy storage (Rufer 2018)

3.3.2 Compressed air energy storage

Like PHES, Compressed air energy storage system (CAES) projects have been deployed for decades (Rufer 2018). At its simplest form, CAES compresses air using electricity during the low grid demand, storing it inside air-tight vessel or reservoir. During the high grid demand, fuel (usually natural gas) is used to heat the pressurised air, creating rapid expansion. The expanding air drives a turbine linked with an electric generator. (Carnegie et al 2013.)

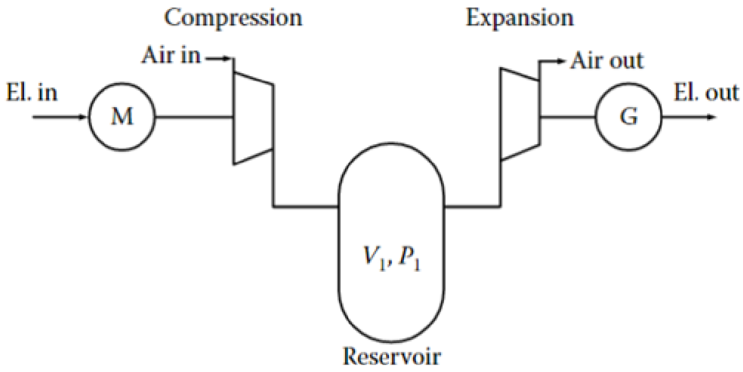


FIGURE 7. Schematic of CAES (Rufer 2018)

Figure 7 provides a schematic of CAES. In the compression stage, an electric motor (M) drives a compression machine. Then the compressed energy is stored in a reservoir at volume V_1 and pressure P_1. For the electricity discharge, the compressed air goes through a volumetric expander driving an electric generator (G). (Rufer 2018.)

First CAES was built in 1978 in the aftermath of the oil crisis of 1973. Albeit numerous projects have been proposed, issues ranging from project siting to technoeconomic issues have kept CAESs to a few. The interest in CAES have resurfaced recently with the increasing need for long-term storage. (Carnegie et al 2013.) Newer CAESs usually utilise liquid air or man-made reservoirs, have a higher round-trip efficiency in between 60% to 70%, offer a long lifetime and have relatively cheap components that are individually exchangeable (Rufer 2018).

3.3.3 Flywheel energy storage

Flywheel energy storage (FES) uses the momentum of a spinning mass to convert the rotational kinetic energy into electricity. For charging, an electrical machine with a bidirectional power converter sets a flywheel rotor in motion. For discharging, the flywheel rotor’s kinetic energy is captured by the electrical machine and converted into electricity (Sebastian & Pena Alzola 2012). The flywheel rotor and its bearings are sealed in air vacuumed container to minimise friction. Unlike lithium-ion batteries, the power and energy capacities of the FES are relatively independent from each other, and the technology could be used for long-term storage. But due to the overall high cost of the technology, FES is used only for short duration power quality applications. (Carnegie et al. 2013) The increasing need for fast reacting power quality applications without significant lifetime degradation could provide emerging technologies, such as FES and supercapacitors, market opportunities as the tools to dampen the frequency fluctuations of wind and solar power (Arup 2015).

3.3.4 Supercapacitors

Capacitors are one of the most fundamental passive components in electronic circuits. They are used to store energy, supress voltage spikes and filter noise from the electric signal. Capacitors store energy in large electrostatic fields between two minimally separate conductive plates, and the voltage differential between the positive and negative plates charges the capacitor. Supercapacitors hold thousands of times more electrical capacitance than the normal circuit capacitor and can provide frequent charge-discharge cycles for power quality services. The rapidity of charging and discharging is one of the main attributes of supercapacitors, with full charge reached within seconds. (Floyd 2004.)

Invented in 1950s by the engineers at General Electric, supercapacitors provide still a limited attraction to energy project developers: with low energy density and limited storage capabilities compared to batteries, no major projects deployed, and high costs have kept supercapacitors in the margins of energy storage systems. Graphene supercapacitor development would alleviate the energy density and cost issues, but the technology needs more research and development (R&D) to become a viable utility-scale technology. (Yu, Chabot, Zhang & Zhang 2013.)

3.3.5 Hydrogen Fuel Cells

Renewables like wind and solar power do not possess the same properties as fossil fuel energy sources of oil, natural gas, and coal, and cannot just outplace them. But, the smallest element of the periodic table, hydrogen, can act as an energy carrier to be used in similar applications to fossil fuels. Hydrogen produced by renewables provides one of the most promising solution for decarbonising hard-to-abate sectors of heavy industry, transportation, and heating and cooling. Hydrogen's potential to replace all fossil fuels and create a new energy system - referred as "the hydrogen economy" - has created cycles of inflated expectations followed by disillusionment since the 1970s. (Hydrogen Council 2017.)

Low carbon 'green' hydrogen is manufactured by an electrolysis process. In the process a water molecule is divided into hydrogen (H_2) and oxygen (O) using renewable energy (Hydrogen Council 2020). H_2 is stored in a compressed tank or a geological formation, and then converted back into electricity using regenerative hydrogen fuel cell technology. Like batteries, fuel cells are electrochemical devices, but they need fuel - such as hydrogen - to charge instead of utilising electricity from a power source. (Sharaf & Orhan 2014.)

Hydrogen storage has a very low rate of self-discharge, making it a promising solution for long-term storage. But all-encompassing hydrogen economy has been set back by low return efficiency (around 30%), difficulties of storing hydrogen and high costs of production. Hydrogen has a real potential to become widely deployed storage solution for the power sector, but it is unlikely to happen in the 2020s. (BloombergNEF 2020b.)

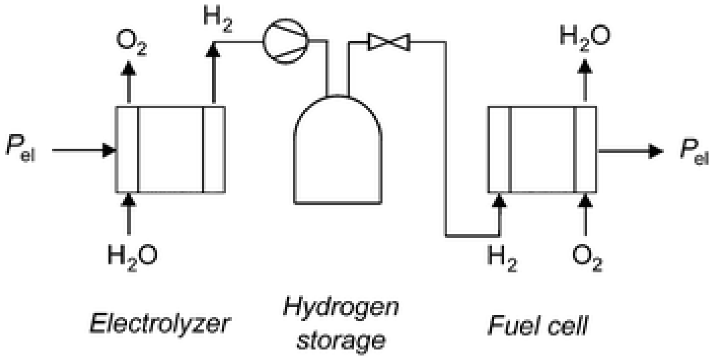


FIGURE 8. Schematic of hydrogen storage (Pellow et al. 2015)

4 BATTERY ENERGY STORAGE SYSTEMS

Rechargeable batteries store electricity into electrochemical form and then convert it back to electricity when needed. This process is driven by electrochemical oxidation-reduction reactions between two electrodes, the negatively charged anode, and the positively charged cathode. Closing the system loop by introducing a load, charged electrons flow from anode to cathode, creating electric current. Between the electrodes is an electrolyte, a medium of transfer for the charged ions. The electrodes and the electrolyte make up a battery cell, as seen in figure 9. Battery cells can be connected either in series or parallel to create the desired battery voltage and the storage duration. (Beard 2019.)

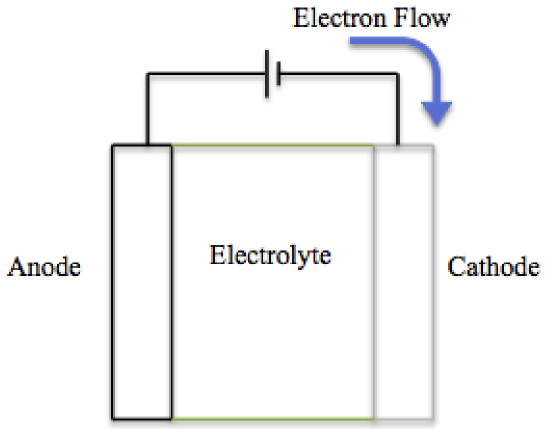


FIGURE 9. Schematic of rechargeable battery (Wikipedia 2017)

There are two general types of batteries: the primary battery and the secondary battery. The main difference is that the primary batteries are not rechargeable, but of single use. Alkaline batteries used in many household items are an example of primary batteries. In the secondary batteries, the chemical oxidation-reduction reaction is reversible by charging the battery from a power source. For energy storage applications, all batteries used are secondary batteries. (Anglin & Sadoway 2019.)

Batteries are relatively simple, reliable, and cost-effective. They appear in wide range of products and applications, including in power supply systems, portable electric and electronic devices, and transportation and space applications. With new and innovative battery uses, especially in the mobility sector, the demand for batteries is poised to grow: Freedonia Group estimated in 2016 that the battery market in the U.S. alone will grow from $18 trillion in 2015 to $28 trillion in 2025. (Beard 2019.)

