Chapter

Electricity Storage in Local Energy Systems

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Abstract

Traditionally, power system operation has relied on supply side flexibility from large fossil-based generation plants to managed swings in supply and/or demand. An increase in variable renewable generation has increased curtailment of renewable electricity and variations in electricity prices. Consumers can take advantage of volatile electricity prices and reduce their bills using electricity storage. With reduced fossil-based power generation, traditional methods for balancing supply and demand must change. Electricity storage offers an alternative to fossil-based flexibility, with an increase expected to support high levels of renewable generation. Electrochemical storage is a promising technology for local energy systems. In particular, lithium-ion batteries due to their high energy density and high efficiency. However, despite their 89% decrease in capital cost over the last 10 years, lithium-ion batteries are still relatively expensive. Local energy systems with battery storage can use their battery for different purposes such as maximising their self-consumption, minimising their operating cost through energy arbitrage which is storing energy when the electricity price is low and releasing the energy when the price increases, and increasing their revenue by providing flexibility services to the utility grid. Power rating and energy capacity are vitally important in the design of an electricity storage system. A case study is given for the purpose of providing a repeatable methodology for optimally sizing of a battery storage system for a local energy system. The methodology can be adapted to include any local energy system generation or demand profile.

Keywords: Battery sizing, flexibility, lithium-ion battery storage, local energy systems, trading mechanisms

1. Introduction

In the context of the power system operation, 'flexibility' can be defined as the capability of the power system to match demand and supply in the face of rapid and large swings in supply and/or demand. Traditionally, flexibility has been provided by large scale dispatchable power generating units such as gas and coal power generating plants. This type of flexibility is referred to as 'supply-side flexibility'. The increasing share of variable renewable sources of energy in power systems intensifies the challenge of balancing electricity supply and demand. However, the decommissioning of the fossil-based dispatchable generating units necessitates the use of alternative sources of flexibility to compensate for the variations of renewable power generation. Battery storage technologies are a key alternative source of

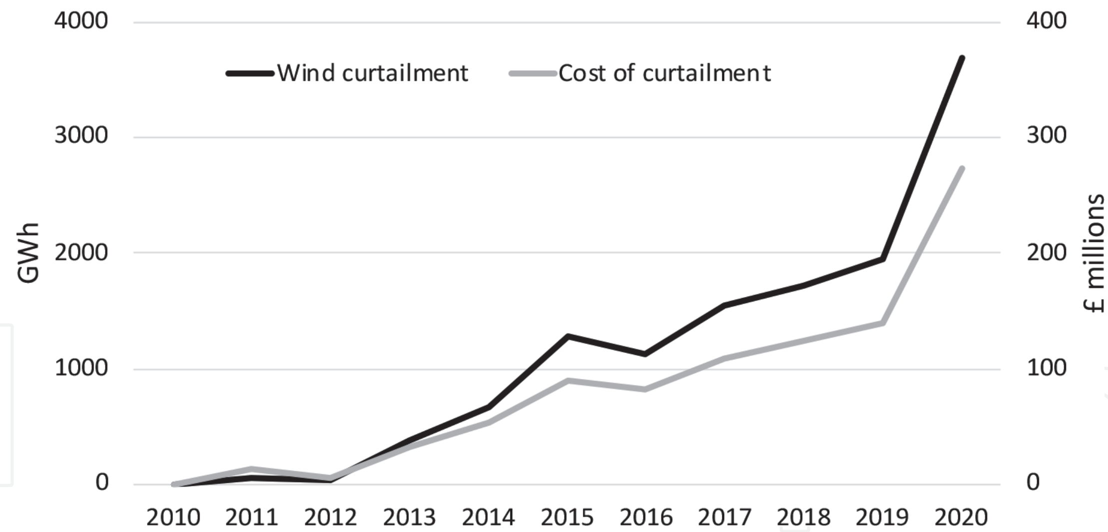

Figure 1.
Annual wind curtailment and cost of curtailment in Great Britain. This figure is produced using data from [1].

flexibility along with demand-side response and interconnectors with neighbouring power systems.

The increase of wind and solar generation capacity in the GB power system and the lack of sufficient flexibility in recent years have led to the curtailment of renewable energy. **Figure 1** shows the annual wind curtailment and the cost of curtailing wind energy in GB from 2010 to 2020. When the electricity generated by wind is high during the low demand period, and the system cannot absorb all the electricity generated by wind due to lack of storage, demand turn-up and downward generation capacity, a fraction of wind generation is curtailed to ensure the supply and demand are balanced and the system frequency is kept as close as possible to 50 Hz.

The variability of power outputs from renewable generation also has an impact on short term electricity prices in day ahead and intraday wholesale markets. At times when there is excess renewable electricity in the system, the electricity price decreases (sometimes it becomes negative) to encourage consumers to use more electricity and encourage generators to reduce their outputs. On the other hand, during high demand periods when the electricity generation by renewable is low, the electricity price rises to encourage consumers to consume less electricity. The increased variation in half-hourly electricity prices is a market signal for flexibility requirement and can make investment in electricity storage financially viable. Being able to shift electricity consumption, consumers that are able to shift their electricity consumption will be able to reduce their electricity bill.

For achieving the net-zero target in the UK by 2050, which was passed as a law by the British government in 2019 [2], National Grid suggested three scenarios namely '*System Transformation*'[1], '*Leading the Way*'[2] and '*Consumer Transformation*'[3]. These scenarios envisaged different mixes of technologies and measures to achieve the net zero target. According to National Grid's scenarios [3], the share of electrical energy generated from wind and solar is expected to increase from 33% in 2019 to between 74% (for System Transformation scenario) and 87% (for Leading

[1] ***System Transformation scenario*** emphasis on hydrogen for heating, consumers less inclined to change behaviour, lower energy efficiency, and supply side flexibility.

[2] ***Leading the Way scenario*** emphasis on fastest credible decarbonisation, significant lifestyle change, mixture of hydrogen and electrification for heating.

[3] ***Consumer Transformation scenario*** emphasis on electrified heating, consumers' willingness to change behaviour, high energy efficiency, and demand side flexibility.

the Way scenario) [3]. **Figure 2** shows that the significant increase in the capacity of wind and solar generation is expected to coincide with the reduction of the capacity of dispatchable generation. To ensure the future power system can balance supply and demand under various operating conditions, there will be an increasing role for electricity storage. According to the National Grid scenarios [3], by 2050, the capacity of electricity storage will increase from 3.75 GW in 2019 to 37.3 GW in Customer Transformation scenario, 23.5 GW in System Transformation scenario and 40.4 GW in Leading the Way scenario.

Figure 3 demonstrates how battery storage can be used to support the balancing of electricity supply and demand, and mitigate the variation of renewable

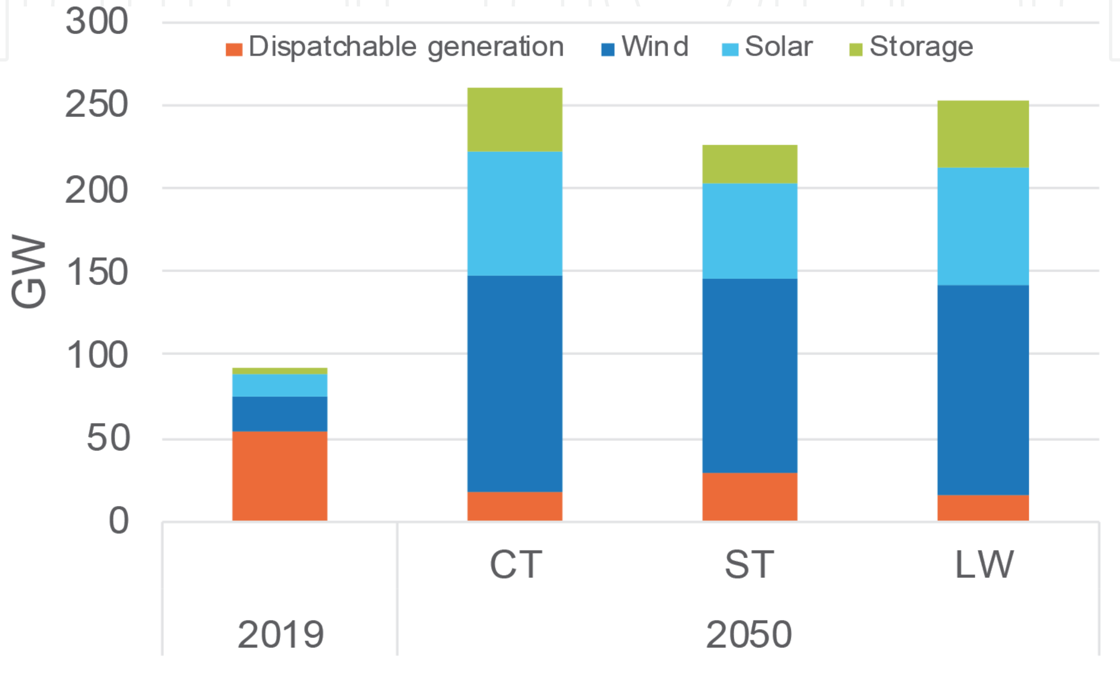

Figure 2.
Capacity of dispatchable generation plants, renewable and storage. Dispatchable generation in this figure accounts for nuclear, biomass, hydrogen and fossil power plants. Columns above year 2050 represent a range of future scenarios; CT: Consumer Transformation, ST: System Transformation, LW: Leading the Way. This figure was produced using data from [3].

