The Role of Domestic Integrated Battery Energy Storage Systems for Electricity Network Performance Enhancement

Corentin Jankowiak [1],* **, Aggelos Zacharopoulos [1], Caterina Brandoni [1], Patrick Keatley [1], Paul MacArtain [2] and Neil Hewitt [1]**

[1] Centre for Sustainable Technologies (CST), University of Ulster, Shore Rd, Newtownabbey BT37 0ZQ, UK; a.zacharopoulos@ulster.ac.uk (A.Z.); c.brandoni@ulster.ac.uk (C.B.); p.keatley@ulster.ac.uk (P.K.); nj.hewitt@ulster.ac.uk (N.H.)

[2] School of Engineering, Dundalk Institute of Technology, Dublin Road, A91 KS84 Dundalk, Ireland; Paul.MacArtain@dkit.ie

* Correspondence: Jankowiak-c@ulster.ac.uk; Tel.: +44-7510-132673

check for updates

Abstract: Low carbon technologies are necessary to address global warming issues through electricity decabonisation, 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, analysing 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 optimise domestic photovoltaic electricity utilisation. 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.

Keywords: batteries energy storage systems; integrated; behind-the-meter; grid services; electricity network

1. Introduction

Three main challenges are emerging and threatening the present structure of the electricity network. (1) Mitigation measures against climate change including greener electricity production means, (2) significant changes in the electricity demand enhanced by the need to electrify the heat and transport sectors, and (3) the ageing of the network, leading to substantial replacement investments.

The production of electricity by renewable energy systems is appealing when addressing climate change, as they do not emit Greenhouse Gases (GHG) during operation. However, renewable sources are usually weather-dependent: Wind and solar are intermittent and non-dispatchable (in contrast with conventional fossil-fuel based systems) therefore an integration large enough to have an impact on GHG emissions is a real challenge [1]. The capital investment of a renewable plant represents a large part of the total expenditures as no fuel costs are involved [2], therefore enough electricity must be produced during its lifetime to create enough revenue and become profitable [1]. Small installed capacities are likely not to provide enough at the right moment, whereas bigger plant ratings could result in the

impossibility to become profitable because of too much curtailment. In addition, renewable sources are site specific and diffuse. Their contribution to electricity generation tends to be in a larger number of lower-rating plants, connected to lower voltage layers in the network (i.e., distribution network), as opposed to the large-scale, centralised generation for which the network was originally developed.

Today's electricity networks are the result of continuous improvements and developments [3], originating in the 19th century following the discoveries and developments of electricity [4], and in the 20th century, when electricity became accessible to the majority of houses in cities in developed countries.

The structure of the networks was shaped by the following: When the number of aggregated load increases, the required capacity per-customer and the variability of demand decrease [5], leading to easier predictability. This stems from similarities in most people's life habits: Cooking is more likely to happen at certain times of the day, lights are mostly switched on at night times, and so on.

To illustrate this, the two extremes are represented on Figure 1. The normalised electricity consumption of dwelling in Northern Ireland [6] is represented in red, and that of the entire country [7] in blue over the same three-day period (24 to 26 October 2018) (The data for the individual house comes from one of the "Test Houses", located at the University of Ulster, representing about 28% of the UK's housing stock, introduced by Shah et al. [6]. The national demand data was downloaded from the Eirgrid group website [7]. For each case, the 15-min resolution data was divided by the average over the 3-day period, and plotted Figure 1.). The normalised consumption was chosen in order to illustrate in both cases how the consumption varies, compared to its average over the considered period (a value of 1 on the vertical axis). The national demand remains between 50% and 150% of its average value, when for a single dwelling, the variation goes from 0% to nearly 800%. Additionally, the three days of national demand present a repeating pattern over each 24-hour period, whereas such a trend is impossible to identify for the single house.
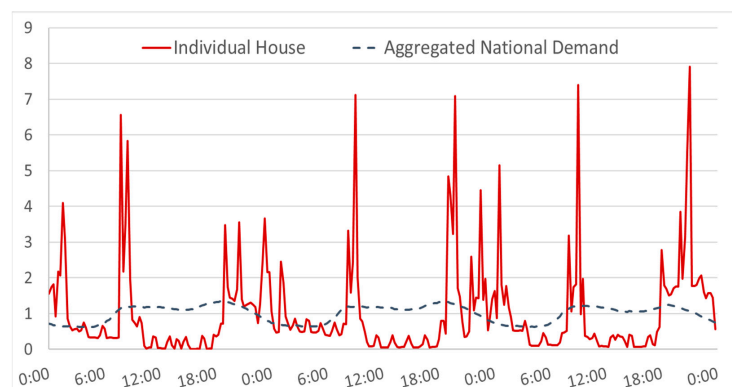

Figure 1. Normalised electricity consumption of an individual house (red) in Northern Ireland [6], and the entire country (dashed blue) for a three-day period (24–26 October 2018) [7].

For this reason and due to economies of scale, the structure of the network was designed to have large centralised generators on one end of the network, enough aggregated loads on the other end, and a system of transmission and distribution of electricity in between, with higher voltages for long distances, and lower voltages closer to the loads for shorter sections of the grid. Therefore, the electricity generation fleet could be designed optimally and perform efficiently, as short term variations are small and predictable, relative to the overall production [8].

In case of non-optimised and unsupervised penetration of renewable sources, problems such as mismatch between production and demand, voltage rise, or reverse power flows at transformers [8] are more likely to arise. Installing electricity storage—particularly on the low-voltage layers of the network [9]—could help reduce this problem by bridging the mismatch between demand and production.

Storage may also play a role in addressing the evolution of the demand on the electricity network. The electrification of heat and transport sectors at different scales presents a potential for reducing

GHG emissions as they are currently responsible for a substantial amount of pollutant emission [10], and draw the vast majority of their energy from the combustion of gas, oil and other fossil fuels [11]. However, shifting a significant part of the heat and transport demand to the electricity network is extremely challenging. The amount of energy it represents would generate a substantial stress on a network, which was not originally designed for it. Figure 2 gives an order of magnitude of the consumption of heat energy compared to electrical energy (in Great Britain, for the year 2016) illustrates the fact that the electricity consumption patterns would be significantly affected by a total transition of heat generation from fossil fuels to electricity [12,13]. As for renewable sources, the distribution network is the more likely to be affected, as systems such as electric heaters, heat pumps, or Electric Vehicles (EVs) should connect to such layers. Once again, having storage assets on these parts of the network would significantly help the electricity network by shaving the peaks coming from these systems [14]. The last challenge concerns the ageing of infrastructures and components. In the present design strategies, components are upgraded when their performance decreases due to ageing or to the increase of demand. Additionally, they are sized to be able to carry at least the peak demand, which occurs only a few minutes per year. This kind of approach represents a huge investment [15]. Installing and operating storage instead could ensure lower variations between peaks and average values, thus leading to infrastructures with lower ratings—hence, cheaper to upgrade—and more optimally used, therefore ageing more slowly [16,17].
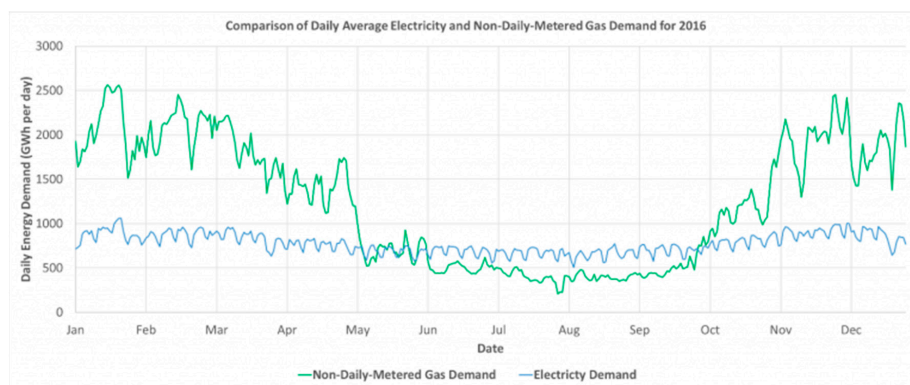
Figure 2. Seasonal variation of the heat demand compared to the electrical demand [13].

The different types of energy storage technology have been extensively reviewed and compared in the literature [18]. The focus usually varies from one publication to another: Electricity network oriented applications [19,20], smart power systems [21] flexibility [22], the integration of renewables [23,24]. In addition, under their economics aspect [25,26], or based on sizing [27], placement and operation strategies [28,29].

Although the literature does not give a definitive answer to where exactly is the best location to connect energy storage, the trend seems to be that the further downstream the better for connecting storage devices [9]. Battery Energy Storage System (BESS) is the technology that best suits this part of the network thanks to its scalability [24,30]. However, this solution is still not developed or thoroughly reviewed in particular regarding the benefits that it could provide. Moreover, the literature regarding domestic integrated BESS mostly focuses on making photovoltaic (PV) self-consumption viable for the battery owner [31,32].

The present paper focuses on integrating Battery Energy Storage System (BESS) in the domestic sector, offering a review on the specific solution of integrating BESS straight at the loads—behind the meter of customers—as a way to provide the flexibility necessary to respond to the challenges faced by the electricity network presented above. The technology considered is electro-chemical Energy Storage (ES)—more commonly referred to as batteries—and more specifically secondary (i.e., rechargeable) batteries.

The paper is organised as follows: First the technology is introduced in detail, then its potential for improving grid performance is assessed, and finally the obstacles faced are reviewed. The state-of-the-art of domestic batteries are reviewed in Section 2, including basic principles, available products and numerical modelling, and field trials done so far. Based on that, the potential role domestic integrated batteries can play to help enhance the electricity network's performance through service provision and compared with other energy storage technologies is presented in Section 3. To finish, Section 4 reviews the barriers to domestic battery development, explaining why this solution is still not quite present despite its potential.

2. State-of-The-Art Development of Domestic Integrated Batteries

2.1. Generalities about Batteries

2.1.1. 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 [33].

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 [33]. 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 [34].

2.1.2. 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). Table 1 introduces the properties of the main cell types with a potential role in the domestic sector. The numbers provided are to be taken as guide values considering that each chemistry type is composed of a spectrum of variations [35], since the performance vary depending on the precise chemical composition [36].

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 [37]. Despite this, other chemistries are overtaking PbA batteries, as their applications are limited because of potential toxicity, weight, and low energy density [38], in particular Lithium-based chemistries since the early 2000s.

Table 1. Features of the main battery chemistries.