Compared to the other energy storage technologies, battery energy storage systems are very diverse set of technologies, with differing material constitution, operating temperatures, technological maturity and strengths and weaknesses. But all battery technologies usually share high round-trip efficiency and high energy density compared to other storage technologies. Compared to gasoline-fuelled internal combustion engines, batteries have a higher round-trip efficiency (20-35% vs. 70-90%), but a much lower energy density (10,000 Wh/kg vs. 50-200 Wh/kg). (Rufer 2018.)

4.1 Lithium-ion BESS

4.1.1 The main components of li-ion battery cells

Since its commercial breakthrough in 1991, lithium (Li) has been considered the most promising metal for storing energy: it is relatively abundant, nontoxic, and very light. Especially the low electronegativity of lithium it suitable for applications that need high energy density.

The performance and the price of the li-ion cell is largely determined by the material prices of the cathode and the anode, especially the cathode: the financial consultancy firm Bloomberg estimated that 75% of the price of a battery cell utilizing nickel manganese cobalt cathode comes from the cathode (50%) and the anode (15%) (Frith 2019). The rest of the cost comes from other raw materials (16%), labour and manufacturing (12%) and depreciation (7%). For the anode, graphite has been the conventional material. Lithium and other metal anodes have been suggested as an alternative to graphite anodes, as they would have higher energy density and faster kinetics. But the trade-off is that increased chemical reactivity causes safety concerns, requiring further research before a wide-scale deployment. Instead of development focus on the anode, most R&D has been on the price reductions and performance increases on the cathode. (Kwak et al. 2020.)

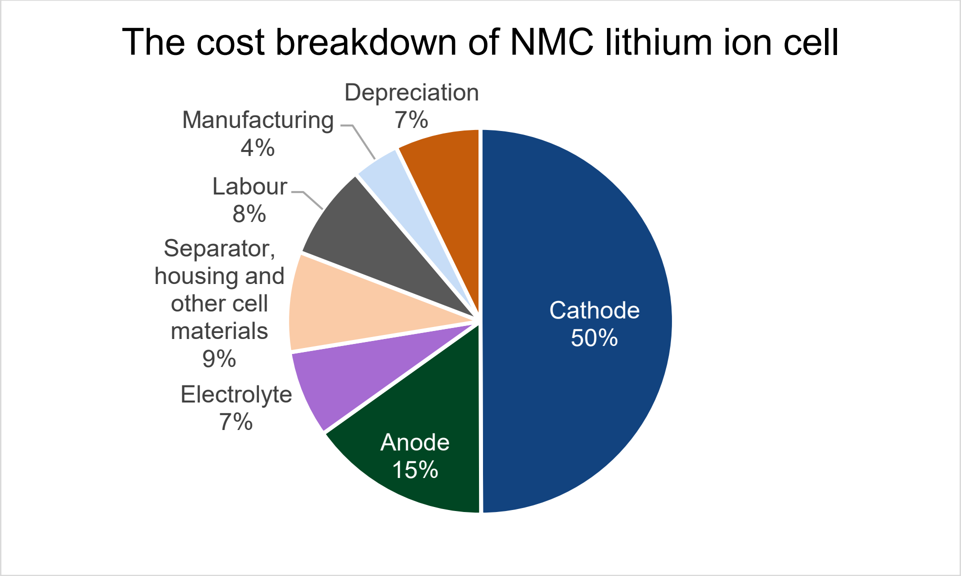
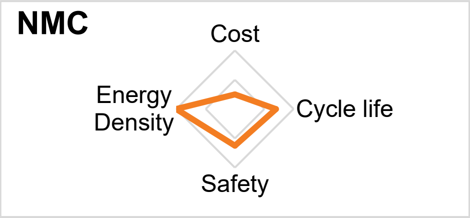
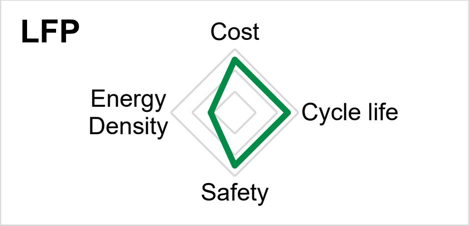


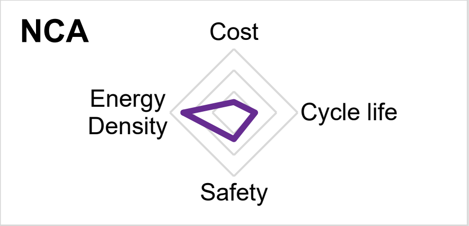
FIGURE 10. Raw material costs of cathode and anode make the majority costs of nickel manganese cobalt cathode (NMC) lithium-ion cell manufacturing (Frith 2020b)

There are various competing cathode chemistries in the market. In this study, three commercial material compositions are compared: nickel manganese cobalt (NMC), lithium iron phosphate cathode (LFO) and lithium nickel cobalt aluminium oxide cathode (NCA) The table on the next page provides a side-to-side comparison of these cathode materials (table 3). Two commercial compositions, lithium cobalt oxide cathode (LCO) and lithium manganese oxide cathode (LMO), are not part of the comparison. LCO is used for hand-held applications but is expensive and has significant safety risks; it has not been deployed in EVs and is unlikely to be used for energy storage. LMO has the energy density one third lower than the chemistries with cobalt and does not have the equal performance and life span to the LFP. (Frith 2019.)

TABLE 3. Comparison of properties of the li-ion cell cathode materials (Frith 2019; Battery University 2019)







Cathode chemistry	**Nickel Manganese Cobalt**	**Lithium Iron Phosphate**	**Nickel Cobalt Aluminium Oxide**
Main materials (by weight)	For NMC 622: Nickel 54.2%, Cobalt 18.1%, Manganese 16.9%, Lithium 10.8%	Iron 60%, Phosphorous 33%, Lithium 7%	For NCA 622: Nickel 71.0%, Cobalt 13.8%, Lithium 11.0%, Aluminium 4.2%
Market pricing in 2020 ($/metric tonne)	From $23,281 (NMC 111) to $27,221 (NMC 811)	$6,519	For NCA 622: $29,370
Stationary storage market share 2019 and forecast 2025	2019: 68% (of which NMC 111: 47%) 2025: 63% (of which NMC 622: 39%)	2019: 31% 2025: 36%	2019: 0% 2025: 0%
Energy density	150 - 220 Wh/kg	90-120 Wh/kg	200 - 260 Wh/kg
Cycles (full cycles)	1,000 - 2,000	2,000	500
Environmental impact	High	Medium	High
Safety	High charge promotes thermal runaway (at 210°C)	Safe battery, high charge does not promote thermal runaway	High charge promotes thermal runaway (at 150°C)
Strengths / Opportunities	+ High energy density + Can be tailored to different uses + Mature supply chain	+ Cheap and abundant materials + High longevity + Lowest environmental impacts + High safety	+ Highest energy density + High manufacturing output
Weaknesses / Threats	- Needs thermal management - Cobalt can create a material bottleneck	- Low energy density	- Unlikely to be used in stationary storage - Needs thermal management - Cobalt can create a material bottleneck

The reason that the battery makers and the market has not yet converged around a single cathode chemistry is that each technology option involves trade-offs: for example, LFP batteries are cheap, fire resistant, more environmentally friendly and with improved cycling rates, making them an excellent choice for energy storage applications. But the trade-off for LFP is lower energy density in the range of 90-140 Wh/kg, which makes the chemistry less appealing to the mobility sectors' applications. (Zubi et al. 2018.)

Even when LFP batteries have currently a marginal role in EVs deployment, battery manufacturers are diversifying their cathode approach. For example, Tesla is using LFP in shorter-range EV applications and for energy storage, and NCA and NMC chemistries for applications that need the increased energy density (Tesla Battery Day 2020). For the denser chemistries (NCA & NMC), the key innovation driver is to minimise the use of cobalt, the priciest battery metal, for their future batteries. Earlier NMC 111 batteries had 1 part of nickel, manganese, and cobalt each. The newer NMC 811 has 8 parts of nickel to 1 part of manganese and cobalt. The financial consultancy Bloomberg forecasts LFP (with a share of 36%) and various types of NMC chemistries splitting the stationary storage market share by 2025 (figure 11). (Frith 2019.)