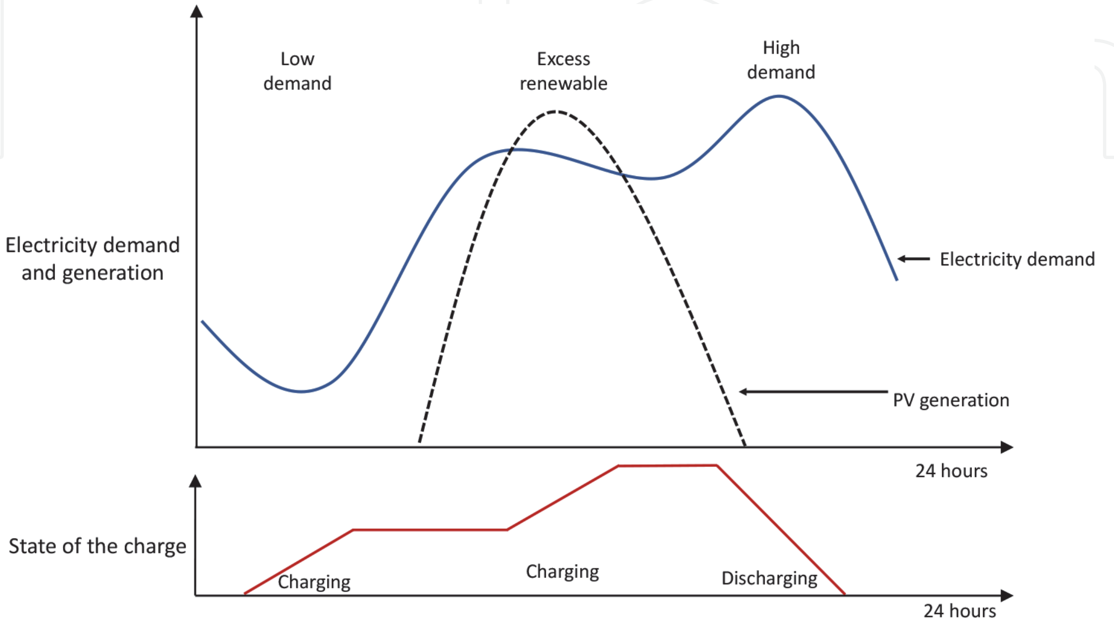

Figure 3.
A schematic depicting the application of battery storage to balance electricity demand and supply.

generation. One of the key uses of battery storage is to smooth the net electricity demand (i.e. total electricity demand minus renewable electricity generation). The battery storage is charged when electricity demand is low and also during periods when electricity from renewable is high. The stored electricity will be discharged during peak demand hours to reduce the stress on the power system.

2. Electricity storage technologies

There is a variety of electricity storage technologies that use a range of mediums to store energy. Electricity storage systems can store energy in mechanical, chemical, electrical and magnetic mediums. Several technologies have characteristics that make them suitable for use in local energy systems. This section identifies electricity storage technologies that are available and those that have characteristics that make them suitable for use in local energy systems. Detailed characteristics of each technology are given, as well as short descriptions of how they work.

There is a variety of existing technologies that can store electrical energy for later use. These have a range of size and operating characteristics that are summarised in **Table 1**. In the context of electricity storage for local energy systems, some of the technologies in **Table 1** are more suitable than the others. The technologies that are promising for applications in local energy systems are listed in the latter half of **Table 1**.

Technology	Power capacity	Energy capacity	Efficiency (%)	Response time	Lifetime (years, cycles)
Pumped hydro storage	100–3000 MW	Up to 100 GWh	75–85	Seconds to minutes	40–60 years
Compressed air energy storage (CAES)	5–1000 MW	100 MWh – 10 GWh	70–89	1–15 min	20–40 years, 13,000+
Flywheels	0.1–20 MW	10–100 kWh	70–95	ms - secs	>15 years, 100,000+
Capacitor	0–50 kW	0–50 kWh	60–65	ms	5, 50,000+
Supercapacitor	0–300 kW	0–300 kWh	90–95	ms	>20 years, 100,000+
Cryogenic [8]	100 kW – 300 MW	100 kWh – 2.4 GWh	40–60	Minutes	25+, 13,000+
Promising (battery) technologies for local energy systems					
Lead-acid	Some kW – 10 MW	Up to 10 MWh	75–90	5–10 ms	3–15, 500–3000
Sodium sulphur [9, 10]	50 kW – 34 MW	400 kWh – 58 MWh	80–90	1 ms	10–15, 2500–4500
Lithium ion	1 kW – 100 MW	Up to 10 MWh	85–98	10–20 ms	5–15, 1000–10,000
Nickel-cadmium [11, 12]	0–40 MW	Up to 13 MWh	60–65	ms	10–20, 2000–3500
Flow batteries (Vanadium and Zinc) [13]	30 kW – 10 MW	3.75 kWh – 32 MWh	75–85	< 1 ms	5–10, 2000–2012,000+

Table 1.
Characteristics of electricity storage technologies [4–7]. The technologies that are most suitable for local energy systems are identified.

Pumped hydro storage: pumped storage is a large-scale mechanical storage technology that stores electricity as potential energy. A difference in height is required between two large volumes of water. Water is pumped to the higher reservoir during charge and flows to the lower reservoir during discharge. Traditional pumped hydro storage is less suited to local energy systems due to its large-scale, high cost, long construction times and niche geographical requirements [4, 7, 14].

Compressed air energy storage: CAES stores electricity as highly pressurised air, in the form of potential energy. During the charging process, air is pumped into large storage caverns. At discharge, the pressurised air is released through a turbine to generate electricity. Similar to pumped hydro storage, the application of traditional CAES in local energy systems is limited by its large-scale, high cost and specific geographical requirements [4, 7, 15].

Flywheel storage: Flywheels store kinetic energy in a rotating mass or rotor. The rotor is situated within a low pressure (vacuum) chamber and connected to a motor/generator. During charging, the rotor speed increases, during discharge the rotor speed decreases. Flywheels have high power density with rapid response times. However, they have relatively low energy storage capacity and high self-discharge. These factors, as well as relatively high cost per kWh mean flywheels are less suited to provide flexibility in local energy systems. For further detail on flywheels, their design, operation and applications, refer to [16].

Capacitors: Capacitors consist of two electrical conductors with a thin insulating layer between them. When a capacitor is charged, it stores energy in an electrostatic field [14]. They have high power density but have limited energy capacity, low efficiency and relatively high self-discharge losses [7, 14, 17]. These factors make capacitors less suited to applications within local energy systems.

Supercapacitor: Supercapacitors are electrochemical double-layer capacitors [7, 14, 18]. In comparison to a traditional capacitor, supercapacitors provide higher energy densities but with lower power density [19]. Despite having a higher energy density than capacitors and better efficiency than most other storage technologies, supercapacitors still have relatively low energy density in comparison to other available technologies and higher levels of energy capacity are very costly. For further details on the state of the art of supercapacitors, refer to [20].

Cryogenic storage: During the charging process of cryogenic or 'liquid air' electricity storage, a cryogen (liquid air) is produced and stored in vacuum insulated tanks [21]. During the discharge process the cryogen is heated and boils. The boiled cryogen is sent through a cryogen heat engine which generates electricity. Cryogenic electricity storage has relatively high energy density, low capital cost per kWh and the potential for increased energy capacity with relative ease [7, 21]. However, cryogenic electricity storage has an efficiency range of less than 50%, making it significantly less efficient than alternative technologies [5, 22].

