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Aggregated applications and benefits of energy storage systems with application-specific control methods: A review

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Abstract

Distributed energy storage systems (ESSs) are becoming essential components for the operation of the increasingly complex electricity grid, where dispersed generation is causing power-flows occurring both top-down and bottom-up. Specifically, the combination of ESSs coupled with application-specific control methods can achieve the interdependent objectives of system stakeholders such as the system operator, electrical utilities, retailers, equipment vendors, the government and the electricity customers. The necessity for an accelerated rate of transition to a multi-directional grid arrangement has been exacerbated by the rapid proliferation of distributed renewable energy sources (RESs) that are now price comparable to traditional supply sources. While there are review articles covering ESS technologies and applications as well as the plethora of future advanced grid arrangements that may eventuate, there is none which comprehensively covers individual and aggregated ESS applications and the corresponding benefits, comparing different technology selection methods and providing application-specific controls. Both operational and monetary benefits are identified and critically reviewed from the perspective of the aforementioned stakeholders. Wholesale and retail energy market regimes are also considered for monetisation of the benefits. The control methods that are provided cover both balanced and unbalanced grid conditions. This comprehensive review paper will be of immense value to researchers and practitioners seeking to understand and unpack the aggregated benefits of ESS in the electricity grid.

Keywords: Energy storage; control systems; smart grid; selection; renewable energy sources.

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1. Introduction

There is a growing interest in the role of ESSs integrated into the electricity grid due to a number of different drivers, such as improvements in power electronics and storage technologies, more stringent operational requirements of the electricity grid (e.g., in terms of power quality), deregulation of the electricity market, continuous load growth leading to higher regional power transfers, variability in load profiles and most importantly the rapid growth of distributed RESs [1-6].

On a global level, efforts are progressing in order to further increase the deployment of RESs and decrease greenhouse gas (GHG) emissions as a measure to tackle climate change impacts [4, 7, 8]. There are many recent examples of RESs promotion in the United States (US), Europe and Australia. In the US, the state of California has committed itself to reach 33% renewables participation in its energy mix by 2020 [9], Wisconsin's target is 10% by 2015 [10] while the state of New York has a more ambitious short-term goal of a minimum of 30% renewably generated electricity by 2015 [11]. The European commission has established a roadmap for reducing GHG emissions by 80% - 95% by 2050 and a key factor in achieving this target is further deployment of RESs in the countries belonging to the union [7]. In Australia, organisations have been established such as the Australian Renewable Energy Agency (ARENA) and the Clean Energy Council (CEC), which have the aim to support further RESs deployment either by government partial funding of RESs ventures (i.e., ARENA) or by developing and advocating clean energy policies (i.e., CEC) [12, 13].

The enhanced presence of RESs in the electricity grid is grist to the mill of environmentally friendly energy. However, if renewables are not properly integrated into the grid, they can have an adverse impact on its operation in terms of voltage rise at the feeder terminals, overloading of grid components at times where there is a high amount of reverse power-flow, voltage fluctuation where RESs are connected, increased spinning reserve requirements in the case of sudden loss of renewable generation, additional difficulty in generation dispatch and unit commitment, effect on electricity market trading, to name a few. Due to these unintended impacts on the grid from RESs, a number of measures have to be taken to ensure normal grid operation can be reinstated in the presence of the evolving, intermittent and distributed RESs generation [1, 2, 4, 10, 14-18]. It should be noted that these mitigating measures introduce a considerable additional cost. For instance, for every 10% increase in wind penetration, another 2-4% of the wind power capacity is required from regular generators to maintain the balance and stability of the system [2]. Photovoltaic (PV) generated power also requires higher generation capacity reserves to be used as backup, while the additional cost is paid by the electrical utilities and in turn by the end-users [19]. Greater utilisation of ESSs is essential for an increasingly complex electricity grid to accommodate higher volumes of RESs, as it assists in mitigating or preventing the aforementioned phenomena [18, 20]. ESSs enable the process of converting electrical energy from a power network into a form that can be stored, and for converting back to electrical energy when needed [1]. An ESS can also be seen as energy transfer through time, from generation to consumption [14, 21] or as a generator which consumes electricity as fuel, this is converted into potential energy which is used at a later time for electricity generation [22].

The integration of storage into the electricity grid is usually realised through a converter or a power conditioning unit (PCU) [1, 2, 4, 5, 14, 23] which can belong to a grid support device such as a static synchronous compensator (STATCOM) [2, 5, 24]. The reactive power capabilities of the converter coupled with the active power capabilities of the storage, create an impeccable combination for mitigating grid disturbances, support grid efficiency, enhance reliability and assure power quality [1-3, 5, 6, 8, 14, 20, 21].

Since further grid planning experience is required associated with ESSs (and particularly ESSs combined with RESs integrated into the grid [18]), the US Department of Energy (DOE) has provided extensive research support to a number of organisations examining a future

grid that would be able to incorporate this technology for sound and economic operation, including the Sandia National Laboratories [3, 14, 23], the California Energy Commission, the New York State Energy Research and Development Authority (NYSERDA) [21], the Electric Power Research Institute (EPRI) [5] as well as a number of electrical utilities [21]. Numerous energy storage pilot projects were created, driven by the 2009 American Recovery and Reinvestment Act (ARRA), with the purpose to provide technical, economic and energy market insights, for gaining experience, inquire in the financial viability and configure/reappraise energy market policies which constitute challenges for further ESSs deployment [25].