Chemistry	Voltage	Power Density	Energy Density	Cycle life Performance	Self-Discharge	Cost	Safety Issues
Lead-Acid (PbA)	2 V	High output current can be achieved for their size	10 s of Wh/kg	Limited, especially if deep-cycled	low	Inexpensive	Toxicity of lead
Nickel-Cadmium	1.2 V	High output achievable and not too harmful	10 s of Wh/kg	Long, if properly maintained, but memory effect	High	Inexpensive	Robust, resistant to abuse. Toxicity of Cadmium
Nickel Metal Hydride	1.2 V	Medium, but does not absorb high discharge rates well.	120 Wh/kg	Limited, especially if deep-cycled. Memory effect	High	Average	Relatively environmental-friendly
Nickel Iron	1.2 V	Medium	10 s of Wh/kg	Limited, especially if deep-cycled	High	Around 4 times as expensive as PbA	Overcharging and full-charge idling causes increased temperature, gas builds up and dry-out
Nickel Zinc	1.65 V	Relatively high	100 Wh/kg	Limited, due to high dendrite growth	High	Low	No toxic component, good temperature operating range
Nickel Hydrogen	1.25 V	Medium	10 s of Wh/kg	Long, thanks to low corrosion	minimal	Expensive	Need for high pressure hydrogen vessels
Li-ion NMC	3.7 V	Medium to low. Higher rates reduce battery life	220 Wh/kg	Around 1000–2000 cycles	Low	Expensive	
Lithium-Iron LFP	3.3 V	Medium. High output pulse can be achieved	120 Wh/kg	Around 1000–2000 cycles	Relatively high for a Li-based cell	Expensive	Very safe chemistry
Lithium Cobalt Oxide	3.6 V	Medium. Higher rates reduce battery life	240 kW/kg	Around 500–1000 cycles	Low	More expensive than other Li-batteries (because of Cobalt)	Safety issues due to cobalt
Lithium Manganese Oxide	3.7 V	Medium. High output pulse can be achieved	150 Wh/kg	Around 300–700 cycles	Low	Expensive	Safer than Li-cobalt
Lithium Nickel Cobalt Aluminium Oxide	3.6 V	Medium. Higher rates reduce battery life	260 Wh/kg	Around 500 cycles	Low	More expensive than other Li-batteries (because of Cobalt)	Safety issues due to cobalt
Lithium Titanate	2.4 V	High rates achievable	80 Wh/kg	Up to 7000 cycles	Low	More expensive than other Li-batteries	Very safe. Better thermal stability than other Li-based batteries

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 (NiH$_2$). 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 [37]. 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 [39].

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 (LiNiMnCoO$_2$ or more commonly NMC), and Lithium Iron Phosphate (LiFePO$_4$, 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 [40]. 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 (Li$_4$Ti$_5$O$_{12}$) 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 [40].

Flow batteries have a slightly different functioning principle to the other batteries—which makes them difficult to be compared with the criteria used in Table 1. 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 increases the costs and reduces the overall performance [41]. 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 [42], and to Linden and Reddy [33] for thoroughly detailed nuances of chemistries and operating principles of batteries.

2.1.3. 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 [43]. 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) [37].

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 [43] or grid corrosion in PbA cells [44]. Low temperatures on the other hand reduce these kinetics according to Arrhenius law, increasing the internal impedance which limits the performance, but also favouring lithium plating for instance [45]. 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 [44]. High rates of charge or discharge lead to higher reaction rates in general that can enhance SEI formation in Li-based cells [43] 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. Numerical thermal models are developed by Rao and Wang [46] and temperature-management technologies are reviewed by Al-Zareer, Dincer and Rosen in [47]. The degradation of cells was shown to have a considerable impact on achievable revenues by Al-Zareer, Dincer and Rosen [48], and a significant increase in potential profitability can be achievable by optimising cell operations to decrease ageing [49].

2.2. Products Available

The present section provides an overview of different commercialised BESS suitable to be integrated in the domestic sector.

2.2.1. Solar PV Batteries

As will be seen and developed in Section 4 of this paper, there are still barriers to a large integration of ES—which does not only regards 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 [50], and Staffell and Rustomji [51], 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 [9,52]. Under five years is achievable, especially if the technology costs were to decrease as stated by Neubauer and Simpson [53], and Muenzel et al. [54] states that systems could become economically attractive "in the near future". Two specific cases studied and reported by Günter and Marinopoulos [55] 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-off between cost, cyclability, safety, and energy density, as developed previously in Section 2.1).

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 [56]. 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. Table 2 summarises the characteristics of the different products.

Table 2. Existing products and their characteristics.

Name	Chemistry	Energy (Usable)	Power (Continuous/Peak)	Inverter	Cycle Life	EoL	Warranty	Round-Trip Efficiency	Price US$/kWh	Source
Tesla Powerwall 2	Lithium NMC	13.2 kWh	5.8/7.2 kW	DC-AC inverter-charger	3200	70%	10 years	89%	440	[57,58]
LG Chem RESU	Lithium NMC	12.4 kWh	5/7 kW	none	-	60%	10 years	92%	510	[56,59]
PylonTech	Lithium LFP	19.2 kWh	2.4/4.8 kW	none	6000	80%	5 years	94%	475	[60]
Simpliphi PHI	Lithium LFP	3.5 kWh	1.6/3 kW	-	10,000	80%	10 years	98%	480	[60,61]
Narada	Lead-Carbon	4 kWh	5/10 kW	-	3000	80%	10 years	83%	440	[60]
BAE	Gel Lead-Acid	14.6 kWh	5/9 kW	-	3000	80%	5 years	82%	430	[60]
SonnenBatterie ECO	Lithium LFP	13.5 kWh	3.3 kW	DC-AC included	10,000	80%	10 years	94%	400	[62,63]

(EOL: End of Life).

2.2.2. 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 [64] or independent companies such as Relectrify [65], 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 [66].

Still, as explained by Robinson [67], 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 [67].

2.2.3. Performance and Characteristics of Available Systems

Different products available are presented by Muoio [64] and Svarc [56]. 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. Table 2 gives examples of available models and their characteristics.

2.3. Numerical Modelling of BESS

Numerical models used to describe batteries as well as electricity network models have existed for a long time but are mostly separate from one another. The present section offers to critically analyse these models and introduces existing simulations and results of integrated BESS.

2.3.1. Main Battery Models

Batteries are complex systems, storing electricity through chemical reactions and exchanging heat as losses with the environment. This complexity makes it a real challenge to create a numerical model accounting for all the different phenomena and compute results in a reasonable time. Therefore, depending on the application, simplified models can be chosen, as well as models that depict more accurately certain types of phenomena leaving some others aside [68].

The general aim of the different models is to predict the behaviour of a battery of given characteristics (capacity, chemistry, etc.) operating in a given environment. Depending on the very model, the computed parameters are: The ageing of the cell, its dynamic response, the State of Charge (SOC), the thermal behaviour, and so on. The most popular model used in the literature are presented in the following. Figure 3 gives a schematic representation of the three types of models introduced in the following: The Bucket model, the equivalent electrical circuit model, and a Single Particle Model (SPM) which is a certain type of electrochemical model.

The Bucket model is presented by Reniers et al. [49] and used by Simpkins and Donnell [69]. It considers the storage unit as a "tank" (or "bucket"), in which energy is accumulated and be pumped

in and out by virtual "pipes". The total volume of this bucket is the Energy Capacity, the size of the pipes is the power ratings, and one could imagine self-discharge and charging/discharging efficiencies as energy "leaking" out of the bucket or the pipes.

This model only accounts for exchanges in bulk energy and takes the system: [Cells + Inverter + BMS] as a "black box" that can just receive energy, accumulate it to a certain extent, and discharge it. This model itself does not provide information concerning transient response at the chemical level, the ageing of the cells, or any thermal aspect. Such characteristics can be added to the model, for instance a decrease in available capacity over time to simulate the ageing mechanisms, by estimation, thanks to empirical results, or results from other models.

The main advantage of such a model is its computational efficiency thanks to basic mathematical foundations, enabling very short calculation times. Nevertheless, some complexity must be added in order to account for particular aspects that cannot be neglected in some contexts.

An illustration of a possible equivalent circuit model is found Figure 3B. They are broadly used when integration to some larger electrical systems in simulation software is required. Different circuit layout exists with different combinations of fundamental electronics components. All these components model one or part of an electrochemical phenomenon taking place in the real battery. The Thevenin models for instance detailed by Gao, Liu and Dougal [70] are used for their capability to provide cell transient response, taking account of effects such as charge depletion and recovery [68]. They are composed of:

- A voltage source (Or Equilibrium Potential) which value is a function of the SOC of the battery, the discharge rate (current) and the temperature.
- Resistors, used to model the "potential losses": The conductivity of the electrodes and the separator is not infinite, in addition to the effect of concentration gradients of ions near the electrodes and the limits in the kinetics of the chemical reactions. The value of these resistors depends on the chemistry, the geometry, the temperature and the discharge rate of the cell.
- A capacitor in parallel to one of the abovementioned resistors, to model the capacitive effects due to the structure of the cell, leading to electrical polarisation, and pseudo-capacitance (diffusion limited space charges). In other words, this capacitor accounts for transient effects in the cell.
- In some models, other parallel RC circuits maybe added in series, increasing the accuracy of the modelled transient response, adding at the same time complexity and computation time [68].

The value of all these electrical components and their evolution with other parameters of the circuit can be determined by comparing the response to pulses of charge and discharge at different temperature and SOC, and their value adjusted accordingly. The second category of electrical circuit equivalent models are the Impedance models. They are based on an experimental method, the Electrochemical Impedance Spectrum (EIS), which consists of analysing the battery response to a spectrum of low frequency AC excitation. This method provides information on the SOC and the State of Health (SOH) of the battery. In such models, half cells are represented as Randles circuits composed of a resistor, an inductor, a capacitor and a non-linear impedance. Once again, the adjusting of the different parameters is done with comparison to empirical results [68].

Electrochemical models are based on a more explicit description of the chemical processes taking place inside of the cell, which makes them much more accurate than the previous types, and therefore requiring substantially more computational resources or time. The lump parameter model described by Seaman, Dao and McPhee [68] has been used since the early development of numerical models. It assumes a uniform spatial distribution and solves differential equations that represent time-dependent electrochemical phenomena between the electrodes. If well optimised, it can provide accurate results in short simulation times, but only for NiMH or PbA batteries: The model is not valid anymore to represent modern chemistries such as Lithium Ion, which is a major drawback regarding their broad and fast expansion.