In the remainder of this section, the electrochemical (battery) storage technologies that show most promise for local energy system are discussed.

2.1 Electrochemical energy storage

Electrochemical energy storage can be split into two major categories, integrated energy storage systems and external energy storage systems [7]. Integrated energy storage systems have their electrochemical charging and discharging reactions taking place within the battery, with no spatial separation [7]. In contrast, flow batteries house their liquid electrolytes in separate containers, bringing them together for a reversible chemical reaction, which enables charging and discharging [7].

Integrated energy storage systems are common with battery technologies such as Lead-acid, Sodium-sulphur, Nickel-cadmium, Nickel-metal hydride and Lithium-ion [7, 23]. One of the major advantages of integrated energy storage systems is their scalability. A very wide range of power and energy capacities are possible as individual cells can be amalgamated into a larger system.

There is a variety of chemistries for integrated energy storage systems (common examples are given in **Table 1**). These chemistries differ in their chemical construction, resulting in differing storage characteristics.

Among the available integrated energy storage technologies, lithium batteries are of increasing importance for energy storage in recent years [24]. Their high specific energy and energy density make lithium batteries suitable for transport applications [25]. In addition to these characteristics, lithium batteries have long life cycles, low maintenance, scalability, power and energy rating flexibility, very high efficiency and low self-discharge [4, 7, 25].

Flow batteries are electrochemical energy storage systems that consist of two electrolytes separated by an ion-selective membrane, in an electrochemical cell. The electrolytes are stored in separate tanks, giving the advantage of total decoupling of power and energy ratings [4, 7, 17, 24]. The chemical reaction that occurs is entirely reversible [7]. The most common flow battery technologies are polysulphide bromide (PSB), vanadium redox (VRB) and zinc bromide (ZnBr) [24]. The flexibility in power and capacity rating, in addition to their scalability from adding additional storage tanks or electrochemical cells, makes flow batteries suitable for a range of applications. Flow batteries have fast response times and long service life, no degradation with deep discharge and low self-discharge [4, 7, 26]. However, while currently being in early commercialisation stage, drawbacks such as relatively low energy density and complex system requirements (including sensors, pumps, flow and power management) mean flow battery storage systems make up a very small proportion of current storage [6, 26–28].

2.2 Lithium battery storage systems

Lithium-ion (Li-ion) battery technology was first patented in 1982 and commercialised in 1991 [29]. Since then, lithium-ion has dominated battery technologies and has replaced nickel-cadmium (NiCd) batteries in mobile phones, doubling the energy density of on-board battery storage [29]. Multiple chemistries are commercially available (these are listed in **Table 2**) however they work in a similar way. Lithium ions move through the electrolyte between the anode and cathode. As the battery discharges, lithium ions are released from the anode and are diffused into the cathode. Anodes are typically made from graphite-based material due to the low cost and availability of carbon. Cathode materials are the dominant factor in determining energy storage performance and hence differentiates technologies. The battery chemistries in **Table 2** are listed by the material used for the cathode. For further details on anodes, cathodes and electrolytes and more details about how lithium-ion batteries work, refer to [32].

2.2.1 Advantages

Lithium-ion battery storage is the second most mature battery energy storage technology in the market, after lead acid batteries [30]. For a detailed review of lithium-ion chemistries, refer to [33].

Lithium-ion battery technology has a variety of advantages that make it a popular choice for portable electronic devices, where energy density, size, weight,

Chemical composition	Acronym	Common application
Lithium manganese oxide	LMO	Electric vehicles, consumer electronics
Lithium iron phosphate	LFP	Electric vehicles, consumer electronics, power tools, aviation
Lithium nickel manganese cobalt oxide	NMC	Electric vehicles, power tools, grid energy storage
Lithium nickel cobalt aluminium	NCA	Electric vehicles
Lithium cobalt oxide	LCO	Consumer electronics
Lithium titanate	LTO	Automotive and grid storage

Table 2.
Existing lithium-ion battery chemistries [25, 30, 31].

Advantages	Disadvantages
High energy density [4, 7, 17, 29, 34, 35]	Highly flammable, fire hazard, safety hazard [25, 29, 30, 35]
Longevity, long cycle life [6, 17, 29, 35]	Highly sensitive to temperature [30, 36]
Versatility and scalability [4, 29]	Accelerated degradation during tough operating conditions [7, 14]
High efficiency [7, 14, 17, 34, 35]	Advanced battery management system required [7, 14, 35, 36]
Rapid response [6, 14]	High initial cost [35]
Low self-discharge [7, 34, 35]	Potential for material bottleneck with high demand [35]
Low operation and maintenance requirements [35, 36]	Currently weak recovery and recycling schemes [35]
Satisfactory operating temperature ranges [35]	
High reliability [35]	
Relatively fast recharge [35]	

Table 3.
Advantages and disadvantages of lithium-ion battery storage.

longevity and efficiency are important. A summary of lithium-ion battery advantages and disadvantages are shown in **Table 3**.

NMC chemistries are the most typically used in grid-scale storage applications due to their balanced performance of energy, power, cost and cycle life [30]. One of the most attractive characteristics of lithium-ion batteries for stationary energy storage applications is their scalability. The ability to connect individual cells together to create an energy storage system with higher energy and power rating makes lithium-ion batteries very versatile. Creating storage systems in this manner means lithium-ion batteries can provide an extremely wide range of power and energy ratings, as shown in **Table 1**: power ratings range between 1 kW – 100 MW and energy ranges up to 10 MWh [4]. Another characteristic that makes lithium-ion battery storage well suited to local energy system electricity storage is the rapid response time. This allows local energy systems to respond quickly to changes in electricity price and market signals to alter their demand, which can allow them to participate in a wider range of markets.

2.2.2 Disadvantages

Lithium is highly flammable and is therefore a safety and fire hazard. Lithium-ion batteries are sensitive to temperature, requiring an active cooling system to maintain an optimal operating temperature. To ensure the safety of lithium-ion batteries, active battery management systems are required to track key parameters such as voltage, current, state of charge, state of health and temperature [35].

A common drawback of battery storage is degradation over time. As shown in **Table 1**, lithium-ion batteries have a long life. However, they are still subject to degradation that can be accelerated by their operating conditions. Batteries are subject to calendar and cycle aging [35, 37]. Calendar aging occurs when batteries are stored without cycling. Cycle aging is degradation related to charge and discharge. Both types of aging cause capacity fade and loss of power, leading to reduced energy and power capacity. Operating conditions such as temperatures outside of the recommended operating range, overcharging, deep discharging and high currents, typically accelerate battery degradation [35, 38]. Optimal operating temperatures depend on the manufacturer, typically these vary around 21°C [30]. Extended periods with the temperature too far from this can lead to loss of performance of the battery.

Typical battery degradation characteristics are non-linear. **Figure 4** shows a representation of the fall in energy capacity seen in batteries, which can be split into three sections. (1) being a rapid initial fall, (2) is a steady reduction and (3) is another rapid drop in energy capacity [37].

Batteries that are at 'end-of-life' are no longer suitable for their application and must be replaced. For high energy density applications such as electric vehicles and portable electronic devices, the battery end of life is typically 80% of its original energy capacity [35, 37]. For stationary storage applications, such as in local energy systems, energy density is not as vital. Therefore, batteries can be utilised to a lower level of degradation before replacement.

2.2.3 Sustainability and recyclability of lithium-ion batteries

Increasing use of lithium-ion batteries in transport and power applications will lead to high demand for battery minerals and large numbers of spent batteries. The three main options for correct disposal of lithium-ion batteries that have reached their end of life are remanufacturing, repurposing and recycling [39].

Remanufacturing is the process of refurbishing lithium-ion batteries and utilising them for the same application. This process is the most effective in terms of maximising the value of end-of-life lithium-ion batteries, as well as minimising life-cycle energy consumption and emissions. However, remanufacturing has relatively strict requirements such as an acceptable state of health and must meet regulatory requirements for power, energy, life cycle and others. For example, electric vehicle batteries that have less than 80% of their original energy capacity left are not suitable for their application.