The efforts made to demonstrate the capabilities of the ESS, have seeded a growth in its global rated power over the past years [26]. The DOE Global Energy Storage Database shows that the rated storage power remained almost constant at 1 GW between 1991 and 2015, however from 2006 and onwards there is a steep increase to an anticipated 4.5 GW by 2020. The growth in ESS installations will be attributed to the key drivers discussed at the beginning of the introductory section (e.g., ESS technological improvements leading to lower costs and higher efficiencies, role in managing the intermittency of renewable generation and peak demand, among many others).

This review article seeks to combine and review industry and research information from a number of sources related to the applications, benefits, selection processes and power controls, surrounding the ESS. There are presently no comprehensive review articles in the literature to cover all of the above topics supplemented by aggregated applications towards benefits maximisation.

Based on the goal to produce a review article that could compile this information in a logical and useful manner, the following objectives were set:

1. To shed light on ESS applications and the corresponding benefits; from the perspective of different stakeholders (e.g., electrical utilities and electricity customers).
2. To explore wholesale and retail energy market regimes in order to monetise the various ESS applications.

3. To present and compare storage technology selection methods regarding a specific application; leading to a definite technology selection result, even in the presence of competent candidate storage technologies.
4. To review and describe application-specific control methods required for the functionality of the ESS under balanced or unbalanced grid conditions.
5. To suggest and discuss aggregated applications performed by an ESS for the acquisition of greater economic and operational benefits when compared to single applications.

ESS applications and control methods discussed in this review article are those that have been well-documented and clearly defined in the literature. Other applications and control methods exceed the scope of the present review paper.

2. ESS applications

ESSs have numerous applications across the levels of the electricity grid [27]. Effectively integrating the intermittent generation of distributed RESs is viewed as a core goal of ESSs. An overview of the applications that will be discussed in this section are presented in Fig. 1, which has been adapted from [1, 28, 29]. Larger scale ESSs are more appropriate for the generation and higher voltage levels of the electricity grid, while smaller scale ESSs can serve a number of purposes at the lower voltage distribution level and for the important ‘beyond the meter’ applications (i.e., commercial, industrial and residential) [1, 28].

ESSs are essential for the various stakeholders of the electricity grid, including electrical utilities, end-users, energy services providers (ESPs), corporations, manufacturers, vendors and the environment. For utilities, RESs smoothing and peak demand reductions leading to avoided costs and/or deferred investments are an expected goal accruing from storage integration, along with the facilitation of reliable and economic grid operation [30, 31]. End-users will be able to manage their electricity costs by changing their consumption and demand patterns or by better utilising the renewable energy at the premises. Commercial and industrial customers can reap significant benefits from ESSs through reductions in peak demand charges (i.e., kVar charges apply from their utility) they may have incurred prior to ESS installation, along with improved power quality resulting in reduced power interruptions hence higher productivity. ESPs will have the opportunity to provide a range of new services

under the smart/micro-grid paradigm, such as distributed generation, storage coupled with power control solutions, thereby positioning them as key players in the transitioning electricity marketplace. Market opportunities also arise for corporations conducting research and development (R&D), manufactures involved in the production of the devices, and vendors in charge of procuring the assets. In terms of the environment, affordable ESSs will enable a much greater penetration of RESs across the levels of the electricity grid, as the normal grid operation is permitted even in the presence of considerable fluctuations introduced by RESs. Moving towards higher levels of RESs along with ESSs, results in decreased reliance on fossil-fuelled generation and the associated GHG emissions, as RESs become more firm or can even be despatched via time-shifting. Storage could also reduce the current degree of use of inefficient fuel consumption from thermal generation at part load operation by being used in applications such as load following and spinning reserve [1-5, 8, 14, 20].

An example of unit commitment performed via a common independent system operator (ISO) practice is provided in [17], and it includes the scheduling of regular thermal generation along with an ESS in the form of compressed air energy storage (CAES). The objective of the unit commitment is to determine the lowest power generation cost by minimising a cost function, which takes into consideration unit parameters and security constraints imposed by the grid.

Reducing ESS costs together with an improved level of understanding of the numerous simultaneous applications of ESS and their stacked benefits has seen a recent rise in the number of ESS implementations globally. By year's end 2014, The USA had the largest market for energy storage in terms of both the number of projects and by installed capacity, commissioning 95 energy storage projects, with installed capacity exceeding 357 MW. Japan was second with 310 MW of installed capacity and China second in number of projects with 63 [32]. In recent years, Australia has formulated a rapidly expanding energy storage agenda. The Australian Capital Territory (ACT) Government is committed to supporting the implementation of 36 MW of energy storage across more than 5,000 Canberra residential properties and business premises until 2020. In their quest to become carbon neutral, the Australian city of Adelaide has fostered a strong sustainable cities agenda providing subsidies to businesses, residents and schools for installing energy storage [32]. Energy

storage projects are gathering momentum worldwide, with expectations that the energy storage market will be in the order of \$250 billion or more by 2040 [33].

Fig. 1. ESS applications across the grid levels including RESs and the SCADA at the dispatching centre (DC).

2.1. Energy shifting - arbitrage

An ESS with discharge duration in the range of tens of minutes to an hour is suitable for this application. The principle of operation is storing/purchasing energy from the grid (or from renewable surplus) when prices are low and discharging/selling energy when prices are high, as illustrated in Fig. 2 [1, 34] for a day with a morning and an evening peak [2, 5, 23, 34]. Real life data about load demand and the price of electricity (Fig. 2), can be obtained from the Australian Energy Market Operator (AEMO) or similar organisations in other nations [58].