Lithium Ion models and other modern chemistries can be described by Porous Electrode Theory. This model is developed by Newman and Tiedemann [71], and is based on solving partial differential equations, which can be done using finite element methods. Hence, very accurate results can be obtained but at the cost of very high computation times. A number of simplification methods were developed, reviewed by Seaman, Dao and McPhee [68] based on mathematical or conceptual simplification, either decreasing the accuracy, or the field of application of the model. Modifications increasing the complexity are also reported, which aim to increase even more the accuracy and quality of predictions [49]. The illustration in Figure 3C represents a SPM, which is a certain type of model developped based on the Porous Electrode Theory.
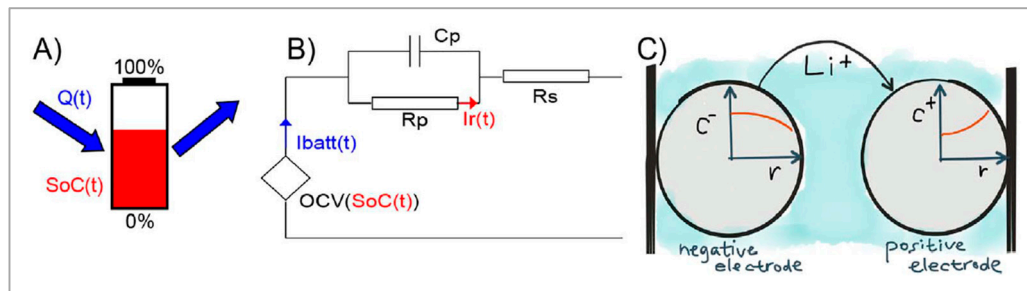
Figure 3. Representation of the numerical models. (**A**) Bucket Model, (**B**) Equivalent Circuit Model and (**C**) Electrochemical Model [49].

2.3.2. Electricity Network Modelling

Electricity networks are extremely complex systems, composed of a number of already complex components. Additionally, considering how developed countries are dependent on electricity, real-scale experiments that could potentially compromise the infrastructures and the users' loads are not conceivable. Therefore, robust numerical models must be developed and validated to predict the impact of any modification on the grid prior to any large-scale implementation [72]. This complexity inevitably forces numerical models to be either computationally heavy, or inaccurate to some extent, and a trade-off must be found between confidence in results, and a sensible time of computation.

Power flow models consist of a steady-state representation of the electricity network, solving non-linear and time-independent equations (usually solved using iterative methods). Dynamic effects are therefore neglected, but this approximation is enough to represent a large proportion of grids' operation time. Still, some events such as faults or other transient events may have a significant impact on the network and threaten the stability and safety of equipment. Thus, dynamic and transient models are also developed, which describe such conditions, and enable the design of protection techniques and technologies. They mostly consist of solving differential equations, leading to even more complexity than the load flow analysis models. Once again, a decision must be taken between computation time and accuracy. More details on these models, and solving methods can be found by referring to Andersson [73].

Such analyses are now broadly computer based, as it would not make sense to try to analytically solve this type of problems. Software packages such as MATLAB/Simulink, NEPLAN, DIgSILENT Power World, DYMOLA, Plexos, and many others offer to implement and run simulated networks with various performance in various contexts. A number of packages used by network companies, researchers and others, and their capabilities for a wide number of applications were reviewed by Hay and Ferguson [74].

2.3.3. Results from Numerical Simulations

The literature involving some sort of modelling and simulation of BESS used to operate one or more of the applications previously described in this paper is substantial. However, many publications are still regarding different contexts of utilisation, such as a connection to renewable generation assets [75],

or for LV applications but not necessarily Behind the Meter (BtM) [76,77]. Even for papers regarding BtM applications, the focus is rather on sizing and scheduling systems: The economically optimal battery size regarding PV generation was assessed in [54,78–82]; a degradation aspect considered by Angenendt [83], and Yoon and Kim [84] also deals with integration in households without PV resource. Finally, Babacan et al. [85] presents a similar approach, but grid relief objectives start to appear, through a reverse power flow diminution objective.

Most of the publications reviewed here, which address some sort of grid relief objective deal with voltage regulation, for instance Yang et al. [86] and Aichhorn et al. [27]. With similar objectives, it is reported by Zillmann, Yan and Saha [87] that in the context of their simulation, installing coupled PV panels with batteries proved to be cheaper than grid reinforcement. The impact of location of the BESS system on the voltage profiles is studied by Nazaripouya et al. [88] and by Lindstens [89] which suggests that better results are achieved further from generation assets and closer to bigger loads. Additionally, Marra et al. [90] and Zeh and Witzmann [91] propose a more sensible way to operate batteries by charging when the net PV export to the grid becomes higher than a threshold value (and study the impact of this very value on other parameters) rather than just charging as soon as energy is available—which could potentially resulting in an peak exports in the early/middle of the afternoon when the sun shines but the battery is already full. Finally, the compatibility of grid release and PV self-consumption is addressed by Moshövel et al. [92], concluding forecast is a key parameter in reaching satisfying compromise.

These publications mostly focus on one single domestic system and how to economically optimise it for the benefit of the owner. The grid-relief aspect is introduced as a solution to the stress induced by PV systems exporting to the grid when the energy is not needed, which reduces the exploitation of the real domestic BESS potential developed earlier. Only a few authors look in this direction, such as Müller et al. [30], concluding that low voltage storage is potentially beneficial for both high voltage and medium voltage layers of the network, and that a number of smaller spread units may operate better than a single centralised storage asset. Furthermore, "Cloud Energy Storage" [93] regard the operation of storage assets by an aggregator, generating revenue by providing services to the electricity network. This promising strategy is however not backed up by simulation results, and the technical benefits provided by storage is stated as an assumption, and not a conclusion of the work.

Eventually, although these papers provide consistent conclusions, their results remain true for the very context of modelling and simulation. Any grid section presents very specific characteristics which cannot be easily generalised, and a strategy of sizing, locating and operating a fleet in one of them may or may not be efficient in another.

2.4. Trials and Real-Scale Implementation

The paragraph shows an overview of trials and reals-scale implementation where BESSs have been implemented at domestic level.

Sonnen Community—Probably the most advanced real scale demonstration of the benefits and profitability of deployment of domestic ES is the company Sonnen and its growing community of battery owners. Sonnen was founded as a start-up in the late 2000s in Bavaria, and now consists of over 10,000 battery owners claimed in Germany, and 180,000 in the world [94]. Its particularity is that it does not only sell batteries, but also acts as an aggregator and manages all its storage unit fleet. The business started in 2015 when its status of nationwide cloud-base Virtual Power Plant was established, enabling the members to exchange electricity with one another at different (and supposedly cheaper) tariffs than the average German ones. In mid-2017, tariffs changed and decreased even more as Sonnen's Batteries started to take part in the frequency regulation market in Germany, by allowing TenneT—the network operator—to use a small fraction of the capacity of each battery to regulate the frequency fluctuations on the network, in exchange of revenues. If similar activities are started in Austria, Italy and Australia [95], the American market has been harder to reach for the German company so far.

An interesting project to follow is the Jasper project, in Arizona, in which Sonnen is partnering the efficient builder Mandalay Hones in a 2900-house microgrid connected to a Virtual Power Plant (VPP) of 23 MWh storage and 11.6 MW of power. The business model is based on differential tariffs this time, and the aim is to demonstrate the integration of much renewables, as well as the decreased dependence on fossil fuels. The first residents are residents expected during the year 2018 [94].

Network Operator Projects—A few Network Operator-lead projects took place and are currently taking place in the UK and other countries, but due to the newness of the systems and concepts, the necessity to record enough data from a sensibly long period of time, and consequently the time it takes to properly analyse them, there is only so much information and conclusions available to date. A few examples are introduced in the following:

The Sola Bristol project took place between 2011 and 2016 and was undertaken by the British Distribution Network Operator (DNO) Western Power Distribution, in partnership with Siemens, the University of Bath, and Knowle West Media Centre. It consisted of installing coupled PV and battery systems in a total of 26 homes, 5 schools and an office, and implement a "smart tariff" for the participants. The project concludes that such a set up provided benefits mostly to the suppliers and the communities. Despite the small number of systems installed, a good argument—but not strong enough to base economic decisions on it—was made in favour of the potential to achieve grid deferral. Services such as self-consumption, peak shaving and voltage regulation were successfully achieved thanks to an efficient self-managing network, although according to the final report [96], the cost-effectiveness of the solution is questionable.

The Distributed Storage and Solar Study started in 2016 and should finish by 2019, led by another UK DNO, Northern Powergrid, partnering Moixa and Energise Barnsley. Similarly, 40 batteries are installed behind the meter and controlled by an aggregator to provide peak shaving and voltage regulation, and thus investigate how they—associated with PV here as well—could avoid upgrade, and reduce winter peak demand [97].

To finish, a few more projects should be mentioned, such as the "Econamic Grid" by *SENEC* in Germany, which uses batteries for providing "negative balancing". In other words, absorbing extra energy from the network during over-production times as a means of balancing, and leaving the energy in the batteries to be used by the customers. Another UK trial by North Star Solar, consisting of 22,000 social houses equipped with solar batteries, once again to study their possible economical and technical impact for the different stakeholders [98].

3. Potential Roles of Domestic Integrated Batteries

The section focuses on the role of integrated BESS in the electricity network and compares it to other possible ES solutions.

3.1. Behind-the-Meter Storage

First of all, a clarification on why BtM is of particular interest. Remembering that in electricity networks, physical quantities have different span definition: The frequency of the network is, in theory, the same everywhere, therefore any variation is measured as equal throughout the network. However, the voltage is a local quantity, meaning that an event modifying the voltage locally may have little impact far away on another section of the network. A consequence of this is that some services can be achieved regardless of where the storage unit is connected to the network, but some others cannot. Table 3 lists all the services that the grid would require in order to perform efficiently (described in more detail in the following paragraph) and indicates how easily they could be achieved depending on the location considered. As shown in Table 3, the large majority of the electricity network services can be provided or contributed to by BtM units. The exceptions are services for which the storage unit must be closer to the generation sites. Therefore, units located behind the meter would be of particular interest for the distribution networks, by helping address the challenges of increasing the share of

renewable sources and implementing electrification of heat and transport. Table 3 summarises results that can be found for each service in journals or report cited in the "source" column.

Table 3. Likelihood of connection at the different electricity network levels.

