5.4 BATTERIES

Low carbon technologies are necessary to address global warming issues through electricity de-carbonization, but their large-scale integration challenges the stability and security of electricity supply. Energy storage can support this transition by bringing flexibility to the grid but since it represents high capital investments, the right choices must be made in terms of the technology and the location point in the network. Most of the potential for storage is achieved when connected further from the load, and Battery Energy Storage Systems (BESS) are a strong candidate for behind-the-meter integration. This work reviews and evaluates the state-of-the-art development of BESS, analyzing the benefits and barriers to a wider range of applications in the domestic sector. Existing modelling tools that are key for a better assessment of the impacts of BESS to the grid are also reviewed. It is shown that the technology exists and has potential for including Electric Vehicle battery reuse, however it is still mostly applied to optimize domestic photovoltaic electricity utilization. The barriers to a wider integration are financial, economic, technical, as well as market and regulation. Increased field trials and robust numerical modelling should be the next step to gain investment confidence and allow BESS to reach their potential.

Main Components and Working Principles

A battery is a device capable of converting electrical energy to chemical energy and vice-versa via oxidation-reduction (redox) reactions. The base element of a battery is the cell, which is composed of two electrodes (one positive, one negative), the electrolyte, and a separator. During the charging process, a voltage difference is applied between the two electrodes, imposing the current to flow in a certain direction. The consequent excess or deficit of electrons at the electrodes generates reactions between the molecules at their surface, in the electrolyte. The latter consists in the liquid or solid substance in which the electrodes are immerged. Its role is also to enable and facilitate the circulation of charge carriers between electrodes. During the discharge phase, the reverse chemical reactions take place when the circuit is connected to a load, leading to a flow of electron on the other direction until the chemical components are all consumed. The performance of a battery cell depends on the chemistry of its components, and the reactions created: Typically, the elements enabling the highest voltage difference between the electrodes,

at the lowest weight are sought for. The maximum amount of current and voltage a cell can deliver is limited so in order to reach higher values, a number of cells may be connected together in series or parallel. The term “Battery” or Battery Energy Storage System (BESS) are often used to refer to the complete system composed of this group of cells, some control electronics, and the protecting packaging around them. The electronic part is often called Battery Management System (BMS). In simpler systems, its role may only consist in ensuring that the cells’ voltage, current and other physical quantities remain in the range of acceptable values and shutting down the system if not. In more complex systems, individual cell management based on State-of-Charge (SoC) calculation, voltage, temperature, and
other parameter measurements may be provided by more sophisticated BMS.