Fig. 2 highlights that inexpensive energy is aligned with low load demand while expensive energy coincides with high load demand, therefore, storage systems that are placed proximate to end-users intended for energy shifting-arbitrage (or peak load shifting [21]) reduce the necessity for increased power provision from the remote generators to end-users during on-peak times (storage discharges to sell high-cost energy). Therefore, a portion of the load is shifted from the on-peak period to the off-peak period [2, 5]. The aforementioned operating principle has been examined for a CAES installation in Ontario, Canada [35], while the pricing was based on the wholesale ISO market. The investigation revealed that this particular application was financially non-viable; however, to a lower extent compared to the retail energy time shifting application, discussed in Section 2.10. Further improvements in certain CAES technologies such as advanced adiabatic CAES and isothermal CAES are reported in [59]; where the efficiencies have increased by over 30% and the energy storage densities raised by a multiplier of 5 whilst additional research and the associated cost are required, to deploy the full potential of CAES.

This shifting of load can be utilised to defer substantial capital investments in generation or distribution capacity as discussed in Sections 2.2 and 2.5, due to the creation of a more uniform load profile across the electricity grid [1, 23]. Less variable load profiles ultimately deliver a reduced cost for end-users [21]. ESSs have the potential to enable a situation, albeit unlikely to culminate in the near term, where an almost constant load demand is required from the grid both day and night; a term often referred to as load levelling [23].

Fig. 2. Energy shifting illustrative example based on recorded load demand and price variation for Queensland, Australia.

Readers should note that large scale storage capacity deployed in a region will significantly influence market electricity prices during peak periods, as the price pattern that closely follows the shape of the load profile will also flatten, thereby meaning that there will become less financial incentive to further flatten demand at a certain point.

2.2. Supply capacity

ISOs organise auctions to ensure that future generation capacity (MW) is adequate to serve the future peak load under the ‘forward capacity market’ principle. An auction aims to source capacity three years ahead from the date it is carried out; if the ISO did not manage to secure the targeted capacity, additional auctions will take place during the three year period until the targeted capacity is reached. A more detailed description of the market operation is provided in [60].

Capacity is more accurately divided into installed capacity (ICAP) and unforced capacity (UCAP). ICAP is very close to the nameplate power of the generation unit, but in practice it may be found slightly reduced (e.g., resulting from the applied testing procedure). UCAP

derives from an outage rate that has been applied to the ICAP; for example, for a unit with 300 MW ICAP and with 15% outage rate (e.g., due to component failures), the UCAP is 255 MW [61]. UCAP is what is bid to the ISO capacity market.

A comprehensive explanation of the forward capacity market (FCM) is provided in the Regulatory Assistance Project (RAP) completed by Goldstein and Swartz [60]. A simple forward capacity market (FCM) auction example is illustrated in Fig. 3, which illustrates the suppliers' bids (SBs) and the elastic and inelastic capacity requirements. This figure shows that the bids have covered a considerable amount of the inelastic demand, while the point where supply and demand meet represents the clearing price. The clearing price in this example is determined at \$13/MW per day; this is the price that suppliers 1 to 5 will receive, even though some of their bids were lower. The suppliers offering capacity at a higher price than the clearing price are not successful in that auction.

Fig. 3. Forward capacity market auction and clearing price determination example based on PJM's process.

In a situation where energy storage is participating in the bids with, for example, 75 MW (Table 1) at \$13/MW per day, it could replace the SB 5 and therefore avoid the investment in new generation units to be operational in three years' time. The revenue for

the ESS, at the clearing price for one year is \$355,875, while the clearing price chosen for this example is conservative compared to the recorded prices of PJM [37].

Therefore, based on the market arrangement, the presence of energy storage could potentially result in the deferral or avoidance of additional investments in power plants, and also facilitates a more efficient supply system operation [8].

Multiple financial benefits can be attributed to an ESS such as those received from supplying capacity (i.e., MW) [36] and energy shifting-arbitrage (i.e., MWh) [37]. Numerous others can also be added to this list as described in subsequent sections.

2.3. Ancillary services

The following sections outline the anticipated ancillary services of ESSs for ensuring an economic and technically sound grid operation.

2.3.1. Load following

The imbalance between load and generation is addressed by two complementary applications called load following and frequency regulation (Section 2.3.2). For the first, the variation in the output power of the generators is realised on a few minutes to hours basis or even longer, while the AGC signal generated by the ISO is employed in order to transfer the appropriate correction of output power to the dispatched generators [62].

ESSs have been considered for load following, particularly battery-based [6] and CAES [1, 17]. Compressed air storage technology is well-suited for this application because it can switch quickly between charging and discharging modes, it can deliver many cycles, and it is more environmentally friendly than regular generators because it maintains an efficient operation (i.e., better fuel economy and fewer gas emissions than regular generators) in part load conditions [1].

A CAES facility with 95% functional reliability has been operating since 1991 in McIntosh, Alabama. The facility conducts a load following function, while it is also intended for peak shaving, with a rated power of 110 MW and rated capacity of 2860 MWh [17].