Services	Generation	Transmission	Distribution	Behind the Meter	Source
T&D congestion relief	✗	~	✓	✓	[9,55]
Voltage support	✓	✓	✓	✓	[9,30,55]
Power quality	✓	✓	✓	✓	[30,55,99]
Demand-Peak Limiting	✗	✗	✓	✓	[9,30,55]
Arbitrage & load levelling	~	✓	✓	✓	[9,30,55]
RE Capacity firming & smoothing	✓	~	~	✗	[55,99,100]
PV Self-consumption	✗	✗	✗	✓	[9,30]
Black-Start capability	✓	✓	~	✗	[9,30,55]
Backup provision	✗	✗	✗	✓	[9,30,55]
Reserves	✓	✓	✓	✓	[9,30,55]
Frequency regulation	✓	✓	✓	✓	[9,30,55]
Load Following	✓	✓	✓	✓	[55,100]

✓ : Best location for that service; ~: Service achievable although not the optimal location; ✗ : Service cannot be performed from there. (T&D: Transmission and Distribution; RE: Renewable Energy).

In addition, the benefits provided to a section of the distribution network by locally improving power quality, increasing self-consumption or peak-shaving, are likely to decrease the need for services at higher voltage layers of the network. This is consistent with the results of simulations reported by Lindstens [89] which conclude that the further away from the generation plants, the better, and the studies from Müller et al. [30] stating that a number of spread distributed storage assets has a higher potential than a few centralised and larger scale. Finally, units connected BtM have the advantage of distribution-connected systems since services such as increased self-consumption of small-scale renewables, and back-up power are easier to implement, while still enabling services achievable from distribution points.

3.2. Grid Services and Domestic BESS

3.2.1. Services and Applications

Before going further, the terms "Service" and "Application" should be properly defined. Strictly speaking, any operation undertaken by an ES unit comes down to generating an active or reactive power flow [55]. Nevertheless, depending on the amount of power it represents and the timing regarding other events occurring in the electricity network the effect can have drastic different consequences. In the present paper, the terms application and service are interchangeably used, and defined as "any electrical operation (local absorption or injection of active or reactive power) which objective is a local or global improvement in the operating conditions", derived from the definition of service given by Günter and Marinopoulos [55].

3.2.2. Integrated Batteries for Grid Services Provision

The definition and description of the services as presented in Table 4 were broadly derived from descriptions and definitions found in [9,21,22,25,28,69,101–104]. The table contains a brief description of each service, how exactly domestic batteries could achieve them, and if an aggregator is necessary, useful or not needed.
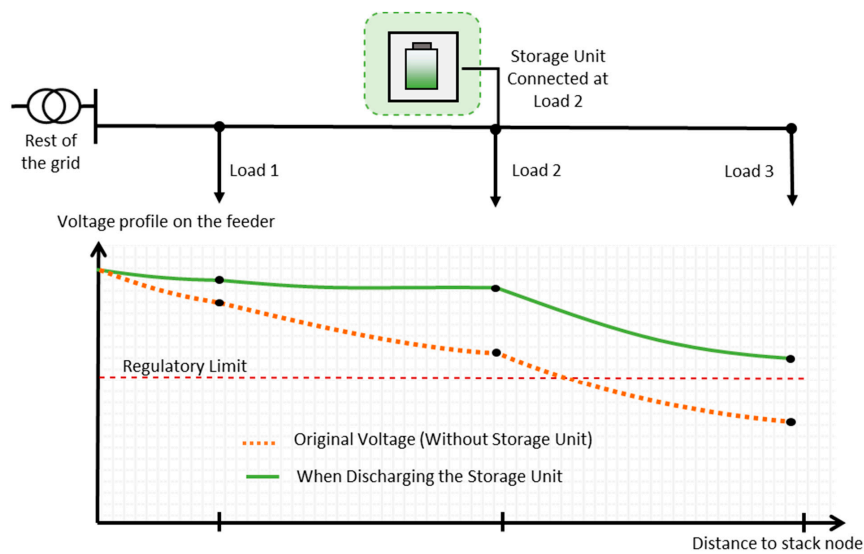
Figure 4. Illustration of voltage support on a fictive feeder.

Services related to energy management in the building such as peak limiting, PV self-consumption, or back up reserve are straightforward to provide, through managing the flows of active power and ensuring a headroom and legroom energy capacity are available when needed. No aggregator is needed, although one can imagine a more advanced management of all the parameters by making batteries communicate and respond to each other. Similarly, services such as voltage or frequency support, or power quality can also be operated independently from an aggregator, by measuring values on the electricity network and appropriately responding. An aggregator could once again improve the overall operation of services but is not strictly required. On the other hand, congestion relief, load-following or reserve services require access to information from elsewhere in the electricity network, and therefore cannot be achieved from behind the meter without the batteries receiving signals from an aggregator. The aggregator should coordinate the response of the BESS fleet adequately to achieve positive effects. Load levelling is in-between, as it could be argued that by increasing self-consumption and reducing peaks on houses, the result at an aggregated level would tend to a more levelled profile, but this is still to be demonstrated, and the coordination from an aggregator is more likely to bring about the desired effect.

Finally, as mentioned previously, a few services are not possible to provide from behind the meter, namely those directly linked to the generation part of the network: Output smoothing, capacity firming, and black start capability.

Figures 4–7 illustrate some of the services mentioned in Table 4.
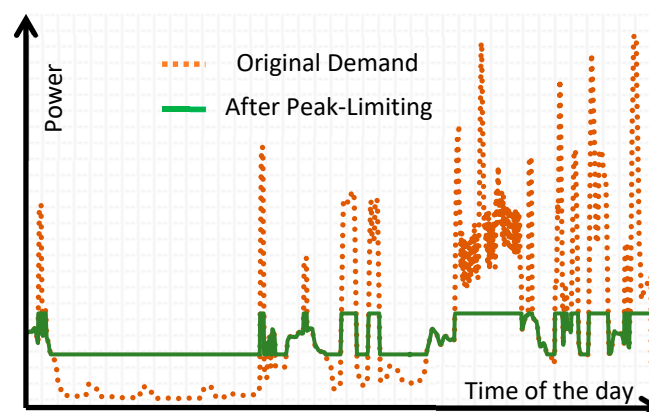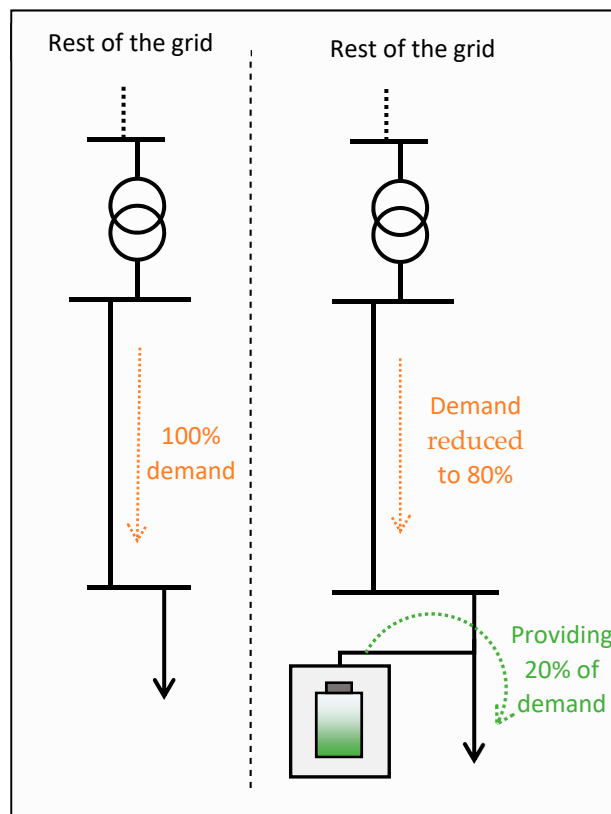

Figure 5. Illustration of Peak-Limiting.

Figure 6. Illustration of Transmission & Distribution congestion relief (from Katsanevakis, Stewart and Lu [103]).
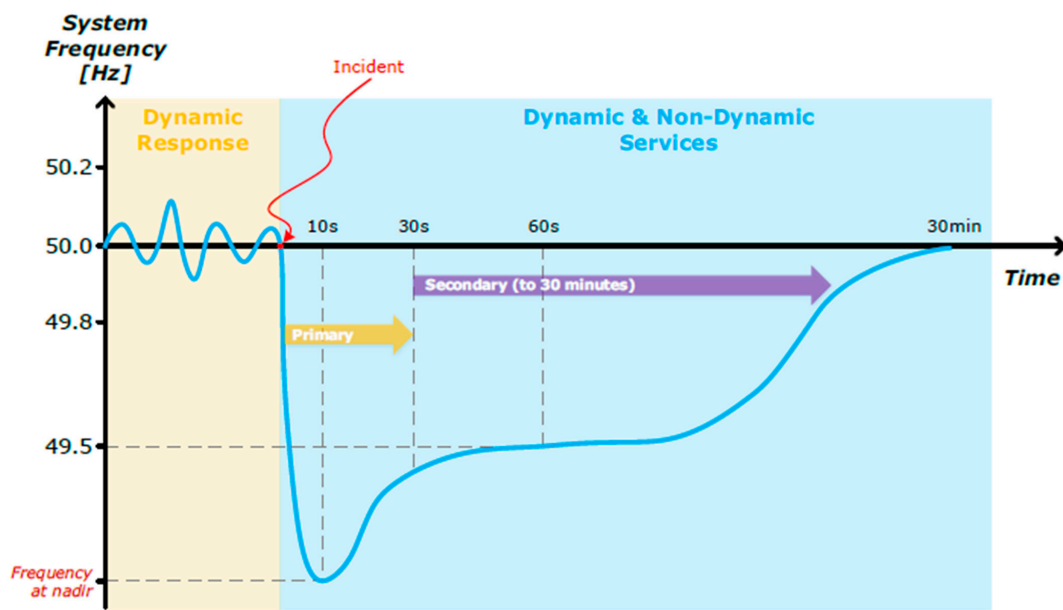

Figure 7. Illustration of reserve response to an unexpected event (From Torrealba [105]).

Table 4. Role of Behind-the-Meter Battery Energy Storage Systems in providing grid services.