Chemistries

There are a wide variety of chemistry compounds out of which a battery cell can be made. However, the different chemistries bring about different properties, such as the energy density (total energy that can be stored by mass or volume unit) or the cycle-life (number of charge-discharge cycle executed before the overall performance drops significantly). The numbers provided are to be taken as guide values considering that each chemistry type is composed of a spectrum of variations, since the performance vary depending on the precise chemical composition. Lead-Acid (PbA) batteries are the oldest type of rechargeable batteries and have evolved in two main categories: Flooded and sealed batteries. They are now a very mature and established chemistry, widely used regarding many possible applications thanks to low costs, low maintenance requirements, and low self-discharge. Despite this, other chemistries are overtaking PbA batteries, as their applications are limited because of potential toxicity, weight, and low energy density, in particular Lithium-based chemistries since the early 2000s. The five most present Nickel-based (Ni-Based) batteries, are Nickel-Cadmium (NiCd), Nickel Metal Hydride (NiMH), Nickel Iron (Ni-Fe), Nickel Zinc (Ni-Zn), and Nickel Hydrogen (NiH2). NiCd batteries rapidly developed in the 1980s as the first competitor to PbA batteries which it remained for a few decades thanks to their robustness and long cycle-lives and good load performance for costs comparable to those of PbA cells NiMH cells appeared in the 1990s as an alternative to the cadmium (toxic element) present in NiCd batteries, with less memory effect, and higher capacities, at similar costs and durability. However, their self-discharge rates turned out to be even higher than the already high ones of NiCd, and their operation more delicate. The other Ni-based cells present variations in performance—which never enable them to overtake neither PbA nor Lithium-based batteries—but still can claim a fair share of the overall battery market, at least for some specific applications. Most of the domestic batteries available and developed nowadays are equipped with Lithium-Based (Li-based) batteries. This chemistry emerged in the late 1990s, first as expensive products, but with rapidly decreasing costs promoted by the need for light and portable Energy Storage (ES) solutions. The two main types of li-based cells are Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or more commonly NMC), and Lithium Iron Phosphate (LiFePO4, referred to as LFP). NMC batteries have higher energy and power densities but their stability is compromised by the presence of Nickel at the cathode. LFP batteries' market share increased in recent years, led by an interest in their much higher stability at high currents or temperatures, with a similar cycle life, its main disadvantage being lower energy density. LFP cells are more and more used for domestic batteries, where a moderate increase in mass or volume is acceptable if it brings about enough extra safety. Lithium Titanate (Li4Ti5O12) is another type of Li-based cell, which provides more safety and increased cycle-life, coming at the cost of lower energy density, and a doubled price compared to NMC cells. Other chemistries should be mentioned: Lithium Cobalt Oxide cells present a high specific energy (therefore very present in portable electronics) but low stability and load capabilities, as well as a short life span. Lithium Manganese Oxide cells trade off a higher stability for lower capacity and a still limited life time, and Nickel Cobalt Aluminium Oxide cells present a great potential in many aspects, but remain a very expensive chemistry. Flow batteries have a slightly different functioning principle to the other batteries—which makes them difficult to be compared with the criteria used. They present the technical advantage of independence between energy capacity and power output and can achieve very long cycle life at full. Depth of Discharge (DoD). Still, they struggle to move away from laboratories for a few reasons, mainly because the energy density is limited by the ion concentration in the electrolyte. Additionally, the need for extra components such as tanks, pumps and pipes increase the costs and reduces the overall performance. Therefore, they are not likely to be part of the early models to be implemented as domestic batteries in the short term. For a more detailed review of the history of the chemistries, the readers are referred to Scrosati, and to Linden and Reddy for thoroughly detailed nuances of chemistries and operating principles of batteries.

Battery Ageing and Degradation

One determining parameter when deciding the chemistry and the operation strategy of a battery is ageing, described as the decrease of its performance over its calendar life (in years) or cycle life (in number of cycles). Aging corresponds to the total amount of energy that a battery can store, and the power output decreases with time and utilisation. The State of Health (SOH) defines the decrease in the maximum amount of energy that a cell can store, compared to its original capacity, and the End of Life (EOL) defined as the time, or number of cycles after which the SOH reaches a certain value (typically 80%, but it can vary depending on the constructor). There exist many different ageing processes depending on the chemistry considered. They stem from either side-reactions occurring in parallel to the normal energy storage process, or from side effects of normal operation reactions. The rate and impact of these reactions can be alleviated or worsen depending on the voltage, current, temperature and SOC operating values. High temperatures tend to increase the kinetics of chemical phenomenon, thus increased side-reactions, for instance the Solid Electrolyte Interphase (SEI) in Li-based cells or grid corrosion in PbA cells. Low temperatures on the other hand reduce this kinetics according to Arrhenius law, increasing the internal impedance which limits the performance, but also favouring lithium plating for instance. High and low SOC usually correspond to less stable states. At high SOC, Ni-based cell experience crystalline formation, reducing the performance, which can be reversed if handled early enough. Low SOCs favour the sulphating of the negative electrode of PbA cells. High rates of charge or discharge lead to higher reaction rates in general that can enhance SEI formation in Li-based cells or more generally elevate the temperature, with risk of bringing about issues mentioned above. For these reasons, the state of each cells in a battery pack is managed—in higher-quality models at least—to keep voltage, current, temperature and SOC values in ranges that are as unfavourable as possible to these unwanted phenomena. The degradation of cells was shown to have a considerable impact on achievable revenues by Al-Zareer, Dincer and

Rosen, and a significant increase in potential profitability can be achievable by optimising cell operations to decrease ageing.