2.3.2. Frequency regulation

This application aims to maintain the system frequency within a band as proximate as possible to its nominal value. The band is 50.1 Hz to 49.9 Hz for 50 Hz nominal frequency

defined by the AEMO [58]. This task is performed by regulating the thermal generation up (increase) or down (decrease) depending on the load demand, with regulating actions in the range of few seconds to a minute [62]. The system frequency is taken as the indicative parameter for regulation actions. In case the load demand is higher than the generated power, the revolutions at the generator's shaft decrease and the frequency therefore decreases. To the contrary, when the generation is higher than the load, the revolutions at the generator's shaft increase leading to a frequency higher than the nominal. The power difference between load and generation is represented by the area control error (ACE), which occurs due to load variation. This is amplified due to the slow inertial response of thermal generation [38]. In turn, the ACE is transmitted to the generators via the automatic generator control (AGC) signal.

An ESS is capable of frequency regulation [2, 8, 21, 23, 38-40] because it is very fast acting [39], even 10 times faster than conventional generators [63]. To be able perform the application, the ESS has to be responsive to the AGC signal or even faster signals generated by the ISO or any other entity in charge of dispatching [21].

A storage system can be used to perform frequency regulation by charging during moments of power generation surplus (i.e., frequency higher than the nominal is avoided), and discharging during moments of generation shortage (i.e., frequency lower than the nominal is avoided) [38]. Furthermore, by discharging during periods of significant under-frequency, load shedding can be reduced or avoided [36, 39].

In terms of pricing of the frequency regulation, there are two components for which the generators, or the energy storage used as replacement of the generators, receive revenues in the ISO markets [64]:

- Energy produced payment - The generators are dispatched based on the AGC signal sent to them by the ISO every few seconds containing a positive, for regulation up, or a negative, for regulation down, power signal. The size of the regulation service is 1% of the peak load while the generated energy is paid based on the current LMP.
- Capacity payment - This payment added to the energy payment is necessary in order to attract generators (or energy storage) to perform frequency regulation. Without this payment, generation units would find it more profitable to participate in the energy market since in that market they can operate at full load, and hence, their

energy production and therefore the revenues are maximised. In contrast, the part load operation which is required in frequency regulation, results in lower energy production and therefore it is less profitable for the generation units to operate under normal market conditions.

The regional transmission organisation (RTO) PJM deems that a 10%-20% reduction in generation capacity procurement, intended for frequency regulation, and substituted by more ESSs, could save \$25-\$50 million for its customers [63]. The Laurel Mountain energy storage project is a representative example of the above, as storage combined with a local wind farm, participates in the PJM market, to provide frequency regulation by maintaining the power output of the wind farm constant [20].

The predominant difference between load following and frequency regulation is that the first application performs changes in the outputs of the generators on a wider time basis to reach a value in the proximity of the current load demand, while changes dictated by the second application are on a narrower time basis and therefore is met the exact load demand, while the system frequency is maintained very close to its nominal value [62].

2.3.3. Generation capacity reserves

To maintain normal grid operation during an unexpected incident, such as the loss of generation resources, capacity reserves are required by the system operator namely spinning reserve, non-spinning reserve and supplemental reserve, where such reserves can be assigned to a storage system. Reserves are often determined in relation to the single largest generator of the system plus a small percentage of the peak load (peak load in ancillary services is considered the period between morning and night e.g., 7 am to 11 pm [65]), or they account for 15%-20% of normal generation. The terminology for generation capacity reserves differs in the literature but in essence has a high degree of commonality [1-3, 6, 8, 14, 17, 23, 40].

Spinning reserve is performed by power sources that are synchronised (online) with the grid or are available on 'hot standby'. They can increase power immediately in the case of a generator or transmission/distribution outage, and they can reach full output within 10 minutes. Spinning reserve is the first reserve to be deployed in a contingency, and it can be driven by the system frequency (e.g., under-frequency for a few seconds). In turn, non-

spinning reserve is out of synchronisation (offline) with the grid, but it can be synchronised within 10-30 minutes. This type of reserve can be comprised of generation or manageable loads. It is also related to the power system mode (i.e., isolated or interconnected) and it can be provided, by fast response units or it can be imported by other systems according to the mode. Supplemental reserve is mainly used in cases where the first two reserves fail to pick-up load. It is non-synchronised with the grid but synchronisation can be achieved within one hour or less [1-3, 14, 23].

If a generator is regarded as an online reserve of the system, it should be in part load operation, resulting in increased fuel consumption and greater emissions per MWh. In contrast, when storage is considered a reserve, efficiency and emission improvements are anticipated, while it should be ready to provide power in case of an unexpected incident [1, 5, 8]. In [14], it is suggested that the size of the storage system should be between 10 and 100 MW, the discharge duration should range between 15 minutes and 1 hour, and the annual cycles to be from 20 to 50 without the provision of specific values for each reserve type.

In order to determine the amount of reserves required to support the sound operation of the power system, the New England (NE) ISO considers the 1st and the 2nd largest contingencies of the system. In case of spinning and non-spinning reserves, their capacity (MW) is defined as 125% of the 1st largest contingency (e.g., loss of the largest generator - MW), while this capacity is divided among the two reserves. For the supplemental reserve, the capacity (MW) is defined as 50% of the 2nd largest contingency [65].

Particularly for spinning reserve, the pricing is similar to the one discussed for frequency regulation because it contains a capacity payment, related to the power availability in case of a contingency as well as an energy payment accounting for the energy provided during an incident (i.e., a few times every year), the energy component is valued based on the current LMP [64].

The pricing reasoning of spinning reserve is extended to non-spinning and supplemental reserves. For generators or ESSs to be able to perform the aforementioned services, they have to participate twice a year in the forward reserve market (FRM) auctions, organised by the NE-ISO (one auction for summer and one for winter), and place a successful bid, a procedure very similar to the FCM auction which is outlined in Section 2.2 [65].