Service Name	Service Description	Role of Domestic BESS	Role of Aggregator/Signal Sender
Voltagesupport	Provide correction to the voltage variations (potentially out of the regulatory values) caused by the resistive and impedance nature of the cables (non-ideal conductors) by injections of active or reactive power.	Using the power converter (STATCOM) to manage reactive power flows and the storage unit to manage the active power flows in order to stabilise voltage close to regulatory values. Figure 4 provides an illustration of this service.	Not necessary. Enable access to more data and thus broaden their positive impact.
Power quality	Supporting any electrical parameters which need to remain in a certain range of value during operation, e.g. harmonic level, flickering, power factor, or voltage.	Using the power converter (STATCOM) to manage reactive power flows and compensate harmonics, and voltage or power factor deviations, for instance.	Not needed.
Peak Limiting	Making up for the demand when it reaches a certain value, so that the power drawn as seen by the grid never overreaches a certain value. Figure 5 illustrates an example of peak shaving	The aggregation of demand profiles which peak has been limited thanks to BtM batteries should result in overall demand with limited peaks. Regardless of the location of storage on the grid, peak limiting only affects upstream components, thus BtM peak limiting should relieve a larger amount of hardware.	Not necessary. Provide coordination between units of a same area leading to overall optimised service.
PV Self-consumption	For buildings equipped with rooftop PV panels: Maximising the on-site used energy.	Sensible charging and discharging schedule to maximise the on-site utilisation of the energy produced.	Not necessary. Could help relief stress on grid by coordinating nearby units.
Backup provision	Guaranteeing operation of at least some critical appliances in the building for a given time during grid outage.	Keeping a certain amount of energy in the battery and storing energy from PV in case of a grid breakdown.	Not needed.
Frequency regulation	Injecting or absorbing power in response to frequency variation in order to maintain it in a between the regulatory limits.	Response to frequency variations by instantaneous injection or absorption of power.	Not necessary, but helpful to make sure this service and others do not interfere with each other.
T&D congestion relief	Downstream a potentially congested line: Charging when the demand downstream is low and discharging to when it increases to diminish the congestion.	Discharging the fleet to cover part of the local demand during peak periods, to decrease the overall energy flowing through the lines. An illustration of this principle for a simple line is found Figure 5.	Necessary to make sure enough energy is stored downstream the congested lines and manage the flows during charging and discharging to keep the line un-congested.
Arbitrage and load-levelling	Privileging charging during low demand and discharging during peak times to flatten the overall profile seen by the grid. Resulting in a larger-scale version of what is seen Figure 5.	Charge during low-demand periods and discharge at peak demands.	Necessary to access large-scale demand forecasts.
Reserves	Covering the loss of some generation capacity shortly enough after the event occurs to maintain grid stability. There are different timescales in the response, a generic example is illustrated Figure 6.	Exploiting the potential very short-term response time to quickly respond to unexpected events occurring in the network such as faults or tripping of a generator.	Necessary to relay the information of unexpected events leading to need for reserve dispatch.
Load Following	Following the variations of the load profile at a given base-load level.	Adjust an individual unit's output to reduce the need from load following by fossil fuel-based generators.	Necessary, to adjust a unit's outputs and ease the effects of overall variations on conventional generator.
Renewable Generation Output Smoothing	Making up for short term fluctuations in renewable generation due to weather instabilities (clouds on PV panels or gusts of wind on turbines).	Not achievable by BtM BESS.	-
Renewable Generation capacity firming	Firm up renewable's capacity by guaranteeing a minimum output regardless weather fluctuations and un-forecasted events.	Not achievable by BtM BESS.	-
Black-start	In case of grid black out, re-energising the generators to enable their re-connection to the network.	Not achievable by BtM BESS.	-

3.3. Comparison of BESS with Other Energy Storage Technologies

Now that the potential value of providing services from behind the meter rather than elsewhere in the network is established, it should be explained why BESS is a particularly adapted technology, by comparing it to other available options. Table 5 lists the different energy storage technologies that could compete with BESS in achieving the previously introduced services and compares them against their ability to provide each of these services.

Energy Storage (ES) qualifies any process that enables transfer energy from a device to another, or an energy type to another where it can be accessed on demand for later usage. Using ES to provide grid services enables to artificially loosen the constraint of having generation and demand synchronised at any time. Different ES technologies all provide various performance characteristics—reviewed in [18–21,24,36,100,101,106]—which makes them more or less capable to achieve the different services introduced previously. Table 5 compares the capability for each technology to provide a given service.

Mechanical energy storage consists of storing energy as potential energy, by pumping water in a higher reservoir, compressing air in a tank, or setting a flywheel in rotation. As found in Table 5, these systems are usually suitable for services requiring large capacities such as arbitrage or reserve provisions [100]. However, such systems are not easily down-scaled, making their integration behind the meter unpractical [18]. Having a fleet of aggregated BtM BESS on the other hand, can allow the provision of services that mechanical energy storage can and more, due to being connected behind the meter.

Thermal ES technologies store energy as either sensible heat (temperature change), latent heat (phase change) or thermochemical reactions. Therefore, they require lower volumes than mechanical ES and are more likely to fit BtM requirements. In particular, if progress is made in latent and thermochemical storage, a significant increase in energy density could be achieved, making this technology a strong potential to domestic applications [107,108] if coupled with HPs for instance. Still, many services require the ES system to inject electricity back to the grid, which is impossible from thermal ES at this scale, and with a decent efficiency. On the other hand, services related to peak shaving and head comfort can also be provided by domestic BESS, making them a stronger candidate.

Chemical ES regards all technologies based on using electricity to force a chemical reaction (electrolysis of water for instance) and creating electricity back by making the chemical products react in the reverse process. These technologies are under development, and the efficiency achieved are still fairly low [101,106,109], which leaves both potential and uncertainty for providing most services, especially facing other more developed technologies.

Electrical ES, consists of Electric Double Layer Capacitor (EDLC) and Superconducting Magnetic ES (SMES) [36,101] which store electricity as electric and magnetic fields respectively. They are mostly fit for high power and low energy application, similar to flywheels. Their limitations stem from high self-discharge rates, in addition to not enough maturity. Consequently, they may be very specialised in certain services related to power quality but are outperformed by other technologies regarding the rest.

From these comparisons, it appears that (a fleet of aggregated) domestic batteries would be more capable to reach a wider range of services than each of the other ES technologies candidate for grid performance enhancement.

Table 5. Capability of each ES technology to achieve grid services.

	Grid Services	Arbitrage	RG Capacity Firming	RG Capacity Smoothing	Increased Self-Consumption	Congestion Relief	Voltage Support	Power Quality Enhancement	Peak Limiting	Reserves	Frequency Regulation	Load Following	Backup Power	Black-Start	Upgrade Deferral
Electro-Chemical	PbA	~	✓	✓	✓	~	✓	✓	~	~	✓	✓	✓	~	✓
	Li-based	~	✓	✓	✓	~	✓	✓	~	~	✓	✓	✓	~	✓
	Ni-based	~	✓	✓	✓	~	✓	✓	~	~	✓	✓	✓	~	✓
	Flow batteries	~	✓	✓	✓	~	~	✓	~	~	✓	✓	✓	~	✓
	Aggregation of domestic BESS	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓
Thermal	Sensible Heat	~	✗	✗	~	~	✗	✗	✓	✗	✗	✗	✗	✗	✓
	Latent Heat	~	✗	✗	~	~	✗	✗	✓	✗	✗	✗	✗	✗	✓
	Thermochemical	✓	✗	✗	~	~	✗	✗	✓	✗	✗	✗	✗	✗	✓
Mechanical	Pumped Hydro	✓	✓	✓	~	✓	~	✗	✓	✓	✓	~	✗	✗	✓
	Compressed air	~	✓	✓	~	✓	~	✗	✓	✓	✓	~	✗	✗	✓
	Liquid air	~	✓	✓	~	✓	~	✗	✓	✓	✓	~	✗	✗	✓
	flywheels	✗	✗	~	~	✗	✗	✓	~	~	~	✗	✗	✗	~
Chemical	Hydrogen & others	✓	~	~	~	~	~	✓	~	~	~	~	~	~	✓
Electrical	EDLC	✗	✗	~	✗	✗	✗	✓	✗	✗	~	✗	✗	✗	~
	SMES	✗	✗	~	✗	✗	✗	✓	✗	✗	~	✗	✗	✗	~

✓ : Technology adapted to the service; ~: Technology adapted, but may not be the best option; ✗ : Technology hardly or not compatible with the service. (RG: Renewable Generation; EDLC: Electro-Chemical Double Layer Capacitor; SMES: Superconducting Magnetic Energy Storage). The background color (grey) regarding this table explains that the aggregation of domestic BESS is better compared to the other Energy Storage technologies presented in this table.

4. Barriers to Domestic Battery Deployment

In spite of the different advantages presented so far, it is a fact that the penetration of domestic integrated BESS remains low. This section focuses on the main barriers and challenges that integrated BESSs are facing: Markets and regulations, financial and economic issues, and technical barriers.

A recurring barrier to integration of domestic BESS and any sort of storage in general is the unclear or often non-existent definition for electricity storage in most electricity network system regulations [25,101]. Thus, storage units may be categorised as generation assets although not capable of generating a net flow of energy [110] making competition with conventional generation challenging. Additionally, as storage units are both loads and generators, owners are intended to pay twice for the connection charges [111].

More generally, the integration of domestic BESS achieving a number of services would add more contractual complexity. Either in the US [9] or in Europe [111], markets may vary a lot, enabling little harmonization. Each contract is too specific to its context, environment and stakeholder to be generalised to other situations without substantial enough adaptation, which may reduce motivation of potential investors [98,111].

The ownership and operation of storage assets is also a concern. For a full utilisation of the potential of domestic batteries, real-time information of the state of the network is required. The transmission or distribution network operators are the most likely to possess these information, still they are not allowed to own and operate storage systems by most regulations [110,111]. Reports such as [9,101] agree on the benefit that could be drawn by giving—careful, limited and regulated—freedom to network operators on the control of such assets. Often referred to as the transition from Distribution Network Operators to Distribution System Operators (or DNOs to DSOs) [98].

According to Ugarte et al. [111], the main challenge to the integration of batteries in the current context is economic. Capital costs are still high and discourage investors, making it difficult for the technology to compete with other better-established centralised generation solutions and conventional grid reinforcements [110]. It is interesting to note that the strictly speaking storage part "only" represents 30% to 40% of the total cost. The rest consists in all the other components necessary for the system to operate, which leaves space for cost reductions [112].

Moreover, the capital cost challenge would have a lower impact if more and more effective remuneration mechanisms [25] or pricing signals [111] were in place. Batteries have been traditionally used for arbitrage and more and more for renewable self-consumption increase [113], but according to Castagneto Gissey, Dodds and Radcliffe J [110], and Fitzgerald et al. [9] and others, they could valuably participate in balancing and ancillary services markets thanks to their potential to provide (ultra) fast response. Regarding the Capacity Market, BESSs still struggle to be competitive, first due to the current requirement of 2 MW, therefore requiring the aggregation of enough assets. More importantly, the mechanism setting no limit to the duration for which the output must be maintained, largely plays in favour fuel-based generation and against BESS [110].