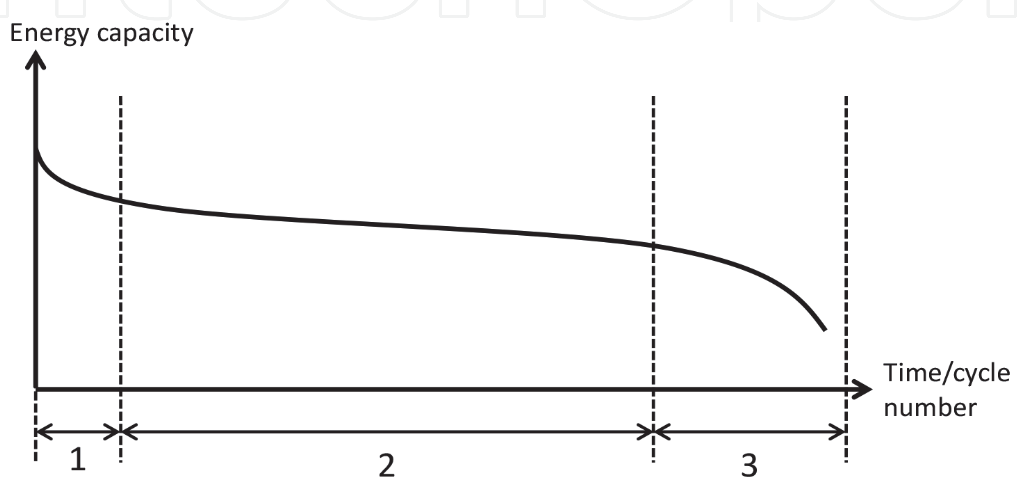

Figure 4.
Typical energy capacity degradation characteristic of a lithium-ion battery storage [37].

Repurposing is the re-deployment of end-of-life batteries for 'second life' applications where power and energy ratings are less critical. Where remanufacturing of spent lithium-ion batteries is not viable, repurposing is an attractive prospect, before recycling. Repurposing is typically the use of spent 'first life' electric vehicle batteries in stationary grid storage applications. However, repurposing of spent lithium-ion batteries faces challenges such as:

- Necessary replacement of damaged cells.
- Integration of a new battery management system that is compatible with the new application.
- Reliably grading of each battery pack.
- Being flexible enough to accommodate for a wide range of manufacturer designs, scales, compatibility and chemistries.

In addition to these challenges, repurposed battery storage systems must be price competitive with first-life batteries, despite complex processing requirements.

Recycling is the final stage of battery recyclability, which is vital for extracting critical materials from spent batteries, creating a circular economy and reducing demand for mining raw materials. Two technologies are commercially used to recycle end-of-life lithium-ion batteries. The first, pyrometallurgy, employs high temperatures to extract and purify metals inside the lithium-ion battery [40]. The second, hydrometallurgy, leaches the internal content of the battery to transfer metals from solid phase to the aqueous solution [40]. A combination of techniques can also be used. Direct recycling has also been demonstrated, using supercritical carbon dioxide for solvent extraction [41]. For further details of recycling methods and a comparison of methods, refer to [40, 41].

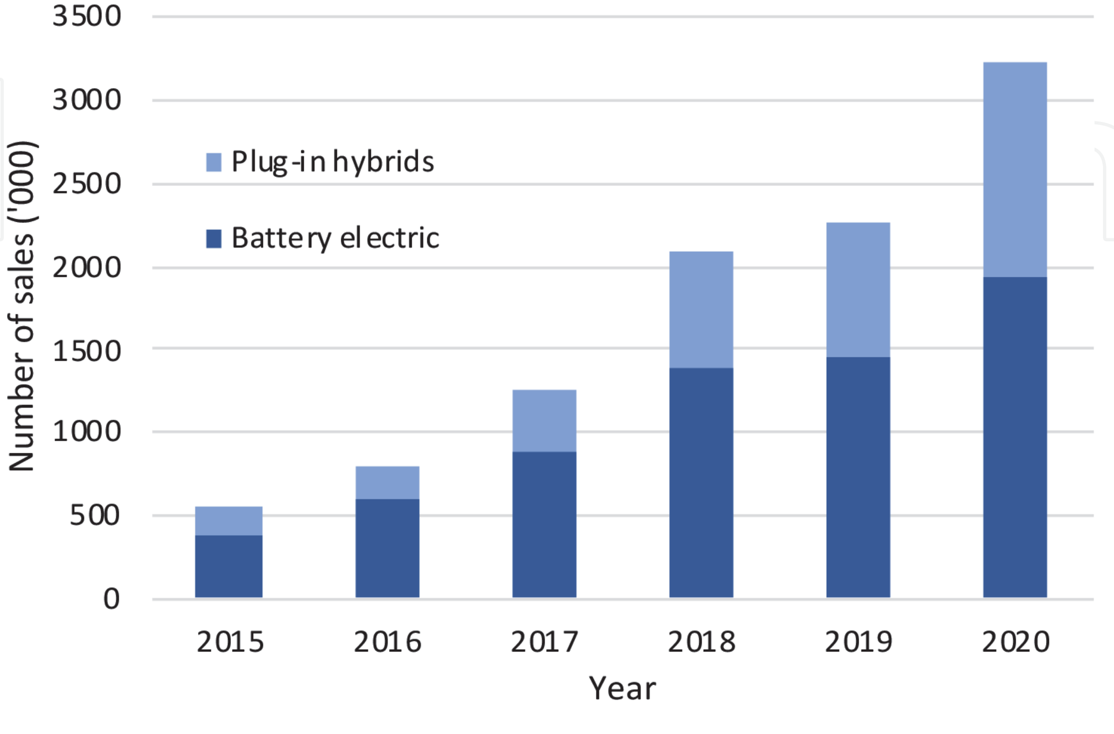

Figure 5.
Global plug-in electric vehicle sales from 2015 to 2020. Reproduced from [42].

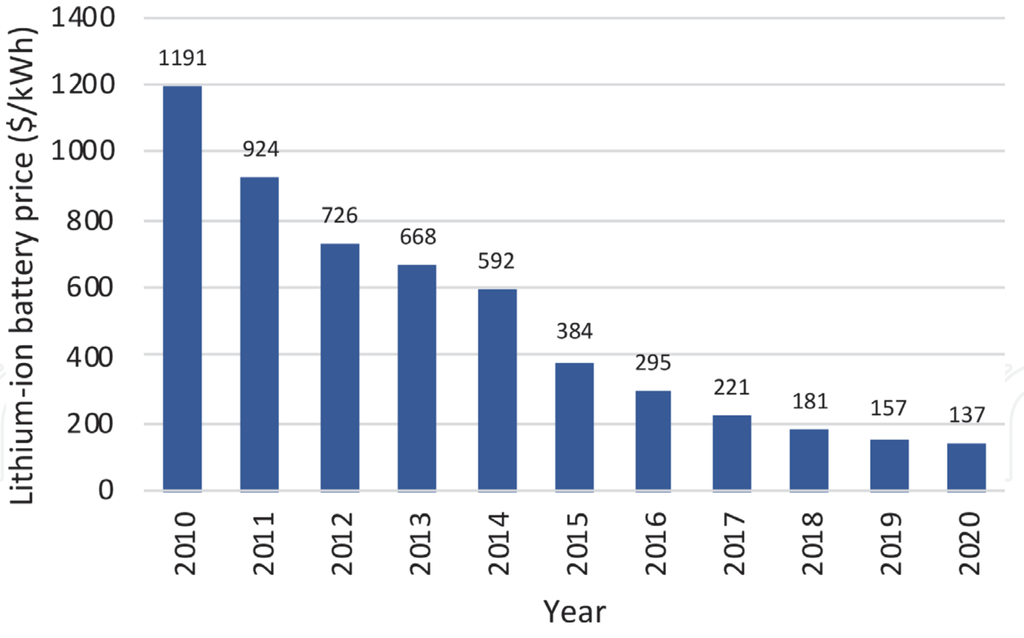

Figure 6.
Lithium-ion battery price, volume weighted average, all sectors from 2010 to 2020. Reproduced from [44].

2.2.4 Market for lithium-ion batteries

Lithium-ion batteries are the dominant storage technology for applications such as portable electronic devices and electric transport. In recent years, the increase in demand for battery electric vehicles has led an increase in lithium-ion battery demand. **Figure 5** shows the increase in purchased electric vehicles over the last 10 years.

The increase in demand for lithium-ion batteries for electric vehicles has contributed to an 89% reduction in cost over 10 years [43]. The BloombergNEF 2020 lithium-ion battery price survey reports on the price of lithium-ion batteries, which is shown in **Figure 6**.

Prices for lithium-ion batteries have been reported at under $100/kWh, with the average price reported as $137/kWh [43]. Although these low prices for lithium-ion batteries have been driven by demand in electric vehicles, there is significant benefit for stationary energy storage applications.