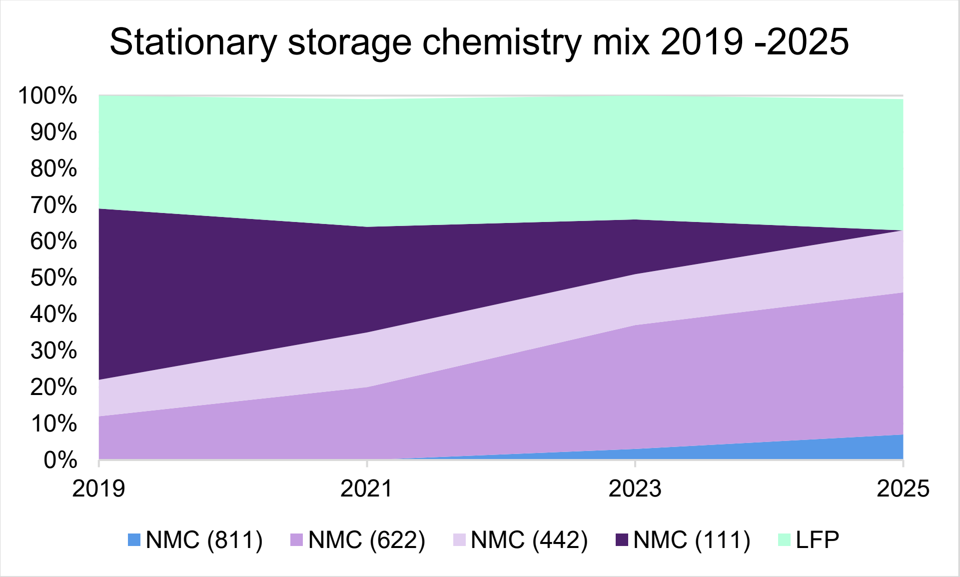


FIGURE 11. Battery manufacturers are minimising the use of cobalt in the lithium-ion chemistries: NMC (111) will be replaced by the other NMC types that wield lower proportions of cobalt (Source: Frith 2019)

4.1.2 Raw materials for lithium-ion batteries

Li-ion BESS manufacturing requires dozens of different metals and non-metals, ranging from abundant zinc (Zn) and iron (Fe) to rare earth elements of cerium (Ce) and lanthanum (La). The most relevant elements for the li-ion BESS are shown in a table below (table 4).

TABLE 4. Most relevant elements for the Li-ion battery sector. (Source: Zubi et al. 2018)

Element	**BESS use**	**Abundance rank**	**Global reserves (Mt)**	**2016 production (Mt/y)**	**BESS industry share**	**Current status**	**Future perspective**
Aluminium (Al)	Cathode foil, NCA	3	11,000	57	<1%	Not critical	Not critical
Iron (Fe)	LFP	4	82,000	1,360	<1%	Not critical	Not critical
Phosphorous (P)	LFP	11	12,000	47	<1%	Not critical	Not critical
Manganese (Mn)	NMC	12	690	16	<1%	Not critical	Not critical
Carbon graphite (C)	Anode, cathode	15	250	1	3%	Not critical	Not critical
Nickel (Ni)	NCA, NMC	24	78	2	1- 2%	Not critical	Not critical
Copper (Cu)	Anode foil	26	720	19	<1%	Not critical	Not critical
Cobalt (Co)	NCA, NCM	32	7	0.1	30%	**Critical**	**Critical**
Lithium (Li)	All cathodes, electrolyte	33	14	0.03	39%	Not critical	**Near critical**

Two metals, lithium (Li) and cobalt (Co) can pose a supply disruption risk for the li-ion BESS industry. Especially cobalt has been a major concern for the industry, with sustained efforts from researchers and battery manufacturers to minimise the need of cobalt for the BESS. Although cobalt is more abundant than lithium, it only exists in low concentrations in soil and is usually extracted as a by-product of nickel or copper (Zubi et al. 2018). Over 70% of the global cobalt production was concentrated in one country, Democratic Republic of Congo (D.R.C). The second biggest producer of cobalt, Russia, accounted only for 5% of total production in 2018 (see figure 12). (Frith 2019.) The lithium-ion battery industry utilises over 30% of cobalt mined, creating a significant supply disruption risk for the sector (Zubi et al 2018).

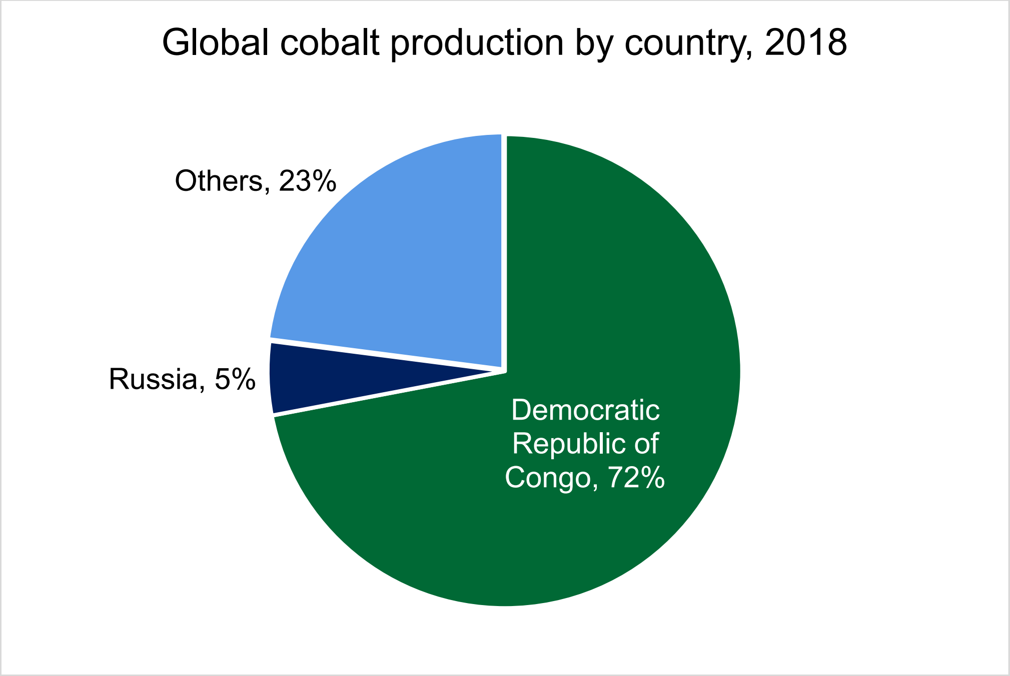


FIGURE 12. Global cobalt production by country in 2018 (Frith 2019)

There are two broad risks in battery industry's reliance on cobalt from the D.R.C: the first is the potential price increases and volatility, and the second is concerns over environmental and social impacts of cobalt mining (see section 4.1.3). The country's political instability can create cobalt supply disruptions: the D.R.C ranked the 5th out of 178 countries on political instability measured by Fragile State Index. The publisher of the index, Fund for Peace, deemed the D.R.C more politically unstable than Afghanistan, Iraq, or Venezuela. (Fund for Peace 2020.) Armed conflicts and weak governance can also deter new mining investments, and there is a risk that the government of the D.R.C will increase the mining royalties, as it did in 2019 (Frith 2019.)

Another potentially critical raw material for lithium-ion batteries is lithium. Its mining is more diversified with 14 million tonnes of global reserves spread across the globe. The biggest global producer was Australia (41% share of lithium production in 2017), followed by Chile (33%), Argentina (12%) and China (10%) (see figure 13). Lithium-ion battery market is growing rapidly, creating a demand for the increased lithium mining: Zubi et al. estimates the market to grow three-fold between 2010 and 2030, from 125 GWh/p.a. in 2020 to 390 GWh/p.a. in 2030 (see figure 14) (Zubi et al. 2018). The financial consultancy Bloomberg is more bullish on their forecast for electric vehicles, estimating that the EV growth in 2030 is nearly seven-fold compared to the estimate of Zubi et al (BloombergNEF 2020a). Even with the greater growth, short-term availability of lithium seems sufficient for a rapid battery market growth; market analysts estimate that the lithium production will almost triple by 2025 and new mines will be deployed across the world (S&P Global 2019). The medium- and long-term projections should also include the recycling of lithium (Phung 2020).