It should also be noted that even if an effective remuneration mechanism was implemented, the deployment of domestic BESS that it would bring about may affect it retroactively, for instance by reducing the value of a given service and then not provide as much value as expected to battery owners [9]. This also leads to lack of confidence in investments.

A significant challenge when it comes to technical aspects, is the inherent complexity. Transforming consumers to "prosumers", adding intermittent, non-dispatchable renewables to the mix means a highly increased number of sub-systems to manage, and the necessity of an optimal management. A poor management could indeed lead to increase the stress on the network and be severely harmful for the nearby infrastructures. For instance, a high number of customers charging and discharging their battery units during similar periods in response to the same price tariffs, leading to peaks and troughs at the sub-station. Or, as presented by Moshövel et al. [92] and Marra et al. [90], batteries used to increase the self-consumption of domestic rooftop PV are used to charge as soon as the PV panels produce electricity: After a few hours of sunlight the batteries are fully charged but the sun

still shines. The electricity produced is not used in the household and suddenly exported to the grid, typically in the early—or mid-afternoon, leading to sudden peaks at the substation. This is avoided by increasing the size of the batteries, but it means higher capital investments, which also represents a barrier to integration as presented above. It is suggested by Marra et al. [90] and Moshövel et al. [92] that for the same battery size, and while preserving good self-consumption, substantial grid relief can be achieved by operating the batteries differently. Still, the complexity of implementation, and the fact that the operation of the batteries (and thus the revenue generated) depends on the quality of forecast of the production and consumption—as introduced above [92]—increase the uncertainty regarding the achievability of profitability by the system.

Other sources of technological uncertainty stem from the evolution of the performance of the systems. Confidence on the progress of the technology could motivate investors but it is never certain what exact level of efficiency the technology will eventually achieve. Additionally, even if an efficient development was certain, BESS are not established technologies yet, and implementation phases may be challenging because of a lack of general know-how [25]: Demonstration projects could alleviate such risks [111]. As developed earlier, the ageing mechanisms are very complex in batteries and still not fully understood. Such projects would help understand the evolution of the performance of installed systems and secure investments [112], reducing the risk of being the first to invest in a yet unproven technology.

5. Conclusions

The electricity sector is facing growing challenges, coming from two main categories: The normal ageing of the infrastructures, and the evolution of electricity sector and more generally electricity consumption and production behaviours—largely motivated by climate change mitigation necessities. This second category of challenges may involve a drastic change in the management of energy flows throughout the electricity network and addressing them with conventional grid upgrades may lead to oversized components, and huge investments to maintain energy security. On the other hand, the alternative option consisting in adding flexibility to the network is gaining interest, as it would enable optimal technology installation, operation and investments.

It was shown that storing electricity is the important missing piece in the present flexibility puzzle. Many different technologies achieving many different types of performance were compared regarding their role in providing this flexibility to the grid, and it appears that the highest amount of value can be achieved by installing batteries (electrochemical ES) behind the meter of consumers. Furthermore, electrochemical energy storage units could be operated to provide benefit to its owner, as well as to the grid, by re-shaping the apparent electricity consumption profile as seen from the electricity network. The role could be key in the transition of consumers into "prosumers", who are willing to introduce photovoltaic (PV) rooftop panels, Electric Vehicles (EVs), Heat Pumps (HP), or simply have a better control on their energy consumption.

The commercialisation of such systems has already started, mostly as an upgrade to rooftop PV. These technologies, their performance, and the numerical models used for their development were examined and compared. Still, the deployment remains low and does not enable the full expected potential yet. The reasons for this are based on market, regulatory, financial, economic, and technical concerns and were developed in the last section.

The paper shows that domestic integrated battery energy storage systems are a very strong candidate to address the challenges faced by the electricity sector. The relevant technology is now emerging and there is still room for performance improvement and decrease in costs. However, investments that could lead to a large deployment are held back by a number of barriers and challenges acting as a vicious circle. The present small number of installed batteries leads to a lack of regulation effort, as not enough systems are present in the network, which makes market regulations and competition unfavourable to domestic BESS. The situation brings about higher risks in investments, therefore only a small number of systems are installed every year, leading to the small fleet growing

too slowly to make regulation efforts worthy. Additionally, the lack of real-world data due to the small amount of installed systems sustains the unfair market and competitions context and the reluctance to investment. Figure 8 illustrates this self-sustained inhibition process.
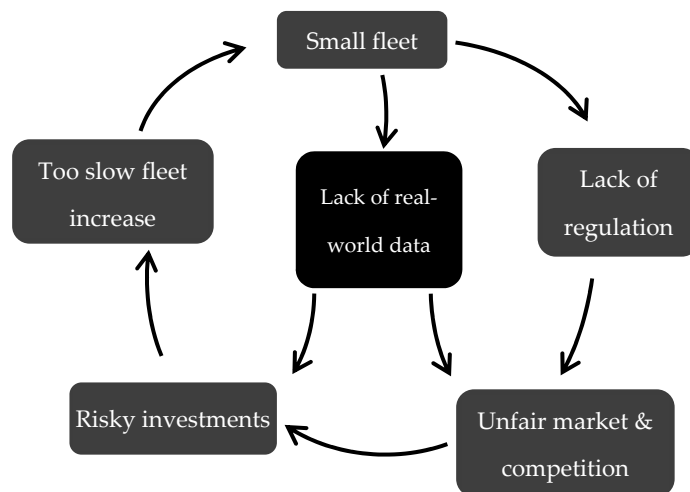
Figure 8. Illustration of the vicious circle in domestic battery implementation.

Now that there is evidence concerning the potential added value of behind-the-meter BESS, a great step forward would be to demonstrate quantitatively the benefits of such a solution. Still, as real-world implementations are expensive and risky—due to the high complexity of implementing such new systems and operating them properly—and may only take place once the trustworthiness of the solution is more clearly demonstrated. In the near future, efforts should be made to generate accurate and valid models that are able to provide reliable quantitative results regarding the technical viability of the solution. From these results, decisions regarding for instance regulation or investments could be made in order to unlock the barriers to deployment and thus releasing all the potential achievable without compromising the operation of the electricity network. As a result, the lack of data leading to difficulties in competition and reluctance in investment (see Figure 8) could be by-passed by providing information that would reverse the competition and investment balance in favour of domestic BESS.

References

1. Spiecker, S.; Weber, C. The future of the european electricity system and the impact of fluctuating renewable energy—A scenario analysis. *Energy Policy* **2014**, *65*, 185–197. [CrossRef]
2. Allan, G.; Eromenko, I.; Gilmartin, M.; Kockar, I.; McGregor, P. The economics of distributed energy generation: A literature review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 543–556. [CrossRef]
3. Ekanayake, J.; Liyanage, K.; Wu, J.; Yokoyama, A.; Jenkins, N. *SMART GRID—Technology and Applications*; Wiley: Hoboken, NY, USA, 2012; ISBN 9780470974094.
4. Brown, M.H.; Sedano, R.P. *Electricity Transmission: A Primer*; Natl Conference of State: Denver, CO, USA, 2004; ISBN 1580243525.

5. Elombo, A.I.; Morstyn, T.; Apostolopoulou, D.; McCulloch, M.D. Residential load variability and diversity at different sampling time and aggregation scales. In Proceedings of the 2017 IEEE AFRICON, Cape Town, South Africa, 8–20 September 2017; pp. 1331–1336.

6. Shah, N.N.; Wilson, C.; Huang, M.J.; Hewitt, N.J. Analysis on field trial of high temperature heat pump integrated with thermal energy storage in domestic retrofit installation. *Appl. Therm. Eng.* **2018**, *143*, 650–659. [CrossRef]

7. EirGrid Group plc—Smart Grid Dashboard n.d. Available online: http://smartgriddashboard.eirgrid.com/#ni/demand (accessed on 24 April 2018).

8. Mcdonald, J.D.; Wojszczyk, B.; Flynn, B.; Voloh, I. Distribution Systems, Substations, and Integration of Ditributed Generation. In *Encyclopedia of Sustainability Science and Technology*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 7–68. ISBN 978-0-387-89469-0.

9. Fitzgerald, G.; Mandel, J.; Morris, J.; Touati, H. *The Economics of Battery Energy Storage: How Multi-Use, Customer-Sited Batteries Deliver the Most Services and Value to Customers and the Grid*; Rocky Mountain Institute: Boulder, CO, USA, 2015.

10. European Environment Agency. *Air Quality in Europe—2017 Report*; European Environment Agency: København, Denmark, 2017; ISBN 978-92-9213-489-1.

11. Bertoldi, P.; López Lorente, J.; Labanca, N. *Energy Consumption and Energy Efficiency Trends in the EU-28 2000–2014*; EUR 27972 EN; Publications Office of the European Union: Luxembourg, Luxembourg, 2016; ISBN 9789279593604.

12. Chaudry, M.; Abeysekera, M.; Reza Hosseini, S.H.; Wu, J.; Jenkins, N. *UKERC Energy Strategy under Uncertainties*; UK Energy Research Center: London, UK, 2014.

13. Smith, B.D. Heat Electrification and Sub-Daily Demand Profiles: A Comparison of Great Britain and Norway—Energy Storage Hub n.d. Available online: http://energystoragehub.org/energy-storage-applications/grid-scale/heat-electrification-and-sub-daily-demand-profiles-a-comparison-of-great-britain-and-norway/ (accessed on 21 January 2019).

14. Pimm, A.J.; Cockerill, T.T.; Taylor, P.G. The potential for peak shaving on low voltage distribution networks using electricity storage. *J. Energy Storage* **2018**, *16*, 231–242. [CrossRef]

15. Jenkins, N.; Long, C.; Wu, J. An Overview of the Smart Grid in Great Britain. *Engineering* **2015**, *1*, 413–421. [CrossRef]

16. Eyer, J. *Electric Utility Transmission and Distribution Upgrade Deferral Benefits from Modular Electricity Storage*; Sandia National Laboratories: Albuquerque, New Mexico; Livermore, CA, USA, 2009.