2.3.4. Voltage support

Loads connected across the levels of the electricity grid, require the consumption of both active and reactive power. This continuous demand for power results in grid voltage deviation from the nominal value required by the system operator; therefore, voltage support should be performed. Both active and reactive power affect the terminal voltage, as it is described by the V-P and Q-V curves [66].

The common way to generate reactive power is by controlling the excitation field of the remote generators or the generators in the distributed energy resources (DERs) to the proximity of the loads. Further voltage support at the feeder level can be provided by on-load tap-changer (OLTC) transformers [41].

The ESS can perform effective voltage support [2, 6, 21, 41] because it is capable of providing and absorbing both active and reactive power by utilising the storage medium for active power and the converter for reactive power. Two voltage support strategies are presented and compared in [41]. The first strategy involves provision/absorption of both P and Q, whereas, the second strategy follows the same principle as the first with the priority to be given to Q. It was found that the Q priority strategy resulted in both better voltage profile and lower battery capacity due to the lower energy requirement.

2.3.5. Black start

This application is performed after a blackout has occurred and power to start up the power plants is required. The units that provide the initial power to the power plants should be able to operate independently; therefore, diesel units are frequently used for black start [42, 43]. A battery-based ESS, is particularly suitable for this application because, in addition to its independency, it outperforms diesel units in terms of response time [43].

As it can be seen in Table 1, this application will be requested around 10-20 times per annum (pa). For this number of cycles, the required energy should always be stored and available in order to restore the power plant after a severe contingency. Considering the low cycling activity per annum, poor revenues are anticipated when an ESS is intended solely for black start and the payment is based only on the delivered energy. If an availability payment is included, such as in the AEMO market [58], then the revenues will be higher. From another perspective, in case a battery-based ESS with, for example, 70% depth of discharge

(DoD) is in service to perform another application, 30% of its energy will always be available so that it can be used, only a few times per year, to perform black start; therefore acquiring some additional revenue [44].

Table 1. Operational requirements for ESS applications.

Application	Size	Response	Duration	Cycles
Energy shifting-arbitrage	> 100 MW [1], 40-400 MW [2], 1-200 MW [5], 1-500 MW [14], 100's MW [23]	mins-hrs [67]	hrs-day [1], 53.4 mins-12.8 hrs [2], 1-10 hrs [3], 1-12 hrs [5], < 1 hr [14], 6-10 hrs [23]	60-250 pa [5], ≥ 250 pa [14]
Supply capacity	1-500 MW [14]		4-6 hrs [3, 5], 2-6 hrs [14]	5-100 pa [14]
Load following	> 100 MW [1], 1-100 MW [14], 100's MW [23]	several mins [14], mins-hrs [67]	hrs-day [1], 1-5 hrs [3], 15 mins-1 hr [14], several hrs [23]	
Frequency regulation	> 100 MW [1], 2-200 MW [5], 10-40 MW [14], 100's MW [23]	< 30 secs-1 min [14], < 1 cycle [23]	hrs-day [1], 1-5 hrs [3], 3-30 min [5], 15 mins-1 hr [14], several hrs [23]	continuous operation [5], 250-10000 pa [14]
Spinning reserve	> 100 MW [1], 2-200 MW [5], 1-100 MW [23]	immediate-≤ 10 min [5, 67], ≤ 10 secs-10 mins [14], < 3 secs [23]	hrs-day [1], 1-5 hrs [3], ≤ 2 hr [5], < 30 mins [23]	5-20 pa [5]
Non-spinning reserve	1-100 MW [23]	≤ 10 mins [5], 10-30 mins [14], < 10 mins [23]	1-5 hrs [3], ≤ 2 hr [5], ≤ 30 mins [23]	5-20 pa [5]
Supplemental reserve		≤ 30 mins [5], ≤ 1 hr [14], 30-60 mins [67]	1-5 hrs [3], ≤ 2 hr [5]	5-20 pa [5]
Black start	≥ 10 MVA [5], 5-50 MW [14]	mins [5], mins-> 1 hr [67]	1-5 hrs [3], hrs [5], 15 mins-1 hr [14]	rare [5], 10-20 pa [14]
Voltage support	1-10 MVAR [14]	immediate [5]	1-5 hrs [3]	continuous operation [5]
Voltage stability	10-500 MW [5]	< 20 msec [5]	≤ 2 secs [2], secs [5]	10 pa [5]
Rotor angle stability	10-500 MW [5]	< 20 msec [5]	secs [5]	10 pa [5]
Transmission access charges			1-6 hrs [3, 5]	