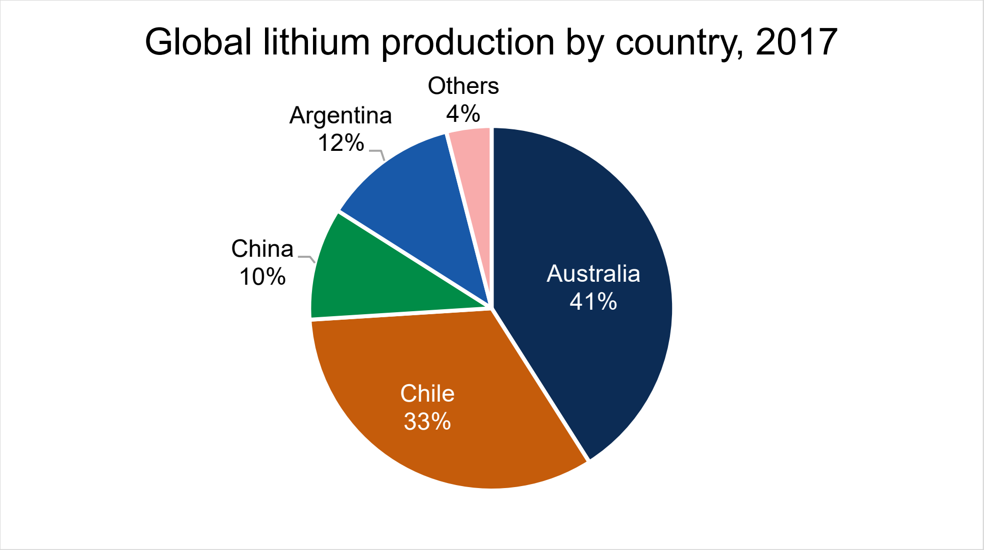


FIGURE 13. Global lithium production by country in 2017 (Frith 2019)

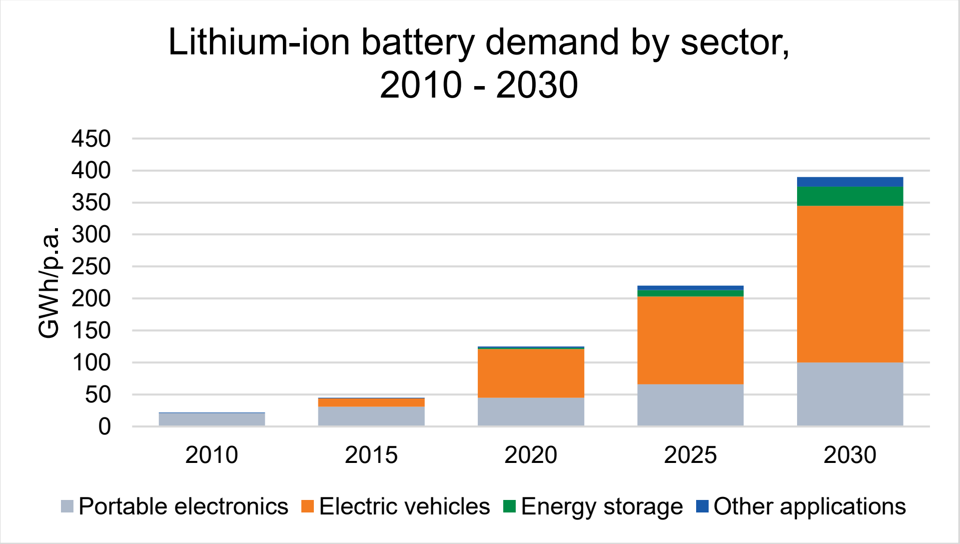


FIGURE 14. Lithium-ion battery demand by sector between 2010 and 2030 (Zubi et al. 2018)

Besides cobalt and lithium, shortages and steep price hikes of nickel and natural graphite could affect the global battery markets, but this seems unlikely. For both elements, batteries consume under 3% of the global production, and there are sufficient global reserves left. The production of natural graphite is highly concentrated in China with 65% of total production, which is a potential risk. The nickel production is diversified across the globe. (Zubi et al. 2018)

The global reserves of relevant metals and non-metals should be sufficient for large-scale uptake of EVs and stationary storage, but supply bottlenecks can happen due to the lack of investments or other problems related to mining or refining. For example, the prices of cobalt soared in 2018 due to exaggerated promises of the EV transition, intensifying political instability in the D.R.C and the market speculation (Slav 2019). After the volatility, the cobalt prices have settled to their historical price of approximately US$35,000/tonne, with forecasts indicating that the cobalt prices go below US$30,000/tonne by Q2 2021 (Trading Economics 2020).

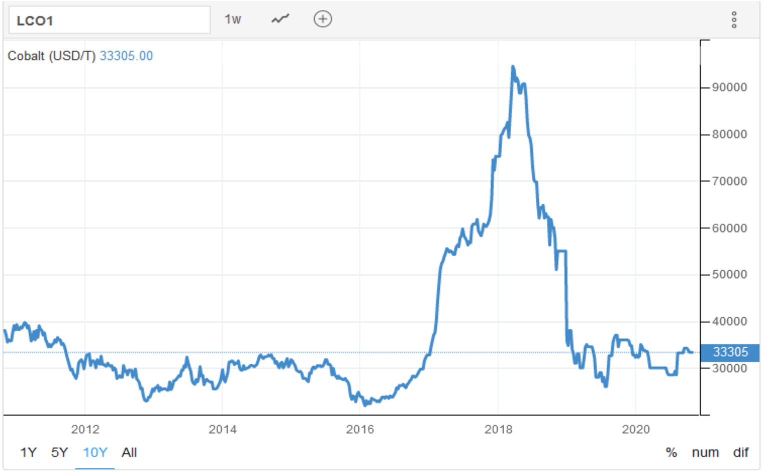


FIGURE 15. Price of cobalt soared in 2018, reaching over US$90,000 per tonne but has since decreased (Trading Economics 2020, screenshot)

For minerals like cobalt the supply is inelastic, meaning that the global supply cannot respond to changes in demand quickly, making them inherently posed to strong price volatility - especially on the spot market. A price escalation can generate pressure to the commodity consumer to undergo material substitutions to reduce the market exposure. But the li-ion battery industry is likely to suffer little from the price volatility: the financial consultancy Bloomberg estimates that the doubling of the price of cobalt and lithium would increase the battery pack prices 4.1% and 4.3%, respectively (BloombergNEF 2020a).

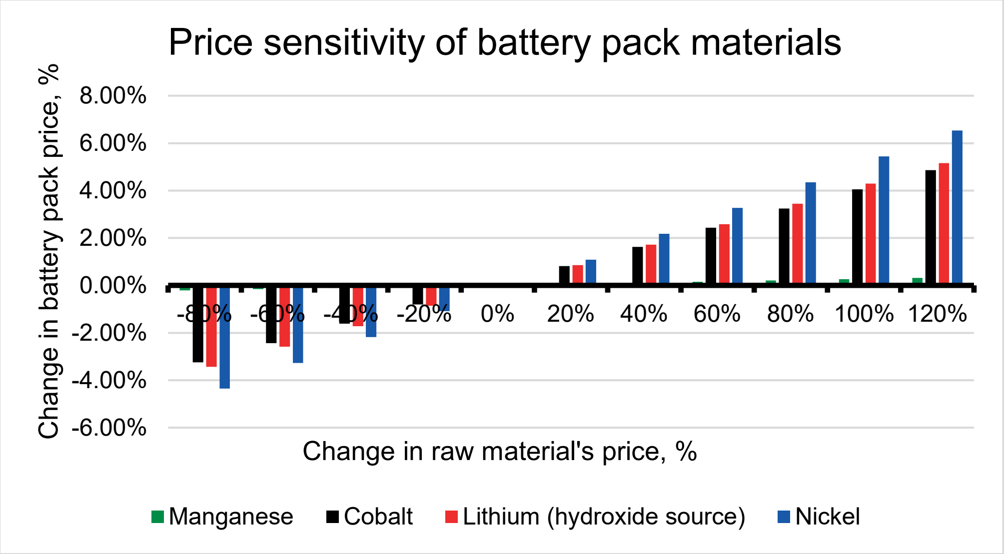


FIGURE 16. When comparing the price sensitivity of manganese, cobalt, lithium, and nickel, the change in nickel pricing can have the most impact to the price of a battery pack (BloombergNEF 2020f)

4.1.3 Environmental impacts of lithium-ion batteries

The environmental impacts of lithium-ion chemistries differ, with each having its own characteristic impacts. But the underlying challenges for all lithium-ion chemistries are the same:

1. The mining of raw materials for battery production has significant environmental and social impacts. The deposits of some raw materials, such as cobalt, are focussed on the developing countries, where poor working conditions and insufficient mitigation of environmental impacts create unsustainable supply chains;
2. As with all emerging technologies, there are deficient know-how and regulation on safety risks of energy storage batteries during transportation, installation, operation, and end-of-life; and
3. At the end of life, battery energy storage can pose social and environmental challenges if not properly managed. Economic drivers and clear policy

directives are needed to establish the waste management ecosystem for BESS. (Florin & Dominish 2017.)

Compared with the other energy storage technologies, lithium-ion batteries have higher environmental impact: Hottenroth et al. compared the environmental impacts of gigawatt-hour scale energy storage systems of lithium-ion BESS and PHES using life-cycle assessment methodology. The methodology compared 14 of environmental and human health impact indicators, including 4 impact indicators for acidification and eutrophication, 3 for human health, 2 for ozone layer, 2 for resource use, 1 for freshwater ecotoxicity, 1 for climate change and 1 for land use (see figure 17). The technologies were assessed for a theoretical lifespan of 80 years, providing 2,600GWh of energy per year in Germany. PHES lasted for the whole lifespan, BESS had to be changed four times. (Hottenroth, Peters, Baumann & Viere 2019.)