17. Deeba, S.R.; Sharma, R.; Saha, T.K.; Chakraborty, D.; Thomas, A. Evaluation of technical and financial benefits of battery-based energy storage systems in distribution networks. *IET Renew. Power Gener.* **2016**, *10*, 1149–1160. [CrossRef]

18. Amirante, R.; Cassone, E.; Distaso, E.; Tamburrano, P. Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies. *Energy Convers. Manag.* **2017**, *132*, 372–387. [CrossRef]

19. Akinyele, D.O.; Rayudu, R.K. Review of energy storage technologies for sustainable power networks. *Sustain. Energy Technol. Assess.* **2014**. [CrossRef]

20. Beardsall, J.C.; Gould, C.A.; Al-Tai, M. Energy Storage Systems: A Review of the Technology and Its Application in Power Systems. *Power Eng.* **2015**. [CrossRef]

21. Koohi-Kamali, S.; Tyagi, V.V.; Rahim, N.A.; Panwar, N.L.; Mokhlis, H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review. *Renew. Sustain. Energy Rev.* **2013**. [CrossRef]

22. Lund, P.D.; Lindgren, J.; Mikkola, J.; Salpakari, J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* **2015**, *45*, 785–807. [CrossRef]

23. Yekini Suberu, M.; Wazir Mustafa, M.; Bashir, N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renew. Sustain. Energy Rev.* **2014**, *35*, 499–514. [CrossRef]

24. Guney, M.S.; Tepe, Y. Classification and assessment of energy storage systems. *Renew. Sustain. Energy Rev.* **2017**. [CrossRef]

25. Hull, R.; Jones, A. *Development of Decentralised Energy and Storage Systems in the UK*; A Report for the Renewable Energy Association; KPMG: Amstelveen, The Netherlands, 2016.

26. World Energy Council World Energy Resources—E-Storage. *World Energy Counc. Rep.* **2016**, *1*, 468.

27. Aichhorn, A.; Greenleaf, M.; Li, H.; Zheng, J. A cost effective battery sizing strategy based on a detailed battery lifetime model and an economic energy management strategy. *IEEE Power Energy Soc. Gen. Meet.* **2012**, 1–8. [CrossRef]

28. Das, C.K.; Bass, O.; Kothapalli, G.; Mahmoud, T.S.; Habibi, D. Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. *Renew. Sustain. Energy Rev.* **2018**. [CrossRef]

29. Johnson, R.C.; Mayfield, M.; Beck, S.B.M. Optimal placement, sizing, and dispatch of multiple BES systems on UK low voltage residential networks. *J. Energy Storage* **2018**, *17*, 272–286. [CrossRef]

30. Müller, M.; If, T.D.; Viernstein, L.; Nam, C.; Eiting, A.; Hesse, H.C.; Witzmann, R.; Jossen, A. Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe. *J. Energy Storage* **2017**, *9*, 1–11. [CrossRef]

31. Hoppmann, J.; Volland, J.; Schmidt, T.S.; Hoffmann, V.H. The economic viability of battery storage for residential solar photovoltaic systems—A review and a simulation model. *Renew. Sustain. Energy Rev.* **2014**. [CrossRef]

32. Khalilpour, R.; Vassallo, A. Planning and operation scheduling of PV-battery systems: A novel methodology. *Renew. Sustain. Energy Rev.* **2016**, *53*, 194–208. [CrossRef]

33. Linden, D.; Reddy, T.B. (Eds.) *Handbook of Batteries*, 3rd ed.; McGraw-Hill: Blackclick, OH, USA, 2002; ISBN 0071359788. [CrossRef]

34. Buchmann, I. BU-908: Battery Management System (BMS)—Battery University n.d. Available online: https://batteryuniversity.com/learn/article/how_to_monitor_a_battery (accessed on 8 October 2019).

35. Battery IInformation Table of Contents, Basic to Advanced n.d. Available online: http://batteryuniversity.com/learn/ (accessed on 4 December 2017).

36. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]

37. Kularatna, N. *ENERGY STORAGE DEVICES FOR ELECTRONIC SYSTEMS—Rechargeable Batteries and Supercapacitors*; Hayton, J., Ed.; Elsevier: Amsterdam, The Netherlands, 2015.

38. Isidor Buchmann. How does the Lead Acid Battery Work? Battery University, 2018. Available online: https://batteryuniversity.com/learn/article/lead_based_batteries (accessed on 15 August 2018).

39. Buchmann, I. Nickel-based Batteries—Battery University. 2018. Available online: http://batteryuniversity.com/learn/article/nickel_based_batteries (accessed on 29 June 2018).

40. Buchmann, I. Types of Lithium-Ion Batteries—Battery University. 2018. Available online: http://batteryuniversity.com/learn/article/types_of_lithium_ion (accessed on 3 July 2018).

41. Garg, B. Introduction to Flow Batteries: Theory and Applications. 2011. Available online: http://large.stanford.edu/courses/2011/ph240/garg1/ (accessed on 4 July 2018).

42. Scrosati, B. History of lithium batteries. *J. Solid State Electrochem.* **2011**, *15*, 1623–1630. [CrossRef]

43. Kabir, M.M.; Demirocak, D.E.; Dotterweich, F.H. Degradation mechanisms in Li-ion batteries: A state-of-the-art review. *Int. J. Energy Res.* **2017**, *41*, 1963–1986. [CrossRef]

44. Isidor Buchmann. Capacity Loss and Discovering What Causes a Battery to Fade—Battery University. 2016. Available online: http://batteryuniversity.com/learn/article/capacity_loss (accessed on 28 June 2018).

45. Vetter, J.; Novák, P.; Wagner, M.R.; Veit, C.; Möller, K.C.; Besenhard, J.O.; Winter, M.; Wohlfahrt-Mehrens, M.; Vogler, C.; Hammouche, A. Ageing mechanisms in lithium-ion batteries. *J. Power Sources* **2005**, *147*, 269–281. [CrossRef]

46. Rao, Z.; Wang, S. A review of power battery thermal energy management. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4554–4571. [CrossRef]

47. Al-Zareer, M.; Dincer, I.; Rosen, M.A. A review of novel thermal management systems for batteries. *Int. J. Energy Res.* **2018**, 1–24. [CrossRef]

48. Wankmüller, F.; Thimmapuram, P.R.; Gallagher, K.G.; Botterud, A. Impact of battery degradation on energy arbitrage revenue of grid-level energy storage. *J. Energy Storage* **2017**, *10*, 56–66. [CrossRef]

49. Reniers, J.M.; Mulder, G.; Ober-Blöbaum, S.; Howey, D.A. Improving optimal control of grid-connected lithium-ion batteries through more accurate battery and degradation modelling. *J. Power Sources* **2018**, *379*, 91–102. [CrossRef]

50. Rappaport, R.D.; Miles, J. Cloud energy storage for grid scale applications in the UK. *Energy Policy* **2017**, *109*, 609–622. [CrossRef]

51. Staffell, I.; Rustomji, M. Maximising the value of electricity storage. *J. Energy Storage* **2016**, *8*, 212–225. [CrossRef]

52. BEIS; Ofgem. *Upgrading Our Energy System—Smart Systems and Flexibility Plan*; Ofgem: London, UK, 2017; pp. 1–32.

53. Neubauer, J.; Simpson, M. *Deployment of Behind-The-Meter Energy Storage for Demand Charge Reduction*; Technical Report NREL/TP-5400-63162; National Renewable Energy Laboratory: Golden, CO, USA, 2015; p. 30.

54. Muenzel, V.; Mareels, I.; De Hoog, J.; Vishwanath, A.; Kalyanaraman, S.; Gort, A. PV generation and demand mismatch: Evaluating the potential of residential storage. In Proceedings of the 2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 18–20 February 2015.

55. Günter, N.; Marinopoulos, A. Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases. *J. Energy Storage* **2016**, *8*, 226–234. [CrossRef]

56. Svarc, J. Complete Solar Battery Review—Clean Energy Reviews. 2018. Available online: https://www.cleanenergyreviews.info/blog/2015/11/19/complete-battery-storage-comparison-and-review (accessed on 8 June 2018).

57. Powerwall 2 AC Specifications n.d. Available online: https://www.energymatters.com.au/wp-content/uploads/2016/11/tesla-powerwall-2-datasheet.pdf (accessed on 9 October 2019).

58. Powerwall 2 Full Specs Reveal Cheap Storage And Limited Warranty n.d. Available online: https://www.solarquotes.com.au/blog/powerwall-2-warranty/ (accessed on 9 October 2019).

59. Lg Chem Resu Datasheet n.d.:1–2. Available online: https://solarclarity.nl/wp-content/uploads/2018/07/LG-Chem-RESU-13.pdf (accessed on 9 October 2019).

60. Svarc, J. Lithium Vs Lead-Acid Batteries—Clean Energy Reviews. 2019. Available online: https://www.cleanenergyreviews.info/blog/simpliphi-pylontech-narada-bae-lead-acid-battery (accessed on 9 October 2019).

61. SIMPLIPHI PHI Datasheet. 2018. Available online: https://simpliphipower.com/documentation/phi-3-5/simpliphi-power-phi-3-5-kwh-60-amp-specification-sheet.pdf (accessed on 9 October 2019).

62. Svarc, J. Sonnen Battery Review—Clean Energy Reviews. 2018. Available online: https://www.cleanenergyreviews.info/blog/sonnen-battery-review (accessed on 9 October 2019).

63. sonnenBatterie. Technical Data sonnenBatterie. 2019, 2–3. Available online: https://sonnenbatterie.de/sites/default/files/161018_datasheet_sonnenbatterie.pdf (accessed on 9 October 2019).

64. Muoio, D. 10 Home Batteries Competing with Tesla Powerwall 2—Business Insider. 2017. Available online: http://uk.businessinsider.com/rechargeable-battery-options-compete-tesla-2017-5?r=US&IR=T/#8-powervault-is-an-at-home-battery-system-that-is-sold-in-the-uk-all-units-come-with-an-inverter-included-and-the-most-powerful-model-stores-6-kwh-of-energy-prices- (accessed on 12 January 2018).

65. Relectrify n.d. Available online: https://www.relectrify.com/ (accessed on 5 July 2018).

66. Cunningham, W. For Dead EV Batteries, Reuse comes before Recycle. CNET Road Show. 2017. Available online: https://www.cnet.com/roadshow/news/for-dead-ev-batteries-reuse-comes-before-recycle/ (accessed on 5 July 2018).

67. Chris Robinson. Recycle vs Reuse: Why EV Batteries May not Often Get a Second-Life as Stationary Storage Systems. Energy Storage News. 2017. Available online: https://www.energy-storage.news/blogs/recycle-vs-reuse-why-ev-batteries-may-not-often-get-a-second-life-as-statio (accessed on 5 July 2018).

68. Seaman, A.; Dao, T.S.; McPhee, J. A survey of mathematics-based equivalent-circuit and electrochemical battery models for hybrid and electric vehicle simulation. *J. Power Sources* **2014**, *256*, 410–423. [CrossRef]

69. Simpkins, T.; Donnell, C.O. Optimizing Battery Sizing and Dispatching To Maximize Economic Return. In Proceedings of the Battcon 2017 International Stationary Battery Conference, At Orlando, FL, USA, 8–10 May 2017.