Congestion relief	1-100 MW [14]		2-6 hrs [3, 5], 1-4 hrs [14]	50-100 pa [14]
Transmission upgrade deferral	10-100 MW [14]	mins-hrs [67]	4-6 hrs [3, 5], 2-8 hrs [14]	10-50 pa [14]
Distribution upgrade deferral	0.5-10 MW [14]	mins-hrs [67]	2-6 hrs [3, 5], 1-4 hrs [14]	50-100 pa [14]
TOU energy charges	1 kW-1 MW [14]	mins-hrs [67]	2 hrs-tariff's on-peak hrs [3, 5], 1 hr-tariff's on-peak hrs [14]	50-250 pa [14]
Demand charges	50 kW-10 MW [14], < 1 MW [23]	< 1 min [23]	6-11 hrs [3, 5], 1-4 hrs [14], ~1 hr [23]	50-500 pa [14]
Service reliability-UPS	100 kW-10 MW [1], ≤ ~2 MW [23]	msec-< 1 sec [1], secs [23], inst [67]	hrs [1], 0.25 hr-5 hrs [3, 5], ~2 hrs [23]	
Power quality	< 1 MW [1], 1-50 MW [5], 0.1-10 MW [14], ≤ 1 MW [23]	msec [1], < 20 msec [5], < 1/4 cycle [23], inst [67]	10 secs-1 min [3], secs-hrs [5], 10 secs-15 mins [14], secs [23]	1-100 pa [5], 10-200 pa [14]
RES shifting-arbitrage	1-500 MW [14]		6-10 hrs [3, 5], < 1 hr [14]	≥ 250 pa [14]
RES firming	100 kW-1 MW [23]	sec-mins [23]	6-10 hrs [5], ≤ 1 week [23]	
RES smoothing-intermittencies	≤ 10 MW [23]	< 1 cycle [23]	min-1 hr [23]	

2.4. Grid stabilisation

Grid stability is undermined by electrical anomalies and disturbances, such as a short-circuit, the loss of a large generator or the outage of a transmission line or transformer, resulting in stresses on the system leading towards instability [66]. During a scheduled power outage for maintenance purposes, a portable storage device can be used to serve the load. In the case of a sudden power outage, such as loss of an intermediate transmission line, end-users can be served from the energy storage existing in the isolated feeder [5]. Most researchers are supportive of ESSs being integrated in the electricity grid because stability can be strengthened; however, opinions of the most suitable applications to be performed vary considerably [1-3, 45-47].

2.4.1. Rotor angle stability

A grid disturbance could result in generator acceleration or deceleration and the production of power oscillations. The oscillations have to be damped to prevent the loss of synchronisation (not to 'fall out of step') of the generator with the grid. In cases where the synchronisation was lost, the protection system will disconnect the unstable generator to prevent the spreading of synchronisation loss to the other generators [66].

A storage system, by injecting and absorbing active and reactive power can enhance the stability of the power system [2]. The damping performance is investigated in [45] for a three-phase fault, during the fault and the post-fault period. The first of the three investigated cases, demonstrated the response of a two-machine system with no compensation. In the second case a STATCOM was added, while in the third case, the STATCOM was supplemented with a battery. The central finding was that the system with STATCOM and energy storage was the most effective in damping the rotor angle oscillations. The system with STATCOM was fractions of a second slower, followed by the case with no compensation, where its damping capability could not compete with the other two performances, and it was leading to unstable rotor angle.

2.4.2. Voltage stability

If the power system operates near the critical operating point, a possible increase in load power or decrease in generation (e.g., loss of a generator), will result in a new operating state with voltage lower than the one at the critical point of the V-P and/or Q-V curves and therefore, the system will collapse [66].

Voltage stability can be enhanced by employing an ESS [46] that provides both active and reactive power, with the basic characteristics required to include rapid response time and power capability rather than energy capability [1, 2]. A superconducting magnetic energy storage (SMES) is proposed for this application by [1, 46], while a battery-based storage system is suggested by [2]. In terms of operation, 10 cycles pa are proposed in Table 1, which is aligned with the contingency studies carried out in [46] to assess the voltage stability of the system.

Since 2001, the electrical utility Entergy in the US, has operated two SMES units to enhance the voltage stability of its system, one is coordinated with switched capacitors. The

decision to procure the units was made after simulations with various load levels in the presence of grid contingencies, such as loss of a generator and a three phase fault. The results showed that in most of the simulations, the SMES operation supported the grid to remain within the established voltage limits which were 20% voltage dip for maximum 20 cycles. However, in the case with a 60% induction motor as load and in the presence of an electric fault, the system could not maintain an operation within the voltage limits [46].

2.4.3. Sub-synchronous resonance

A resonating coupling can occur between an electrical and a mechanical system and it can be triggered mainly by the presence of capacitor based compensation, connected in series in transmission systems. Under these conditions, the exchange of energy between the electrical network and the turbine generators' shaft leads to the production of torsional oscillations on the shaft, which can have disastrous consequences, such as fracturing of the shaft [47, 66].

Effective sub-synchronous resonance damping requires the utilisation of both active and reactive power, and the ESS intended for this application should be able to modulate both of them simultaneously, to generate counter-oscillations for the elimination of the sub-synchronous resonance [3, 45, 47].

2.5. Transmission and distribution upgrade deferral

Research supports the use of ESSs for transmission and distribution (T&D) upgrade deferral [1-3, 6, 8, 14, 21, 23, 34, 36]. For a few days every year with the highest load, the provision of power from an ESS to a grid segment that is approaching its load carrying capacity could result in the deferral or avoidance of the necessity to augment power transformers or lines [1, 3, 8, 21, 36]. Further, the reduced loading of grid components, such as transformers with many years of service, facilitates the extension of the useful life of the equipment [14]. Some utilities choose to defer the upgrade of the transmission lines, by adding distributed generation to the proximity of loads. However, in the presence of energy storage, distributed generation units are not required, as the storage will supply the amount of energy threatening to overload the grid equipment [23].

The discharging mode of the storage should coincide with on-peak hours, while the charging mode should occur during low load conditions, for example during the night [34].

The principle is illustratively presented in Fig. 4 [14]. The utilised load profile data were provided by the AEMO [58], and they correspond to a peak summer day.