Lithium-ion batteries that are for stationary storage applications have the strongest global growth and market share, in comparison to other electrochemical storage technologies [45]. With global behind the meter battery storage expected to significantly grow in years to come [46]. Lower cost lithium-ion batteries enable local energy systems to affordably increase their flexibility, giving them the ability to control when and how much energy they exchange with the grid.

3. Applications of energy storage in local energy systems

Historically, the electricity system in GB has been based on a unidirectional flow of electricity from large scale power stations to consumers. Power is transported through a high voltage power transmission network, to medium and low voltage power distribution networks, where it is delivered to consumers. Emission reduction targets have driven the transition from this conventional centralised energy system to a decentralised and localised paradigm which integrates diverse distributed energy sources, e.g. solar photovoltaic (PV) and wind generation. This transformation encourages increasing numbers of local energy systems [47]. These local energy systems enable electricity consumers to become prosumers which can generate energy for self-consumption, energy trading with each other, and providing energy and flexibility services to the utility grid. However, the intermittency of renewable energy sources and mismatch between the on-site generation and consumption present a challenge for prosumers. Incorporating energy storage into the local energy systems provides a key solution for prosumers to flexibly manage the distributed energy sources and participate in local energy markets. Instead of curtailing the excessive generation from solar and wind, the surplus generation can be charged into the energy storage devices, and discharged during the peak demand periods.

3.1 Energy arbitrage

Energy arbitrage is affected by a consumer strategically storing the energy when the retail electrical energy price is low, and releasing the stored energy when the retail electrical energy price increases. Energy arbitrage is the most direct method for profiting from energy storage. An example of energy charge of a consumer under peak and off-peak tariffs is presented in **Table 4**. If this consumer stores additional 8 kWh electricity at the off-peak tariff (10 pence/kWh), the total charge would reduce from 258 pence to 130 pence.

Researchers in [48] demonstrated that by providing community battery energy storage systems to prosumers with solar PV and electric vehicles, prosumers could earn additional profits through the energy arbitrage. In [49], a home energy management system was developed for individual prosumers incorporating energy storage systems and solar PV in supporting demand response and energy arbitrage.

3.2 Peer-to-peer energy trading

Advanced metering infrastructure and high penetration of distributed energy sources enable direct energy trading between prosumers. This localised energy trading is referred to as peer-to-peer energy trading, transactive energy, or community self-consumption [50]. Exchanging energy between prosumers results in both bidirectional capital and energy flows within the local energy systems as shown in **Figure 7**. Managing for these bidirectional flows not only requires the localised energy markets and trading mechanisms, but also relies on prosumers to coordinate their distributed energy sources.

Energy storage will improve prosumers ability to participate in peer-to-peer energy trading. Energy storage systems give individual prosumers freedom to make strategic energy trading and battery scheduling decisions to achieve their objectives, e.g. reducing electricity bills or maximising revenue from energy trading. For distribution systems, energy storage can offset the energy imports from the utility grid, in particularly during the peak demand periods. For the whole energy systems.

Tariff	Rate [pence/kWh]	Energy Consumption [kWh]	Charge [pence]
Peak	26	8	208
Off-Peak	10	5	50

Table 4.
Example of energy charge of a consumer under peak and off-peak tariffs.

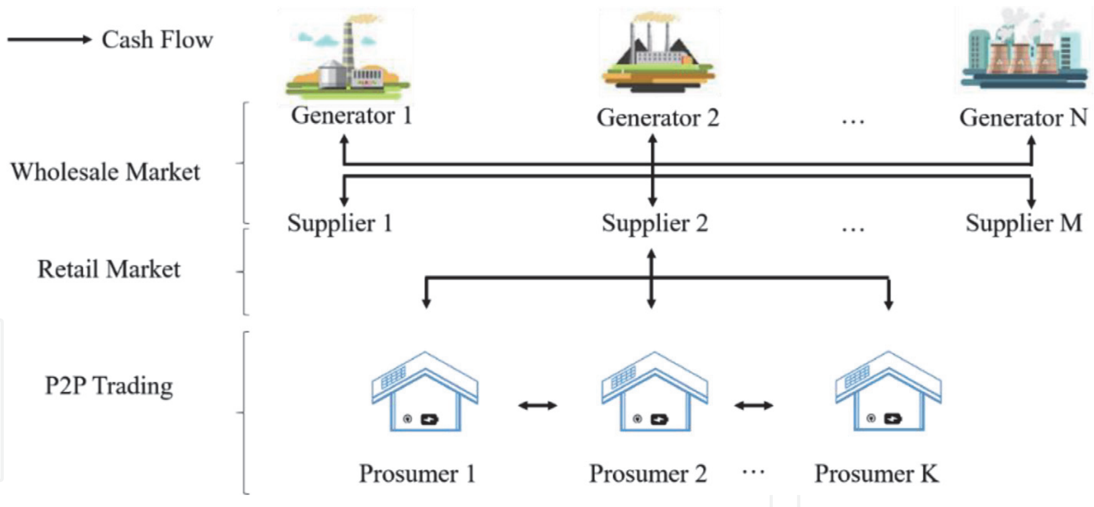

Figure 7.
Schematic illustration of the bidirectional cash flow when a prosumer participates in peer-to-peer energy trading.

Optimally combining energy storage systems with peer-to-peer energy trading can push down market clearing prices and facilitate both the local energy balance and power system energy balance.

3.3 Ancillary services

Local energy systems can participate in a range of ancillary services markets through an aggregator. An aggregator is a company that combines the changes in consumer demand or generation and sells them in markets. The surplus on-site generation of an ensemble of prosumers can be aggregated and stored in local energy systems and later delivered to the utility grid as a service.

There is a wide range of ancillary service with various time scales, e.g. from months ahead to seconds, and multiple functions, e.g. frequency response, energy reserve, voltage support, and demand response [51]. The applications of energy storage in supporting each function of ancillary services are described as follows:

Frequency Response: Frequency response is an action to stabilise the frequency, once power systems encounter sudden loss of generation or load [51]. Energy storage systems play a significant role for regulating the frequency by absorbing or releasing power in response to the deviation from nominal frequency and imbalances between supply and demand.

Energy Reserve: Energy reserve is additional capacity which is online but unloaded to rapidly compensate outages of generation or transmission [52]. The energy storage system can provide this additional reserve capacity without the need for investing an new generation capacities.

Voltage Support: The integration of distributed renewable energy sources, e.g. solar PV, in low-voltage distribution grids would affect the grid voltage profiles during the high generation and low demand periods. The energy storage provides a solution to ensuring the voltage quality requirement while accommodating more distributed generation capacity. The research in [53] suggested the potential of incorporating the storage with reactive power methods to avoid grid reinforcement and active power curtailment.

Demand Response: Demand response refers to reshaping consumption behaviours in response to the dynamic retail electrical energy pricing signals. Instead of curtailing or shifting away loads during high-price periods, a consumer can release stored energy to reduce electricity bills.

4. Design, operation and control of electricity storage systems

4.1 Design considerations

There are many factors to consider for the design of an electricity storage system for a local energy system. Some of those design considerations are:

- Power rating
- Energy capacity
- Physical size
- Response time
- Capital cost
- Lifetime
- O&M complexity and cost

For some electricity storage applications, there may be a specific power rating and energy capacity requirement. When this is the case, this will dictate the design of the electricity storage system to ensure the requirements are met.

For most applications, further analysis must be carried out to maximise benefits from electricity storage. In most cases, the focus is on selecting the optimal power rating and energy capacity for each case. To do this, an in-depth financial analysis must be carried out on a case-by-case basis. The technologies that show promise for local energy system applications have high energy density and fast response times, reducing the need for analysis of physical size and response time.

4.2 Electricity storage operation within a local energy system

Optimal power rating and energy capacity are closely linked to the electricity storage application. Specifically, the way in which the operator intends to use the storage system to benefit themselves. There are any number of operating objectives that the owner of an energy storage system may choose to prioritise. Broadly, these can be assigned to two categories:

- Maximising self-consumption
- Maximising profit by trading electricity

The energy consumed on-site, relative to the total energy generated on-site, is referred to as self-consumption [54]. Energy storage systems, typically batteries, are used as a method to increase self-consumption [54]. This is done by storing surplus electricity from local generation for use at another time, when generation is not enough to meet demand. Self-consumption is particularly attractive due to the difference in import and export electricity prices. The difference between import and export prices is due to some additional charges that apply to import prices. Transmission and distribution network charges recover the cost of building and maintaining all assets in the electricity transmission and distribution networks.