70. Gao, L.; Liu, S.; Dougal, R.A. Dynamic lithium-ion battery model for system simulation. *IEEE Trans. Components Packag. Technol.* **2002**, *25*, 495–505.

71. Newman, J.; Tiedemann, W. Porous-electrode theory with battery applications. *AIChE J.* **1975**, *21*, 25–41. [CrossRef]

72. Banerjee, B.; Jayaweera, D.; Islam, S. Modelling and Simulation of Power Systems. In *Smart Power Systems and Renewable Energy System Integration*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 15–29. ISBN 978-3-319-30425-0.

73. Andersson, G. *Modelling and Analysis of Electric Power Systems*; EEH—Power Systems Laboratory: Zurich, Switzerland, 2008.

74. Hay, S.; Ferguson, A. *A Review of Power System Modelling Platforms and Capabilities*; IET Special Interest Publication for the Council for Science and Technology; IET: London, UK, 2015; pp. 3–13.

75. Meneses de Quevedo, P.; Contreras, J. Optimal Placement of Energy Storage and Wind Power under Uncertainty. *Energies* **2016**, *9*, 528. [CrossRef]

76. Sidhu, A.S.; Pollitt, M.G.; Anaya, K.L. A social cost benefit analysis of grid-scale electrical energy storage projects: A case study. *Appl. Energy* **2018**, *212*, 881–894. [CrossRef]

77. Patsios, C.; Wu, B.; Chatzinikolaou, E.; Rogers, D.J.; Wade, N.; Brandon, N.P.; Taylor, P. An integrated approach for the analysis and control of grid connected energy storage systems. *J. Energy Storage* **2016**, *5*, 48–61. [CrossRef]

78. Ru, Y.; Kleissl, J.; Martinez, S. Storage size determination for grid-connected photovoltaic systems. *IEEE Trans. Sustain. Energy* **2013**, *4*, 68–81. [CrossRef]

79. Weniger, J.; Tjaden, T.; Quaschning, V. Sizing of residential PV battery systems. *Energy Procedia* **2014**, *46*, 78–87. [CrossRef]

80. Sani Hassan, A.; Cipcigan, L.; Jenkins, N. Optimal battery storage operation for PV systems with tariff incentives. *Appl. Energy* **2017**, *203*, 422–441. [CrossRef]

81. Pena-Bello, A.; Burer, M.; Patel, M.K.; Parra, D. Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries. *J. Energy Storage* **2017**, *13*, 58–72. [CrossRef]

82. Nottrott, A.; Kleissl, J.; Washom, B. Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems. *Renew. Energy* **2013**, *55*, 230–240. [CrossRef]

83. Angenendt, G.; Zurmühlen, S.; Mir-Montazeri, R.; Magnor, D.; Sauer, D.U. Enhancing Battery Lifetime in PV Battery Home Storage System Using Forecast Based Operating Strategies. *Energy Procedia* **2016**, *99*, 80–88. [CrossRef]

84. Yoon, Y.; Kim, Y.H. Effective scheduling of residential energy storage systems under dynamic pricing. *Renew. Energy* **2016**, *87*, 936–945. [CrossRef]

85. Babacan, O.; Ratnam, E.L.; Disfani, V.R.; Kleissl, J. Distributed energy storage system scheduling considering tariff structure, energy arbitrage and solar PV penetration. *Appl. Energy* **2017**, 1384–1393. [CrossRef]

86. Yang, Y.; Li, H.; Aichhorn, A.; Zheng, J.; Greenleaf, M. Sizing strategy of distributed battery storage system with high penetration of photovoltaic for voltage regulation and peak load shaving. *IEEE Trans. Smart Grid* **2014**, *5*, 982–991. [CrossRef]

87. Zillmann, M.; Yan, R.; Saha, T.K. Regulation of distribution network voltage using dispersed battery storage systems: A case study of a rural network. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pp. 1–8. [CrossRef]

88. Nazaripouya, H.; Wang, Y.; Chu, P.; Pota, H.R.; Members, R.G. Optimal Sizing and Placement of Battery Energy Storage in Distribution System Based on Solar Size for Voltage Regulation. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015. [CrossRef]

89. Lindstens, J. Study of a Battery Energy Storage System in a Weak Distribution Grid Distribution Grid. Master Thesis, UPPSALA UNIVERSITET, Uppsala, Sweden, 2017.

90. Marra, F.; Yang, G.; Træholt, C.; Østergaard, J.; Larsen, E. A decentralized storage strategy for residential feeders with photovoltaics. *IEEE Trans. Smart Grid* **2014**, *5*, 974–981. [CrossRef]

91. Zeh, A.; Witzmann, R. Operational strategies for battery storage systems in low-voltage distribution grids to limit the feed-in power of roof-mounted solar power systems. *Energy Procedia* **2014**, *46*, 114–123. [CrossRef]

92. Moshövel, J.; Kairies, K.P.; Magnor, D.; Leuthold, M.; Bost, M.; Gährs, S.; Szczechowicz, E.; Cramer, M.; Sauer, D.U. Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption. *Appl. Energy* **2015**, *137*, 567–575. [CrossRef]

93. Liu, J.; Zhang, N.; Kang, C.; Kirschen, D.; Xia, Q. Cloud energy storage for residential and small commercial consumers: A business case study. *Appl. Energy* **2017**, *188*, 226–236. [CrossRef]

94. Sonnen, Storage and VPPs. Grey Cells Energy n.d. Available online: https://greycellsenergy.com/examples/sonnens-community-aggregating-domestic-battery-storage/ (accessed on 12 July 2018).

95. Williams, D. The Vanguard of Decentralized Energy for Sonnen—Decentralized Energy. 2018. Available online: https://www.decentralized-energy.com/articles/2018/05/the-vanguard-of-decentralized-energy-for-sonnen.html (accessed on 12 July 2018).

96. Dale, M.; Hey, R.; Turvey, N.; Swift, P. *Project Sola BRISTOL—Closedown Report*; University of Bristol: Bristol, UK, 2016.

97. Northern Powergrid. Innovation Projects—Distributed Storage & Solar Study (NIA_NPG_011) n.d. Available online: https://www.northernpowergrid.com/innovation/projects/distributed-storage-solar-study-nia-npg-011 (accessed on 13 July 2018).

98. Puckup, D.; Greene, L.; Dunlop, S.; Barwell, P. *Solar + Storage = Opportunities − Solar Trade Association Position Paper on Energy Storage*; Solar Trade Association: London, UK, 2016.

99. Teller, O.; Nicolai, J.-P.; Lafoz, M.; Laing, D.; Tamme, R.; Pedersen, A.S.; Andersson, M.; Folke, C.; Bourdil, C.; Conte, G.; et al. *Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030*; Joint European Association for Storage of Energy (EASE); European Energy Research Alliance (EERA): Brussels, Belgium, 2013; Available online: https://www.eera-set.eu/wp-content/uploads/148885-EASE-recommendations-Roadmap-04.pdf (accessed on 12 September 2019).

100. Palizban, O.; Kauhaniemi, K. Energy storage systems in modern grids—Matrix of technologies and applications. *J. Energy Storage* **2016**, *6*, 248–259. [CrossRef]

101. Becker, B.; Bardají, M.E.G.; Durand, J.-M.; Clerens, P.; Noe, M. European Energy Storage Technology Development Roadmap—2017 Update; Joint European Association for Storage of Energy (EASE) and European Energy Research Alliance (EERA); 2017. Available online: https://eera-es.eu/wp-content/uploads/2016/03/EASE-EERA-Storage-Technology-Development-Roadmap-2017-HR.pdf (accessed on 12 September 2019).

102. Bray, R.; Woodman, B.; Connor, P. *Policy and Regulatory Barriers to Local Energy Markets in Great Britain*; University of Exeter: Exeter, UK, 2018; pp. 1–103.

103. Katsanevakis, M.; Stewart, R.A.; Lu, J. Aggregated applications and benefits of energy storage systems with application-specific control methods: A review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 719–741. [CrossRef]

104. Hesse, H.C.; Schimpe, M.; Kucevic, D.; Jossen, A. Lithium-ion battery storage for the grid—A review of stationary battery storage system design tailored for applications in modern power grids. *Energies* **2017**, *10*, 2107. [CrossRef]

105. Torrealba, P.J.R. *The Benefits of Pumped Storage Hydro to the UK*; Scottish Renewables: Glasgow, UK, 2016; pp. 1–49.

106. Mahlia, T.M.I.; Saktisahdan, T.J.; Jannifar, A.; Hasan, M.H.; Matseelar, H.S.C. A review of available methods and development on energy storage; Technology update. *Renew. Sustain. Energy Rev.* **2014**, *33*, 532–545. [CrossRef]

107. Eames, P.; Loveday, D.; Haines, V.; Romanos, P. *The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption*; Research Report; UKERC: London, UK, 2014.

108. Zhou, D.; Zhao, C.Y.; Tian, Y.; Lott, M.C.; Kim, S.-I.; Eames, P.; Loveday, D.; Haines, V.; Romanos, P. *Thermal Energy Storage—Technology Brief*; IRENA: Abu Dhabi, UAE, 2013; p. 92.

109. Dutta, S. A review on production, storage of hydrogen and its utilization as an energy resource. *J. Ind. Eng. Chem.* **2014**, *20*, 1148–1156. [CrossRef]

110. Castagneto Gissey, G.; Dodds, P.E.; Radcliffe, J. Market and regulatory barriers to electrical energy storage innovation. *Renew. Sustain. Energy Rev.* **2018**, *82*, 781–790. [CrossRef]

111. Ugarte, S.; Larkin, J.; van der Ree, B.; Voogt, M.; Friedrichsen, N.; Michaelis, J.; Thielmann, A.; Wietschel, M.; Villafafila, R. *Energy Storage: Which Market Design and Regulatory Incentives Are Needed?* European Parliament Committee on Industry, Research and Energy: Brussels, Belgium, 2015; pp. 1–5.

112. Gyuk, I.; Johnson, M.; Vetrano, J.; Lynn, K.; Parks, W.; Handa, R.; Kannberg, L.D.; Hearne, S.; Waldrip, K.; Braccio, R.; et al. *Grid Energy Storage*; U.S. Department of Energy: Washington, DC, USA, 2013; p. 67.

113. Zame, K.K.; Brehm, C.A.; Nitica, A.T.; Richard, C.L.; Schweitzer, G.D. Smart grid and energy storage: Policy recommendations. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1646–1654. [CrossRef]