Figure 17 shows the impacts of the PHES compared to the 100% baseline of BESS. The study showed that the PHES had more than 20% lower impacts in all but two of the 14 categories. Especially the BESS accounted for much greater impacts associated with the resource depletion; the PHES accounted only approximately 20% of resource depletion of the BESS. The study acknowledged that as li-ion batteries are emerging technology, the potential sustainability improvements are difficult to forecast. (Hottenroth et al. 2019.) Even with the uncertainties, the study shows the significant impact that the battery cell production, especially the mining of raw materials, has on the environment. Other studies also draw a similar conclusion that li-ion BESS are taking a larger toll on the environment than the other storage systems. (Deghani-Sanij, Tharumalingam, Dusseault & Fraser 2019; Immendoerfer, Tietze, Hottenroth & Viere 2017; Florin & Dominish 2017).

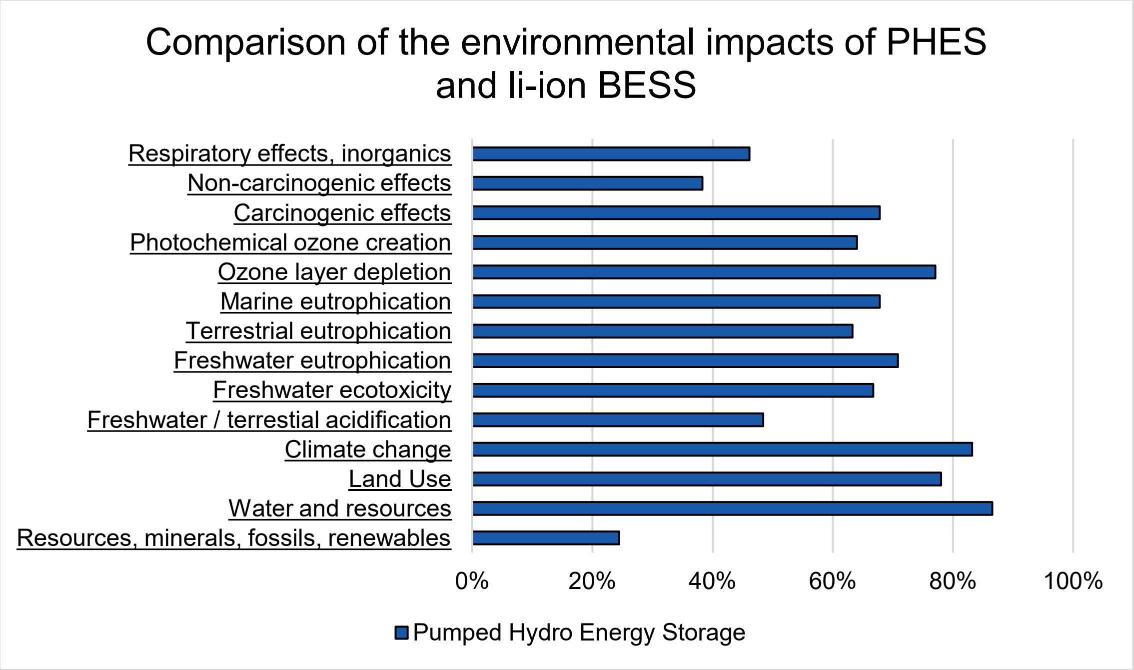


FIGURE 17. Comparison of environmental impacts of PHES and li-ion BESS where the impacts of li-ion BESS are 100% (Hottenroth et al. 2019)

In comparing EVs and gasoline internal combustion vehicles (ICEs), the highly cited study by Notter et al. estimated that ICE has adverse environmental impacts compared to EV by a factor of 1.6. In EVs, most of the environmental impacts are caused by running the motor with electricity generated by fossil fuels. Only 15% of the impact is caused by the production of the li-ion battery. (Notter et al. 2010.) But not all scientists agree: the newer study made by Bicer & Dincer estimated that EVs, even when they use renewable electricity, will not have lesser of an environmental impact compared to ICEs (Bicer & Dincer 2018). Both studies agreed that most of the manufacturing impacts come from copper and aluminium; Notter et al. estimated that the copper causes 43% of the environmental burden of a li-ion battery (2010).

Aside from aluminium and copper, serious concerns have been raised in the recent years regarding ‘artisanal’ mining of cobalt in the D.R.C. The artisanal mining is done by an independent subsistence miner, usually with hand tools and low safety standards. The mining can include child labour, and the poor environmental mitigation exposes the local communities to adverse impacts of soil and water pollution. It is not always easy to identify and exclude the mines with bad practices: the cobalt moves from small mines to local branches of multinational mining companies, and therefore to the international markets. (Zubi et al. 2018.) The financial consultancy Bloomberg estimates that the artisanal mining makes up from 5% to 10% of the global cobalt supply (Frith 2019.)

Even with the harmful environmental impacts, lithium-ion batteries have a potential to contribute to creating more sustainable transportation and power sectors. But this requires serious and sensible efforts from all stakeholders. The key actions include:

- minimising the carbon footprint of electricity generation;
- building an effective li-ion battery collection and recycling scheme;
- minimising the use and improving the sustainability practices of aluminium, cobalt, and copper production;
- emphasising sustainability in the innovation framework of battery chemistries and materials;
- exploiting new concepts of vehicle to grid (V2G) and second-hand batteries; and
- incentivising the wider implementation and market growth. (Zubi et al 2018.)

4.1.4 Safety of stationary lithium-ion storage

Electronegativity measures the tendency of an atom to attract electrons, resulting in enhanced attribute to store and produce electricity. Electronegativity makes lithium a highly attractive material for batteries, but also makes it highly reactive with oxygen and water. The reactivity can cause serious safety issues: for example, if li-ion batteries are excessive heated or the system is short-circuited, the li-ions break free to react with oxygen, causing a fire. There have been especial concerns for the safety of the large-scale li-ion BESS following the South Korean battery fires of 2017-2019.

In 2019 alone, there were 23 BESS-related fires in South Korea. In the aftermath, new safety measures were implemented, and South Korean battery manufactures announced compensation to storage operators for the revenue losses.

(BloombergNEF 2019.) An investigation ordered by the South Korean government found that the combination of poor-quality installations, lack of control systems and faulty operating procedures were at fault for the fires (S&P Global 2019). However further fires were witnessed even after the implementation of the safety measures and the battery installations plummeted in South Korea (Day 2020).

For the fire safety, other battery chemistries are safer - namely, lithium iron phosphate cathode - than others. Extensive R&D is undertaken to make li-ion batteries safer while still improving the energy density and other properties of the batteries. (Zubi et al. 2018.)

4.2 Lead acid and sodium sulphur batteries - legacy technologies

Following lithium-ion BESS, Sodium sulphur (NaS) and lead acid (PbA) batteries are the second and third most deployed battery energy storage systems. The financial consultancy Bloomberg estimates that there are 100 PbA and 26 NaS energy storage systems deployed, with total power capacity of approximately 320MW and 335MW, respectively (BloombergNEF 2020d). Both battery systems are technologically mature and have abundant raw materials. NaS batteries are longer lasting than lithium-ion BESS, and PbA batteries have lower self-discharge rates. However, it is unlikely that they can compete with lithium-ion and other emerging battery chemistries. Both technologies suffer from lower energy density and round-trip inefficiency compared to lithium-ion batteries. This, combined with PbA batteries' susceptibility to high depths of discharge and NaS batteries' fire and other safety issues, creates a limited market appetite for the future utility-scale deployments (see figure 23). (BloombergNEF 2020a; ADB 2018.)

4.3 Emerging battery technologies

Any application that has a voltage difference between two terminals and a medium that can transport the electrons between the terminals can potentially act as a battery. This study cannot possibly include all the emerging technologies that might become commonplace in the future: battery technologies such as the nickel-63 radioactive nuclear battery that has an energy density over ten times that of a conventional lithium-ion battery (3,300 Wh/kg vs. 200 Wh/kg) or an electric eel inspired biological battery - although great examples of human ingenuity and possibly the best choices for storing energy in future - currently remain a research curiosity (Moscow Institute of Physics and Technology 2018; Schroeder et al. 2017). The following two battery technologies, flow batteries and metal-oxygen batteries, provide some superior attributes compared to the current mature technologies while also showing the potential for the techno-economic viability in short- to medium-term.