Solar PV Batteries

There are still barriers to a large integration of ES - which does not only regard the domestic level. The main one to date being probably the economic viability. The latter is highly dependent on individual context elements, but according to Rappaport and Miles, and Staffell and Rustomji, the cost of domestic batteries is still too high to enable the breakeven point to happen before the end of life of the systems. Still, a higher remuneration of service provision would lead to earlier breakeven points. Under five years is achievable, especially if the technology costs were to decrease as stated by Neubauer and Simpson, and Muenzel et al. states that systems could become economically attractive “in the near future”. Two specific cases studied and reported by Günter and Marinopoulos even conclude that storage can already be profitable, under particular conditions. From this literature, it seems that profitability for a full system—rooftop PV panels, Electric Vehicles (EVs), Heat Pumps (HPs), or a combination of them—associated with a battery can be reached in the more or less near future depending on the context. A few companies started the commercialisation of domestic batteries mostly as “Solar Batteries”: Either as retrofitting or for a new PV installation. Elon Musk’s Tesla Powerwall and Powerwall II played a significant role in the acknowledgement of domestic BESS as a potential future mainstream product. Tesla’s batteries are equipped with lithium-based chemistry which also composes the majority of the other battery cells: The German Sonnen, the South Korean LG Chem RESU, the Chinese PylonTech US200B, and the American Simpliphi PHI. LFP and NMC are the most present chemistries in such batteries, as they present an advantageous trade-o_ between cost, cyclability, safety, and energy density, as developed. Still, a few others among the main models are not lithium-based, for instance the Chinese Nerada, the German BAE which are Lead-Carbon and Gel Lead-Acid respectively. This difference in technology illustrates a preference for lithium ion batteries as previously mentioned, due to the performance and lower volumes achievable by this technology.

Electric Vehicles' Batteries Reuse

With the increased acknowledgement of the potential of domestic batteries, the reuse of batteries from EVs or Hybrid EVs (HEVs) starts to be considered. EV and HEV manufacturers such as Nissan and BMW or independent companies such as Relectrify, claim they found a way to reuse vehicle batteries that reached their End of Life (EoL), and could thus buy them from the vehicles' owners, refurbish them, and sell them back to the domestic battery market. Reuse of such batteries has potential, as the performance of EV or HEV batteries are usually higher than that required for domestic applications. Thus, once a battery reaches its EoL, due to degradation processes, the performance achievable may still be good enough for domestic applications. Still, as explained by Robinson, EV or hybrid EV battery requires physical removal of the battery pack from the car, followed by an electric testing of the individual cell, and finally, reconditioning into a "new" battery pack ready for a second life. This whole process would take time, energy and cost money so it is not guaranteed yet that car companies would not just prefer to send batteries for recycling.

Performance and Characteristics

A range of performances are available using different chemistries and technologies as already mentioned, and the selection is made depending on the size of the habitation, energy and power requirements, available resource (usually PV) and the budget of the owner. Energy capacity ranges between a couple of kWh or more (usually corresponding to a single storage unit), and up to slightly lower than 20 kWh (a stack of a number of units in some cases). Higher capacities are expected with reused EV batteries but are not available yet. The power ratings usually depend on the invertor, and range between slightly higher than 1 kW to up to 10 kW. The tolerance of a power output also varies depending in how long this output is maintained. Some systems such as the Tesla Powerwall or the Sonnen ECO are equipped with an integrated inverter/charger, and some other models require the purchase and installation of a compatible inverter.