Fig. 4. T&D upgrade deferral - congestion instance based on recorded load demand for Queensland, Australia.

For the effective operation of the ESS, care is required for its placement in the electricity grid, as it should be downstream from the equipment [36] expected to reach its loading limitations (Fig. 4). Further, a desirable characteristic of the ESS is its potential portability, as it enables operators to respond to changing load conditions in the network due to a range of factors. For instance, during summer it can provide support to a substation with summer peak, while during the winter it can be transferred to another substation with a winter peak, therefore maximising its support to the grid [21]. Table 1 summarises the operational characteristics of the ESS for this application based on the findings of various studies reported in the literature.

In terms of the grid equipment upgrade factor, [36] states that one-third of the existing load carrying capacity of the equipment will be added in the next scheduled equipment upgrade. For example, a transmission line with a load carrying capacity of 300 kVA will be upgraded to 400 kVA. By considering a 2% load growth per year (1.5% is utilised in [34]) and a margin of error of about 25% on the 2%, the rated power of the storage system intended for T&D upgrade deferral for one year can be found. If the 2% load growth for this year is

$300 \text{ kVA} \times 0.02 = 6 \text{ kVA}$ and $6 \text{ kVA} \times 0.25 = 1.5 \text{ kVA}$, then the rated power of the energy storage for one year should be 7.5 kVA.

By deferring the costly investments in the electricity grid, corporations will better utilise their existing assets, and the capital intended for these investments will remain at their disposal for other purposes. In addition, customers also benefit from reduced additional costs in the price of electricity attributed to infrastructure deferrals [1, 3, 36]. Even without ESS integration, electrical utilities had begun to realise the importance of limiting the growth in peak load and have deployed a number of peak reduction strategies. The National Energy Market (NEM) operator in Australia have reported a decrease in maximum peak load demand (MWH) in recent years (i.e. 1.33% annual decrease from 2009/10 to 2013/14 period), even with population growth [68, 69].

While customers have been more responsible with their electricity consumption and reduced their peak load growth, it is inevitable that positive peak load growth will return due to population growth, income growth and new industrial demand from growing energy intensive industry sectors (e.g. liquefied natural gas industry) [68]. Nonetheless, population growth and economic expansion is such that the projected peak load growth, for a 10% probability of exceedance (POE) for the next 10 years, is expected to return to growth [68, 69].

Considering the continuous peak load growth, using ESSs for the purpose of T&D upgrade deferral is a promising option. In areas where peak load growth has levelled out or is reducing, the ESS can be used for other applications or, if portable, it can be moved to another grid segment for its upgrade deferral [14]. Moreover, an important design consideration for ESS installations is that their storage capacity can be extended easily to cater for peak demand growth.

2.6. Transmission access charges

In the case where an electrical utility does not own one or more of the grid levels that are used for the power to flow from the generators to the end-users, it has to pay a service fee to the owner of the grid level (e.g., transmission level), which is mainly intended for the depreciation of the invested capital and for maintenance/replacement costs. This fee is also known as transmission service charge [3, 36]. An example in the deregulated market is the provision of power to end-users by a retailer who does not own T&D grid levels. Yet T&D

levels have to get used for the generated power to reach the end-users; therefore, the customer has to pay the retailer for both the consumed electricity and the access to the T&D levels with a separate charge. In turn, the retailer pays the generators for their energy provision and the owner(s) of the T&D levels for access.

A storage system could reduce the access charges by taking advantage of the price structure in the case where different access charges apply at different hours of the day (see price example in [34]). In general, the lowest fee applies during the low demand period, the fee increases at the morning 'shoulder' hours, while the highest charge applies during the high consumption period.

2.7. Congestion relief

Congestion phenomena in heavily loaded substations and transmission lines can be tackled by ESSs that aim to reduce the peak demand [6]. Therefore, companies have launched congestion relief projects utilising energy storage, such as in 2005, the Pacific Gas and Electric Company (PG&E) launched a 2MW-2MWh flow-battery project, to be installed in a substation threatened by overloading [21].

The contemporary electricity markets operate using the locational marginal price (LMP) principle. In the state of Michigan, the Midwest ISO determines the LMP based on the operational cost as it derives after generator dispatching (or re-dispatching at a different cost, if necessary to relieve congestion, including compensation for transmission losses) in real-time (i.e., every five minutes) and for the day ahead. The electrical utilities that supply the load, or any other load serving entities, purchase electricity from the Midwest ISO market at the LMP and, in turn, the ISO pays the LMP to the generators for their energy production [70].

Other ISOs, such as the one in California (CAISO) [71], in New York (NYISO) and the PJM Interconnection which is in charge of Pennsylvania, Virginia [72] and another 12 entire states or parts of them [73], operate under the LMP principle, which incorporates costs such as differences in generator fuel prices, compensation for transmission losses for the power to flow from power plants to loads, and re-dispatching generators for congestion relief [71, 72]. Particularly for congestion, with the first dispatching the most cost-effective arrangement was determined; however, because of forecasted power congestion in one or more grid components, re-dispatching had to be performed, and in that case, a more costly

generator existing in a different grid segment had to provide the power to the load from a different path, resulting in congestion alleviation. This additional cost from the unit commitment variation, as well as the cost to compensate for the transmission losses from generation to each of the grid terminals, results in individual LMPs – one for each HV terminal (the map with the LMPs at different terminals for various US states is available in [72]). Therefore, the LMP process is an equitable way for pricing electricity, depending on which HV terminal the downstream loads are connected to [71].