4.3.1 Flow batteries

Like lithium-ion batteries, flow batteries are electrochemical devices that use the potential voltage differences in the oxidation states of certain elements to store or discharge electricity (Daggett 2019). But unlike lithium-ion, which utilises battery cells, flow batteries have liquid electrolytes that are stored in external tanks. This feature enables decoupling of power and energy, thus providing flexibility of design and the potential to use flow batteries for longer-duration applications compared to lithium-ion systems (Beard 2019). The use of non-flammable electrolytes ensures that the flow battery technology is generally safer than lithium-ion systems. Also low depletion of active materials provides flow batteries with a long lifetime of over 10,000 cycles (Giovinetto & Eller 2019). All-vanadium redox flow battery, the most mature flow battery technology, use vanadium both in the cathode and the anode, simplifying the battery management during operation, maintenance, and shipment (Beard 2019).

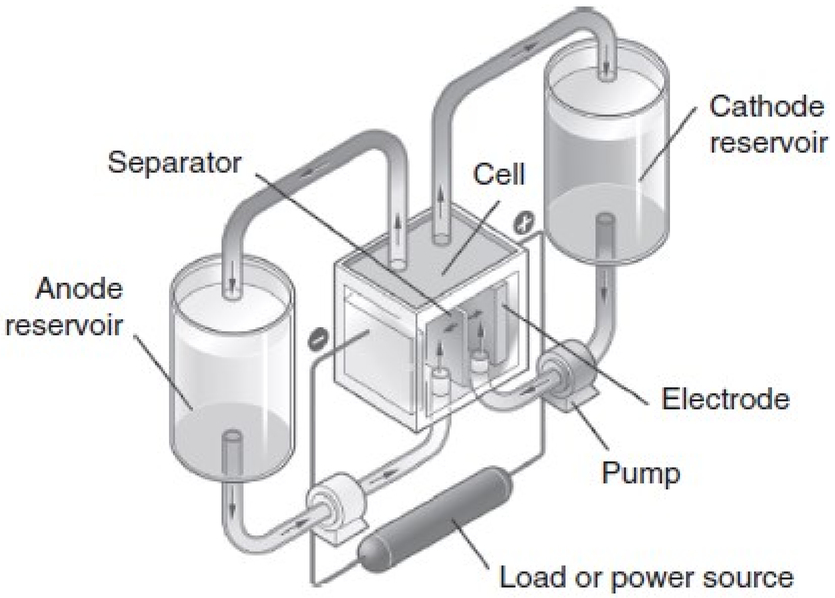


FIGURE 18. General scheme of a flow battery (Beard 2019)

In the early 2010s there were high expectations for flow battery technology: both flow and lithium-ion batteries were at demonstration stage of their technological development, with numerous small projects under way (Dunn, Kamath & Tarascon 2011). But during the years their progress has diverged, and by 2020 there had been only 140 MW of flow battery projects deployed compared to over 4,500 MW of lithium-ion projects (Bloomberg 2020d). Lithium-ion, with the help of economies of scale from the electric vehicle market, captured the nascent energy storage market, and put some leading flow battery companies into insolvency (Deign 2019). As the need for the longer duration energy storage increases in the future, flow batteries still have a large addressable market. But the technology will face an increasing competition from incumbent lithium ion and other emerging storage solutions. (Bloomberg 2020a.)

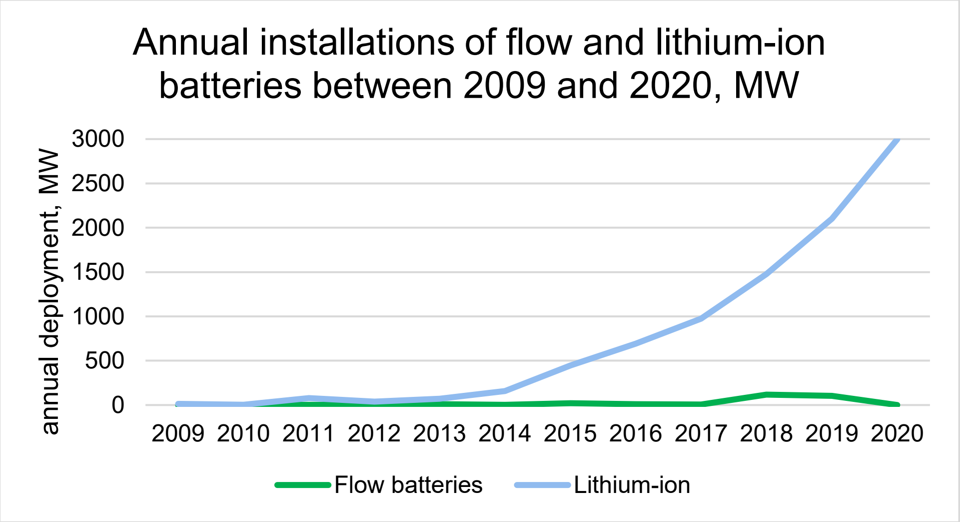


FIGURE 19. Flow batteries, albeit a promising energy storage technology, have not been able to compete with the growing popularity of lithium-ion BESS. (Bloomberg 2020d)

4.3.2 Metal-Air

Metal-air batteries, with a promise of cheap and abundant raw materials, and a higher specific energy compared to lithium-ion batteries, have attracted a significant research interest in the recent years. Metal-air batteries combine some of the characteristics of batteries and fuel cells: instead of closed system, like lithium-ion batteries, metal-air batteries have an open system that uses oxygen from the ambient atmosphere. The oxygen is held by a porous cathode that reacts with an anode consisting of pure metal, such as lithium, sodium, iron, or zinc. Metal-air batteries have high theoretical energy densities, ranging from 1200 Wh/kg (iron-air) to 11,429 Wh/kg (lithium-air), and can be made more sustainably from more abundant metals, such as iron or zinc. The potential energy density of the metal-air chemistries makes the battery especially well-suited for mobility applications. (Li & Lu 2017.)

The metal-air technology is not new; zinc-air batteries entered the market in 1932 and have been used for decades on small, button-type primary cells for hearing aids and similar applications (Liu & Lu 2017). For the rechargeable metal-air chemistries, zinc and lithium have gained the most interest: zinc due to its relative stability, relative raw material abundance and suitability for the electrodeposition from an aqueous electrolyte, and lithium because of its high theoretical voltage and electrochemical equivalence. The other metal-air chemistries suffer from instability, parasitic corrosion, safety, or practical handling issues that have made the development of commercial products unviable to date. (Beard 2019.)

There are still numerous challenges facing metal-air chemistries for the large-scale commercial deployment. The practically attainable energy density has been significantly lower than the chemistry's theoretical energy density: in zinc-air batteries, the energy densities have been between 350 to 500 Wh/kg, compared to its theoretical potential of 1,353 Wh/kg. Both cycling rate and round-trip efficiency of zinc-air have been poor compared to lithium-ion batteries. The lithium-air faces similar issues as zinc-air technology and has an orders of magnitude slower charging rate than lithium-ion, making it an impractical choice for electric vehicles. The metal-air chemistries hold a great promise, but the commercialisation is still years away. (Li & Lu 2017.)

5 ENERGY STORAGE MARKET OVERVIEW

Pumped hydro energy storage system (PHES) accounts a dominant share of the total deployed energy storage globally, with nearly a 97% of total rated energy storage power capacity, according to the U.S. Department of Energy's database. As of August 2020, the total installed pumped hydropower capacity was 168 gigawatts (GW), with deployments in China, the U.S. and Japan constituting over 50% of the total share. New additions of PHES in the developed Western countries have decreased, but China continues to add new pumped hydro capacity to increase its energy system flexibility and optimise its coal and nuclear plant operations (Sun, Wei, Wang, Xu, Sheng, Xie & Nan 2019). Other APAC countries with PHES capacity are Australia (2.5GW), India (6.8GW), Indonesia (1.0GW), South Korea (4.7GW), Philippines (0.7GW), Taiwan (2.6GW) and Thailand (1.3GW). (DOE OE Global Energy Storage Database 2020.)