These are charges that are paid by consumers when they purchase electricity from the grid, effectively increasing their electricity import price. These costs are not recouped when consumers sell electricity back to the grid.

Additional charges that are included in a consumers electricity bill are the supplier operating cost, supplier profit and in some circumstances social and environmental costs. All these costs are added to the basic electricity price to give the customer purchase price. The customer sell price however, consists of only the basic price of electricity. Therefore, the purchase price is higher than the sell price. So, from the local energy system perspective, self-consumption of renewable generation will reduce costs by minimising purchased electricity, effectively avoiding extra charges.

Historically, trading has referred to the trading of energy in the wholesale markets by generators, retailers and large industrial consumers [55]. More recently, smaller generators and consumers can also trade electricity between themselves locally or in the wholesale market through an aggregator [55]. Therefore, energy trading is the buying/selling of energy, whether that be in national or local markets. This allows the maximisation of financial benefits for any grid connected consumer that can control their power exchange with the grid. Electricity storage can give local energy systems the flexibility to capitalise on energy trading to maximise their profits. Energy can be stored while the electricity price is low, and discharged when the price is high, this is referred to as price arbitrage.

4.3 Case study: optimal sizing of electricity storage for local energy systems

When local energy systems are considering installing an electricity storage system, often the most important decision is what should be the power rating and energy capacity of the battery. Among other reasons, this is due to the capital cost of electricity storage being closely related to the power rating and energy capacity. The electricity storage system must be large enough to deliver tangible benefits to the owner and operator. However, the larger the power rating and energy capacity, the higher the investment cost will be. Therefore, a balance must be found between the investment cost and the benefits the storage system can provide. The total lifetime costs of a battery storage system are [56, 57]:

- Total investment or 'capital' cost (£/kWh and £/kW). This cost is paid when the battery storage system is purchased and is determined by the power rating and energy capacity prices.
- Operating cost savings (£/year). These are the operational cost savings that battery storage systems provide over their lifetime.
- Maintenance cost (£/kW/no. of years). Some battery storage systems may require maintenance, the cost of which is determined by the power rating and energy capacity and is paid when necessary. This can be after a specific time frame (for example, every one to five years) or irregularly.
- Replacement and/or disposal. At the battery storage systems end-of-life, it must be either repurposed for a second life application or disposed of. In either case, the battery must be replaced if flexibility is still desired.

Operational optimisation is a method commonly used to calculate the operating cost of an energy system with a given battery storage size [56]. The following example describes how this method works and applies it to a case study to demonstrate its efficacy. In addition, the results of the operational optimisation are used in a net present value (NPV) calculation to assess the optimal battery storage size. As they have shown the most promise for applications in local energy system storage, electrochemical battery storage is used in this example. Specifically, this example considers a lithium-ion battery storage system.

The objectives of this section are to:

1. Describe a methodology for evaluating the optimal power rating and energy capacity of a battery storage system in a local energy system with on-site renewable generation and load, as well as a bi-directional connection to the grid.

2. Apply the methodology to a suitable case study to demonstrate the process and ensure repeatability of the case study.

3. Present a comparison of net present values for various power ratings and energy capacities of the battery storage system and identify the optimal combination.

4.3.1 Methodology

A common method for assessing the optimal size of a battery storage system is to formulate an optimisation problem, using linear programming to calculate the operating costs with a battery storage system. The operating costs can then be compared with capital costs to estimate the optimal battery size. The following methodology is a general formulation to assess optimal sizing of a battery storage system for any local energy system with on-site renewable generation and load.

The power rating and energy capacity are defined inputs, requiring a range of combinations for a comparison. The capital cost is found using the inputs for power rating and energy capacity and their defined prices. Then, the operational optimisation determines the cost savings from operating the battery storage system for a period of time (usually one year). In this case, NPV is used to determine the efficacy of the investment for reducing operating cost.

The operating cost consists of any fuel from on-site generation and the cost of power exchange with the grid. For this general formulation, one battery lifetime is considered, therefore, no replacement/disposal costs are included. The capital cost is calculated as follows:

$$I^T = I^P + I^E = \psi^P P^{max} + \psi^E E^{max}. \tag{1}$$

Where, I^T is the total capital cost, I^P is the power rating capital cost and I^E is the energy capacity capital cost. The two latter values are found by multiplying the power (ψ^P) and energy (ψ^E) prices with the power rating (P^{max}) and energy capacity (E^{max}) values. The NPV was calculated using the following equation:

$$NPV = -I^T + \sum_{y=1}^{Y} \left(\frac{NCS_y}{(1+i)^y} \right). \tag{2}$$

Where, y is the year ($y = 1, \dots, Y$), i is the discount rate and NCS_y is the net cost savings each year. The net cost savings (NCSs) is the operating cost with no battery storage (O^{No}), minus the operating (O_y) and the maintenance (M) cost with battery storage. Effectively, this is the cost savings made by including the battery storage system, shown in (3).

$$NCS_y = O^{No} - O_y - M \tag{3}$$

Where, M is the maintenance cost required for specific battery installations. This could be frequent (every year) or infrequent (every 5 years). The operating cost with no battery storage and yearly operating cost with a battery storage system are found using the operational optimisation. The objective of the operational optimisation is to minimise the total operating cost for the local energy system.

$$\text{Min} \sum_{y=1}^{Y} (O_y) \tag{4}$$

Where,

$$O_y = \sum_{t=1}^{T} \tau \left(\psi_t^{im} P_{t,y}^{im} - \psi_t^{ex} P_{t,y}^{ex} \right) \tag{5}$$

In (4), the total operating cost for all years is minimised. The operating cost for each year is determined by (5), as the difference between the cost of importing electricity and the revenue from exporting electricity. The cost of importing electricity is found by multiplying the import price (ψ_t^{im}) by the import power ($P_{t,y}^{im}$) and the time interval (τ) in each time step. The equivalent can be done for the export price (ψ_t^{ex}) and export power ($P_{t,y}^{ex}$) to give the revenue from exporting. The power terms are multiplied by τ to convert from power to energy, as the import and export prices are per unit energy (£/kWh). The index t is the time step ($t = 1, \ldots, T$) and T is the total number of time steps, or the time horizon. In this case, the local energy system is considered as a price taker in a retail market, simply agreeing a fixed or time-of-use contract with a supplier.

For each time step within each year, the power balance of the local energy system must be met. This is shown in (6).

$$P_{t,y}^{im} + P_{t,y}^{dis} + P_t^{Ren} = P_{t,y}^{ex} + P_{t,y}^{ch} + P_t^{L} \tag{6}$$

Where the import power, battery discharge power ($P_{t,y}^{dis}$) and on-site renewable generation (P_t^{Ren}) are equal to the export power, battery charging power ($P_{t,y}^{ch}$) and local load (P_t^L). Eq. (6) ensures that all power flows are balanced, and that local demand is met. This example does not consider the curtailment of on-site renewable generation. This is justified as no grid constraints are considered and because for any positive export price, the local energy system will export generation, rather than curtail it. The battery storage system constraints are shown in (7)–(11).

$$0 \le P_{t,y}^{ch} \le P^{max} \tag{7}$$

$$0 \le P_{t,y}^{dis} \le P^{max} \tag{8}$$

$$E^{min} \le E_{t,y} \le E_y^{deg} \tag{9}$$

$$E_y^{deg} = E^{max} - \delta y E^{max} \tag{10}$$

$$E_{t,y} = E_{t-1,y} + \tau\left(\eta^{ch}P_{t,y}^{ch} - \frac{P_{t,y}^{dis}}{\eta^{dis}}\right) \quad (11)$$

Eqs. (7) and (8) are the charging and discharging constraints and ensure that the charging/discharging power ($P_{t,y}^{ch}/P_{t,y}^{dis}$) is always within the batteries rated power (P^{max}). Eq. (9) ensures that the energy stored in the battery ($E_{t,y}$) is within the available battery capacity (E_y^{deg}). Where, E_y^{deg} is the available energy capacity of the battery, after degradation has occurred. The available energy capacity is defined in (10), where δ is the percentage degradation per year, y is the year and E^{max} is the battery energy capacity. Eq. (11) is the energy balance equation, which defines how the energy stored in the battery changes from one time step to the next. Both charging and discharge are subject to efficiency losses, which are accounted for with η^{ch} and η^{dis}. In this formulation, the power rating and energy capacity are defined inputs. The model is run with P^{max} and E^{max} as fixed values. These are manually varied, and the optimisation repeatedly run to give operating costs for different sized battery storage systems. The operational cost with no battery storage (O^{No}) is found by inputting power rating and energy capacity as zero.