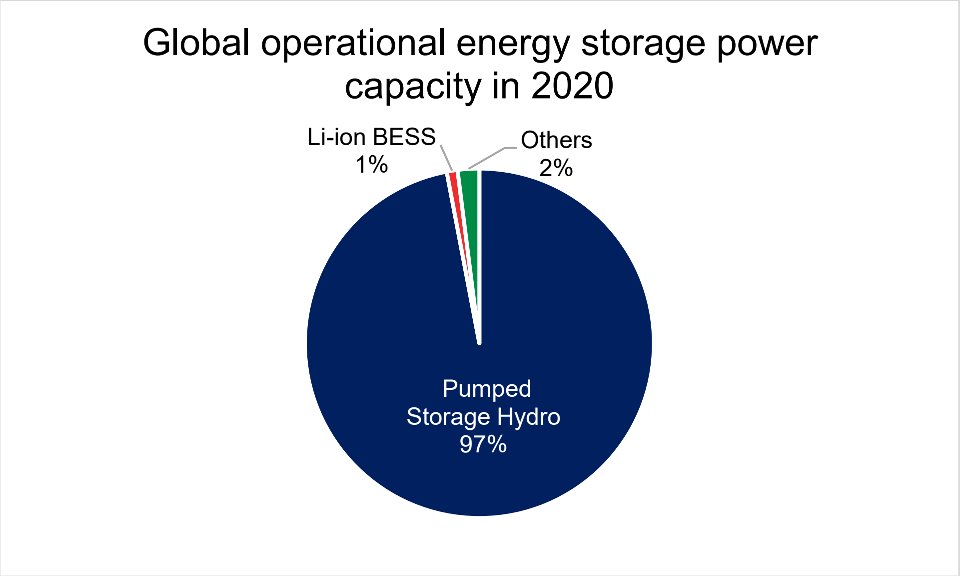


FIGURE 20. Global operational energy storage capacity in 2020 (DOE 2020)

The remaining 3% of the global operational energy storage power capacity comes mostly from lithium-ion and other batteries, thermal storage, and flywheels. The market share of BESS has been hampered by their small size compared to the large-scale PHES deployments: as of August 2020, there has been over two times more battery storage deployments versus PHES ones (768 to 327, respectively), but the average size of PHES has been nearly 250-fold compared to an average battery project (510MW vs. 2.3MW). (DOE OE Global Energy Storage Database 2020.)

PHES deployments are poised to grown in the 10-year horizon. The International Renewable Energy Agency IRENA estimates that PHESs will nearly double its capacity from 2018, growing from 161 GW to 300 GW by 2030. After 2030, the PHES capacity is estimated to only increase 25 GW between 2030 and 2050, as the lack of suitable sites and the emergence of other long-term storage technologies will diminish the deployments. There are multiple ongoing PHES developments across the globe, including:

- PHES in Kyushu, Japan to limit the solar curtailment in the region and provide security in a case of the shutdown of the island's baseload power;
- a 300MW/~16GWh salt-water PHES coupled with a 500MW solar in Atamaca Desert, Chile to provide the baseload power for 5% of northern Chile's demand. This would be the first baseload plant that uses intermittent generation; and
- In Australia, there are multiple PHES project developments, including Kidston PHES project in Queensland, Dungowan Dam PHES in New South Wales and Bendigo Mines PHES in Victoria. (IRENA 2020; Bendigo Sustainability Group n.d.; Power Technology n.d.; Filatoff 2020.)

The increasing need of energy storage services provides the other technologies than PHES opportunities. According to the financial consultancy Bloomberg, in the next ten years the non-PHES energy storage solutions will break the glass ceiling and become commonplace in the energy sector: the consultancy forecasts cumulative energy storage capacity to grow from 39 GWh of 2019 to nearly one terawatt-hour (926 GWh) of 2030, with an annual average installation capacity of over 82 GWh (BloombergNEF 2020d). The consultancy company Deloitte outlined the drivers for the increasing demand for energy storage:

- declining costs of the technologies;
- the increasing need for renewable energy integration;
- the potential to assist in the grid modernisation;

- increasing policy incentives for the emissions reduction and the global movement towards renewables;
- regulatory updates that allow the asset owners to participate in power quality and wholesale electricity markets; and
- the energy storage cost-reductions makes the energy self-sufficiency possible for commercial and residential customers (Deloitte 2018).

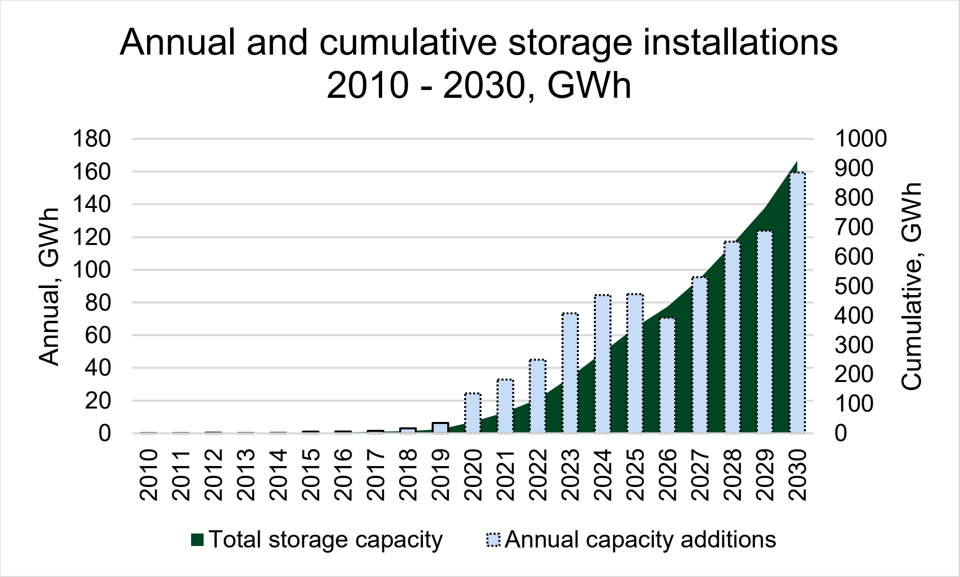


FIGURE 21. Annual and cumulative storage installations between 2010 and 2030. (BloombergNEF 2030d)

Even though that the energy storage can provide variety of services, in the next five years, the expected primary use case for a new storage capacity will be the energy shifting of co-located solar - especially in places where there is already a mature renewables market, such as in Australia and China - and short-term power quality applications - especially frequency regulation (BloombergNEF 2020e). After 2025, the potential uses for grid modernisation, industrial, commercial & residential storage, and intra-week energy shifting will become more viable due to the energy storage cost-reductions. The wide-spread storage solution for seasonal storage is most likely still a decade or decades away.

To this day, non-PHES energy storage deployments have focussed on providing power quality and renewables integration services instead of providing energy shifting: Bloomberg estimated that of the 249 non-PHESs deployed in 2019 only

6 were used primarily for energy shifting (Bloomberg 2020a). Once energy storage technologies reach the price parity with fossil fuel peaking generation - which is estimated to happen in the next few years in markets with a high renewables generation - there will be an increasing uptake of energy storage systems (Mazengarb 2020; Wamsted 2019).

It is likely that lithium-ion BESS will count for the most non-PHES capacity additions, especially in the next five years: li-ion battery costs dropped by a factor of ten in the 2010s, similar to the cost-reductions of wind and solar power. At the same time, the specific energy density increased by nearly 25%. These favourable developments have been driven by increasing applications of portable power tools and electronics (such as mobile phones, tablets, and laptops), and the rise of electric vehicles (EVs). With the cost-reductions and improved properties, the lithium-ion battery powered EVs are expected to fundamentally disrupt the transportation market within this decade. (Hill & Mills-Price 2018.)

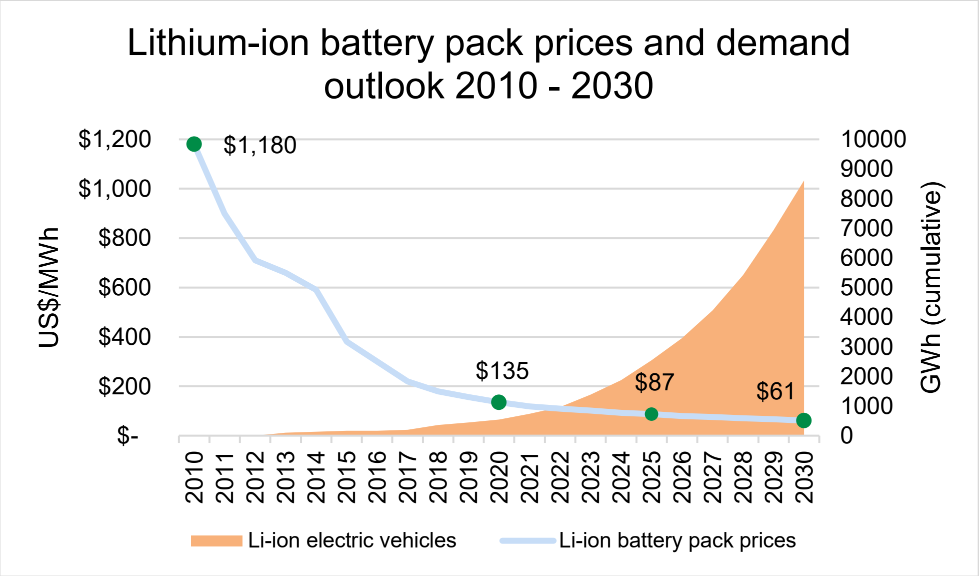


FIGURE 22. Bloomberg forecasts that the continuing cost-decrease in lithium-ion battery packs fuel the intake of li-ion electric vehicles (EVs) (BloombergNEF 2020a)

As the transportation sector lead the way in the deployment lithium-ion batteries, the energy sector is following at increasing rates: at the first half of 2020, 99% of energy storage deployments have been lithium-ion (Frith 2020a) (see figure 23).