Grid connection limits are not considered in this formulation. However, these can be included as additional constraints, limiting $P_{t,y}^{im}$ and $P_{t,y}^{ex}$ to a maximum value.

4.3.2 Case study definition

The case study was designed to represent a general local energy system with on-site renewable generation, local load and a connection to the grid. The local energy system needs to install an optimally sized battery storage system to reduce their electricity costs. The analysis was carried out at half hourly time intervals (τ = 0.5 hour), over a full year of operation. The battery's power rating and energy capacity were varied to assess the NPV for a range of combinations. In this case study, intervals of 5 kWh were used to assess the energy capacity and 0.5 kW to assess the power rating. Smaller intervals in power rating and energy capacity would lead to a more accurate outcome but would increase the computing time. Lithium-ion energy capacity prices are projected to fall to as low as £52/kWh by 2030 [58]. Power rating and energy capacity costs similar to this were used for this case study and are shown in **Table 5**. Modern small-scale lithium-ion battery storage systems require no maintenance over their lifetime [59]. Therefore, the maintenance cost (M), was assumed to be £0/kW/year. The interest rate used for the NPV calculation was 10%. Remaining battery costs and characteristics are defined in **Table 5**.

Characteristic	Value
Power rating capital cost, ψ^P (£/kW)	60
Energy capacity capital cost, ψ^E (£/kWh)	60
Maintenance cost (£/kW/year)	0
Charging efficiency, η^{ch} (%)	94.9
Discharging efficiency, η^{dis} (%)	94.9
Degradation, δ (% of energy capacity/year)	2
Lifetime, Y (years)	10

Table 5.
Battery cost and technical characteristics.

The battery round trip efficiency was assumed to be 90%. Therefore, the charging/discharging efficiencies were the square root of 90%. Battery degradation was included as a reduction of energy capacity that was applied to each year, for the duration of the battery lifetime. A degradation of 2% per year, resulted in 80% of the original energy capacity after the lifetime of the battery (10 years). In some cases, battery system operators will limit the maximum depth of discharge to reduce degradation and extend the lifetime of the battery. In this case, no depth of discharge limit was considered ($E^{min} = 0$).

The local energy systems renewable generation was assumed to be from 30 kW of solar photovoltaic (PV) panels. Publicly available solar generation data was used as the input for PV generation [60]. Additionally, the input load data was publicly available non-domestic load averages for weekdays, Saturdays and Sundays for five sections of the year [61]. Both PV generation and load data are presented in **Figure 8**.

The import and export prices were also defined input data. The import contract was a non-domestic day/night tariff offered by Octopus Energy, where night was considered as the seven hours between 00:00 and 07:00 [62, 63]. The export contract was a fixed tariff offered by Octopus Energy [64]. The import and export tariffs are shown in **Figure 9** for a 24-hour period. The import and export prices were the same every day of the year.

4.3.3 Results

As the lowest import price does not go below the highest export price in this example, energy trading for price arbitrage was not possible. Therefore, the local

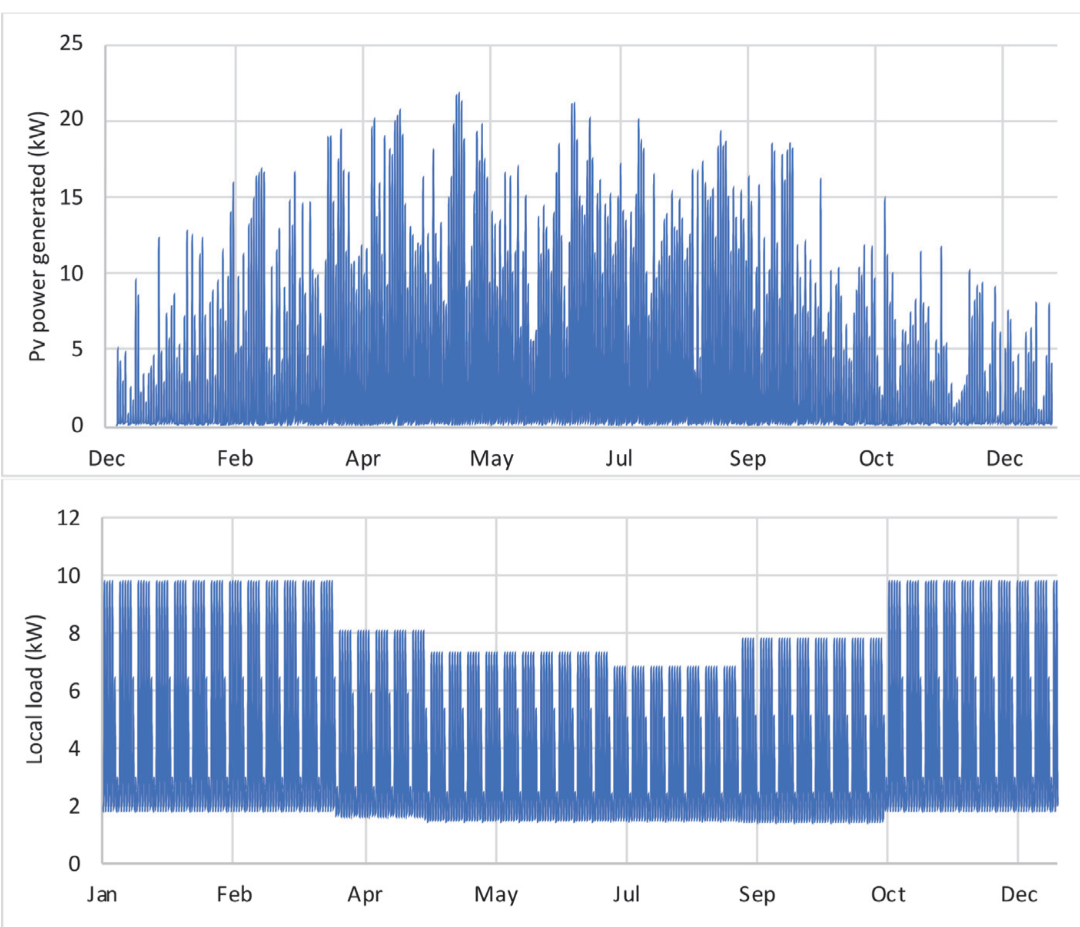

Figure 8.
On-site PV generation and local load profiles for all time steps over a year.

energy system operating objective was to maximise self-consumption of renewable generation, to minimise electricity purchased from the grid.

The local energy systems operating cost for one year with no battery storage system was £2039.14. The operating cost reduced as the battery power rating and energy capacity were increased. However, as the power rating and energy capacity were increased, the capital cost increased. To maximise the benefit of investing in battery storage, a balance must be found between the capital cost and the operating cost savings. NPV was used to assess the lifetime value of a range of power rating and energy capacity combinations. The results are shown in **Figure 10**.

The results in **Figure 10** show that the NPV was impacted by both the power rating and energy capacity. In addition, for each battery energy capacity, there was an optimal power rating. As an example, for a battery energy capacity of 10 kWh, the optimal power rating was approximately 2 kW. Furthermore, the result showed a clear optimal energy capacity of 20 kWh, with an optimal power rating of

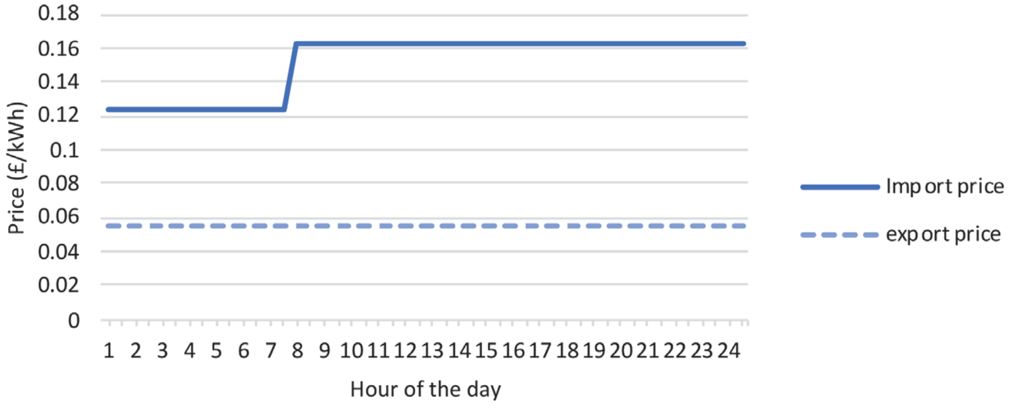

Figure 9.
Import and export prices in the local energy systems 12-month contract with a retailer.