This dominance reflects that financiers are familiar and confident with the technology, developers and engineering, procurement, and construction (EPC) companies have the know-how to develop and install the projects, the supply chain has been established, and there is a confidence in the technology's future pricing and development. This kind of technological maturity is especially important in large-infrastructure projects, where the initial capital expenditure is ranging from tens of millions to billions of U.S. dollars and the revenues are gained during the lifetime of the asset, which can be decades. (BloombergNEF 2020a).

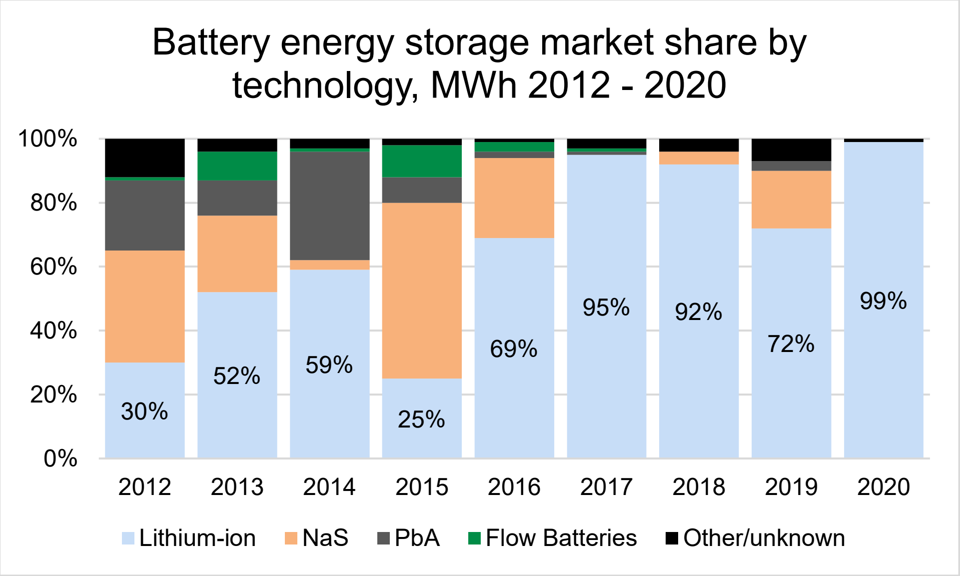


FIGURE 23. In the early 2010s, sodium sulphur (NaS), lead-iron (PbA) and flow batteries were deployed at similar rates to lithium-ion batteries, but as the cost of lithium-ion systems have decreased, the developers have coalesced using the li-ion BESS (Frith 2020a)

The development of business ecosystem around lithium-ion BESS creates an uphill battle for other emerging technologies to gain market share. Especially in power quality applications and daily energy shifting applications, lithium-ion seems to be the energy industry's choice of technology - at least in the medium term. But lithium-ion has some technical and commercial weaknesses that other emerging technologies can expose and create their market niches. Table 5 provides an estimation what services lithium-ion is well suited to provide, and the potential competitive technologies on the applications where lithium-ion is not well-suited.

TABLE 5. Lithium-ion BESS is not suitable for all energy storage applications (green = li-ion is well suited for the application, yellow = there can be challenges for li-ion to provide this application, red = li-ion is not well suited for the application) (BloombergNEF 2020a)

Application	Li-ion suitability	Potential competitors
1-4h energy shifting	🟩	
5+h energy shifting	🟥	PHES and other mechanical storage, CAES, flow batteries
Seasonal energy shifting	🟥	Hydrogen, electrothermal storage
Frequency regulation	🟩	
Inertia	🟥	PHES and CAES
Synthetic inertia	🟩	
Load following	🟩	
Black start	🟩	
Voltage control	🟩	
Potential to use “brownfield” sites	🟥	Some CAES technologies, mechanical storage
Combined Power + Heat	🟥	Electrothermal storage
Not constrained by location	🟩	
No exposure to volatile commodities	🟨	PHES, CAES, electro-thermal storage, Zinc-air, flywheel
Established supply chain	🟩	

The energy market disruption by energy storage is only emerging. Even lithium-ion has a headway compared to the other storage technologies, its unsuitability for some applications, especially for long term energy shifting, will provide market opportunities for other competitors. There are multiple companies and technologies vying for intra-week energy shift of 5 hours or more. These include:

- smaller companies like Highview Power with its compressed liquid air technology, EnergyVault whose technology utilises gravitational potential and sulphur-based storage technology Form Energy have all amassed venture capital worth tens of millions of US$; and
- more established companies such as Siemens Gamesa with an electrothermal storage and Lockheed Martin - better known as an aerospace and arms company - with a flow battery solution (BloombergNEF 2020a).

6 DISCUSSION

One of the most pressing issue for the energy transition is to find a safe, modular, low-cost energy storage solution built sustainably from abundant raw materials. Wind and solar energy can produce decarbonised electricity, but their intermittency demands new solutions, especially in storing energy. Pumped hydro energy storage and lithium-ion batteries have both been deployed at utility-scale for energy storage, but neither of them fulfils all four requirements of safety, modularity, low-cost and sustainability. Pumped hydro energy storage system (PHES) - albeit safe, relatively sustainable, and relatively low cost - is not modular, and lithium-ion batteries are not yet truly low-low cost, have issues with its safety, cannot decouple power and energy for greater modularity, and need raw materials whose production exact high environmental cost.

Even with their deficiencies, both technologies are still ruling the energy storage market: of all the energy storage deployed, nearly 97% is pumped hydro energy storage, and the recent non-PHES deployments are nearly solely lithium-ion batteries. These facts reflect:

- the technological maturity of PHES;
- the increasing use of lithium-ion technology in portable electronics and electric vehicles, ensuring technological breakthroughs and cost reductions for the lithium-ion batteries; and
- that the energy storage market in its early innings, and there has not been enough demand for energy storage for other technologies to break through.

The market is very new and has not united behind any technology, nor even the mode of energy conversion: there are multiple exciting companies creating their proprietary technologies that utilise electrothermal, mechanical or electrochemical energy conversion. As the incumbent technologies, the emerging technologies have too their weaknesses and trade-offs, and it is still too early to assess which technology or technologies will lead the energy sector through the energy transition.

Energy storage is can provide plethora of services and has attracted interest from various stakeholders across the energy supply chain. These services can be divided into short-term power quality services and longer-term energy shifting services. For the energy applications under four hours, both power quality and energy shifting, lithium-ion batteries are currently the market leader. As there is the technological pathway to further improve the lithium-ion battery properties and reduce costs, it is unlikely that other technologies will be used for short-term energy storage applications at a large scale in this decade, except in niche services such as providing mechanical inertia. For the energy applications of five hours and more, lithium-ion BESS will most likely remain prohibitively expensive. This market segment of longer-term storage is led by pumped hydro energy storage, but locational constraints excludes its rise to a sole long-term energy storage technology.

Shifting from fossil fuel economy to one based on renewable technologies is a daunting challenge for the global community. Fossil fuels are the bedrock of the modern societies and have provided the developed world a lifestyle that has been the richest and most comfortable in human history. Even that the current alternative solutions are not there yet, the ever-abundant force of human ingenuity can create an energy system of the future that is even cleaner, cheaper, smarter, decentralised, and sustainable than the current one. Innovations in energy storage provide a crucial element for an energy system of the future.

7 CONCLUSION

The purpose of this study was to provide an overview of the energy storage systems as a part of energy storage business case. It aimed to provide information on the reasons to deploy energy storage systems, the major energy storage technologies, especially on the battery energy storage technologies, and the trends for the energy storage market. As an applied research project, the study utilised wide range of high-quality scientific and sector-specific literature to create a snapshot on some aspects of the energy storage sector.

The research showed that pumped hydro energy storage is the most used system to store electricity, but in the long-term, the geographical constraints and potential emergence of other long-term storage technologies will diminish the new installations of pumped hydro energy storage. Lithium-ion battery energy storage systems have benefited from the rise of the lithium-ion electric vehicle market and are becoming more commonplace in stationary energy storage systems. Both these technologies have their weaknesses, enabling market opportunities for other energy storage technologies.

Creating a comprehensive energy storage business case is an undertaking that requires intricate, multi-disciplinary understanding of various topics. The future research could encompass:

- international, country, and state-wide regulations and subsidies for energy storage projects;
- the identification of potential markets for deploying energy storage projects;
- the structure and the implementation of energy storage services agreements;
- financial modelling of energy storage, including the identification of stakeholders and potential sources of cash flow for energy storage ‘revenue stacking’;
- the contractual framework, including risk-sharing arrangements; and
- the comparison of major lithium-ion battery packs for energy storage,

among other topics.

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