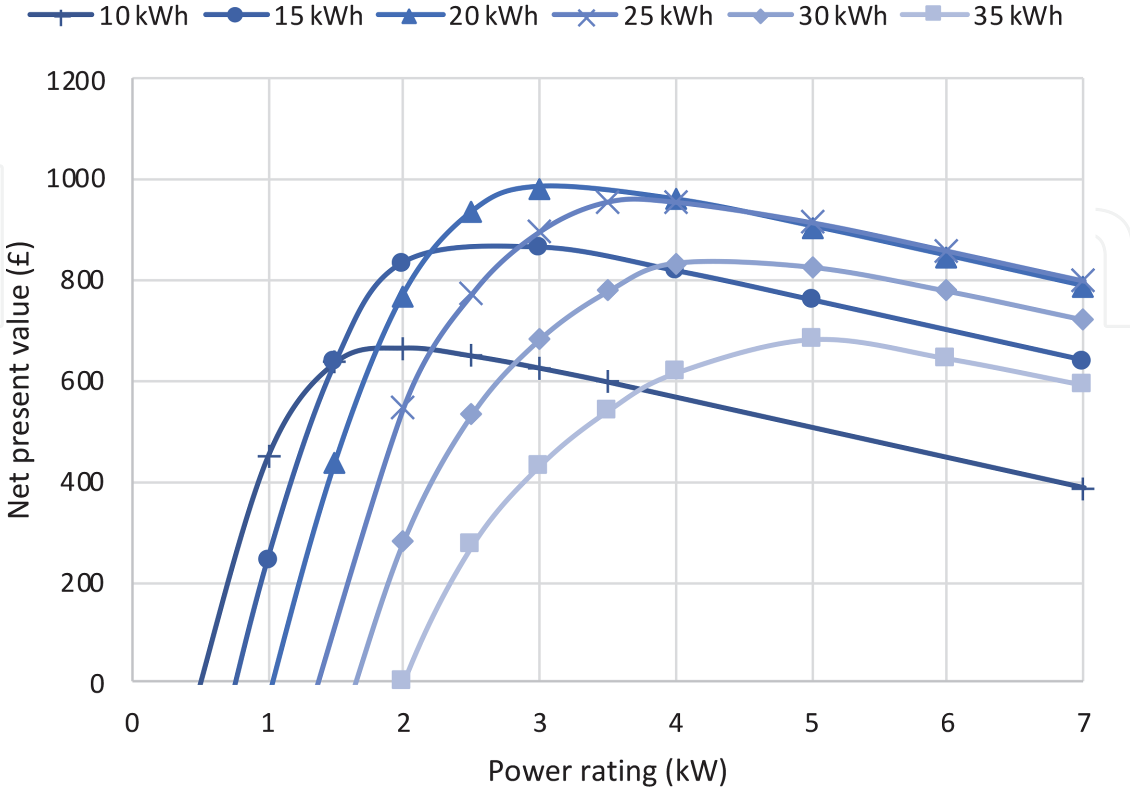

Figure 10.
NPV for a range of power rating and energy capacity combinations.

approximately 3 kW. This result was taken from the highest peak in **Figure 10**, representing the highest value of NPV. This result demonstrates the need to carry out a detailed financial analysis to determine the most suitable power rating and energy capacity for a local energy system.

These results are significantly affected by the assumed input data. In particular, the power rating and energy capacity capital costs. To ensure reliability of result, the input data, especially the prices, must be accurate.

4.3.4 Conclusion

In conclusion, this case study was carried out to describe a methodology for optimal sizing of battery storage for a local energy system. Firstly, a methodology based on operational optimisation and net present value was used to assess the value of adding different combinations of battery power ratings and energy capacities. Then, a case study was defined to demonstrate the practical use of the methodology. The results show clear optimal power ratings for each energy capacity, shown as a peak in net present value. The optimal battery power rating and energy capacity for the case study were 3 kW and 20 kWh, approximately. The result shows that this method can assess the optimal size of a battery storage system for a local energy system. Furthermore, the method can be applied to a wide variety of local energy system configurations, enabling the method to be tailored to specific cases. Finally, the accuracy of the outcome heavily relies on the accuracy of the input data. Therefore, the more detailed and accurate the input data, the more reliable the result.

5. Conclusions

The power system transition from large scale power generation to decentralised integration of distributed energy sources is creating an increasing need for flexibility. With higher penetrations of intermittent wind and solar generation and a decrease in dispatchable fossil-based power plants, flexibility is required to reduce curtailment of renewable generation and ensure a stable frequency by balancing supply and demand. Electricity storage systems can save excess energy during high renewable generation and release it when there is high demand or low renewable generation.

Many electricity storage technologies exist today that store energy in mechanical, chemical, electrical and magnetic mediums. Technologies such as pumped hydro storage and compressed air energy storage have geographical requirements that are generally less suited to local energy systems. Flywheels, capacitors and supercapacitors have relatively low energy storage capacity, limiting their use in a local energy system. In comparison, cryogenic energy storage has high energy density but is limited by its low efficiency of approximately 50%.

The most promising technology for local energy system electricity storage is electrochemical. In particular, lithium-ion battery storage systems have high energy density, longevity, high efficiency and rapid response. Alongside disadvantages such as environmental impact of lithium production and recycling, lithium-ion batteries have a high capital cost. However, increasing demand for large batteries for electric vehicles has driven down the price by 89% over the last 10 years. This, along with improved remanufacturing, refurbishing and recycling technologies has put lithium-ion batteries at the forefront of electricity storage in recent years.

Applications of electricity storage for local energy systems include self-consumption, energy trading and providing services to the utility grid. Local energy systems can strategically store energy when the electricity price is low and release it when the price is high. This is called energy arbitrage and is a common strategy employed by owners of electricity storage systems. An alternative energy trading strategy is peer-to-peer trading, where energy is traded between prosumers and consumers in bidirectional agreements. Finally, ancillary services are a group of flexibility markets that local energy systems can participate in via an aggregator. There is a variety of services including frequency response, energy reserve, voltage support and demand response.

The design and operation of an electricity storage system for a local energy system is unique. Several considerations must be made, including power rating, energy capacity, physical size, response time, capital cost, lifetime and operation and maintenance cost. A balance must be struck between each characteristic to ensure the most beneficial design for the local energy system. A case study provides a methodology for obtaining the optimal size of a battery storage system. Specifically designed for repeatability, the energy generation and demand can be adapted to fit any local energy system configuration. The optimal power rating and energy capacity were determined and presented in the results.

Nomenclature

Symbol	**Description**
Sets	
t	Time step index
y	Number of years index
Input parameters	
E^{max}	Battery energy capacity (kWh)
E^{min}	Minimum battery state of charge (kWh)
O^{No}	Local energy system operating cost with no battery storage (%)
P^{max}	Battery power rating (kW)
P_t^L	Local energy system on-site load (kW)
P_t^{Ren}	Local energy system renewable power generation (kW)
η^{ch}	Battery charging efficiency (%)
η^{dis}	Battery discharging efficiency (%)
ψ^E	Energy capacity price (£/kWh)
ψ^P	Power rating price (£/kW)
ψ_t^{ex}	Export price (£/kWh)
ψ_t^{im}	Import price (£/kWh)
i	Interest rate (%)
T	Total number of time steps
Y	Total number of years
δ	Rate of degradation (%)
τ	Time interval (0.5 hours)
Variables	
$E_{t,y}$	Energy stored in battery (kWh)
E_y^{deg}	Energy capacity available, after degradation (kWh)
I^E	Battery energy capital cost (£)

I^P	Battery power capital cost (£)
I^T	Total capital cost (£)
M	Maintenance cost (£)
NCS_y	Net cost savings for each operating year (£)
NPV	Net present value (£)
O_y	Operating cost with battery storage (£)
$P^{ch}_{t,y}$	Battery charging power (kW)
$P^{dis}_{t,y}$	Battery discharge power (kW)
$P^{ex}_{t,y}$	Export power (kWh)
$P^{im}_{t,y}$	Import power (kW)

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