For the electrical utilities to purchase electricity at the lowest LMP, dispersed storage systems have to be placed at the terminals causing the congestion [39], downstream from the grid equipment threatened by overloading [22] as illustrated in Fig. 5. The discharging of the ESS has to take place during the on-peak period, while the charging has to be realised during the off-peak hours, as shown in Fig. 4. By maintaining this operating principle, the first and most cost-effective generator dispatching (lowest LMP) of the ISO can be realised, while more costly re-dispatching in order to alleviate congestion is avoided [39].

In terms of pricing of the energy coming to or leaving the ESS, [22] suggests that it should be treated like a generator and dispatched by the ISO (Mode 1) and like an electrical utility buying energy from the ISO (Mode 2). When operating in Mode 1, the discharged energy should be priced according to the current LMP paid by the ISO to the generators for their production. When operating in Mode 2, the charged energy should again be priced based on the current LMP paid by electrical utilities to the ISO, when purchasing energy.

For more clarity, an example is presented based on the [22] monetisation concept, which could fit different applications, and it is enriched with real-life data provided by PJM's historical database [74]. The LMP for a HV terminal in Ohio on 01-12-2014 at 2 am was US\$23.66 /MWh, and during the same day at 5 pm, it was US\$60.10 /MWh. The energy requirement to be delivered is 50 MWh between 5 pm and 6 pm, in the case where the storage has 89% efficiency, and it should charge 56.18 MWh from 2 am to 3 am. The cost of the energy required for charging is US\$1329.22, while the revenue from selling the energy is US\$3005, leading to a gross profit of \$1675.78 for this one illustrative cycle.

Fig. 5. Example of an ESS placed downstream from the transmission line BC (TL_{BC}) to prevent congestion.

2.8. Service reliability – uninterruptible power supply

To ride through a power outage in the range of minutes to hours occurring in the electricity grid, an uninterruptible power supply (UPS) is usually employed; its engagement will enhance the service reliability [8, 23, 36, 48], mitigate lost societal productivity, facilitate orderly shutdowns [36], and minimise risks to critical loads such as hospitals, data centres, telecommunications, water facilities, aluminium furnaces, to name a few.

[49] focuses on data centres, suggesting that the UPSs existing at the premises can be utilised to reduce the electricity charges by limiting the power demand spikes of the facility; hence reducing the associated charges (similar to Section 2.11). Further, in the case the servers of the data centre are continuously supplied with power via the PCU of the UPS (as a filter to the power absorbed by the mains), this provision of power can be discontinued for periods where the grid power is of better quality, in order to avoid the conversion efficiency of the PCU. An alternative for achieving higher conversion efficiency, is to employ a modular UPS and depending on the current power requirement the corresponding number of

modules is engaged, so the operation of the modular UPS is as proximate as possible to the ratings of the engaged modules, hence operating with high conversion efficiency.

Combinations of backups can also be performed, such as flywheels and a battery or flywheels and a gen-set from the perspective of initial and brief flywheel engagement (e.g., sub-second to a few seconds), while the battery or the gen-set takes over for a longer time. By maintaining this operation, the battery's cycle life is benefited because of avoided cycles that are undertaken by the flywheel [48].

2.9. Power quality

Within the power system, disorders ranging from sub-cycle to one-minute events threaten the quality of power experienced by loads, including voltage swells and dips. The starting of large motors causes voltage dips, and the injection of RESs power during low load conditions causes swells. Frequency variation from its nominal value, which can be attributed to large loads simultaneous connection/disconnection, and in turn, the frequency regulation operation of the grid with its sluggish response limited by inertia (as explained in Section 2.3.2) results in frequency inconsistency. Other power quality issues include momentary interruptions, for instance sub-cycle to one minute events originating from fault clearing attempts, and voltage fluctuation, which can be caused by the intermittent RESs power generation. Such power quality issues, as well as further symptoms, can be found in [50].

An ESS is expected to be significantly effective when a large inductive load is disconnected. In this case, the local storage can absorb active and reactive power in order to mitigate frequency variation and voltage swell. Conversely, the ESS operation can mitigate the voltage sag caused by the connection of a large load [50]. End-users can be protected against poor power quality, depending on the nature and magnitude of the grid disorder, by utilising the energy capability combined with non-unity power factor operation of the storage [2]. ESSs can play a significant role in the mitigation of voltage disturbances, thereby increasing productivity and reducing incidences of mechanical damage of sensitive equipment when commercial and industrial loads are concerned [8].

2.10. Time-of-use energy charges

For end-users to benefit from switching to the time-of-use (TOU) energy tariff, they have to shift part of their energy consumption from the on-peak period to another billing period. A storage system intended for TOU energy management [6] should be charged during off-peak hours with low cost energy, and it should be discharged during the on-peak period to avoid high cost energy [35, 52]. This operating principle can be enhanced in the presence of PVs (or micro wind turbines), where instead of charging from the grid, the ESS can be charged from PV generated power during the daylight hours, in order to be discharged during the evening peak period [19, 52, 53]. Both of the aforementioned principles allow end-users to continue consuming energy during the peak period without changing their habits, whereas the impact on the grid is minimised.

A pilot study for the commercial year (CY) of 2012 for a residence in Arkansas, US, which is billed via the TOU tariff is presented in [53]. The installation includes small-scale PVs generating power as well as an ESS of 6 kW 24 kWh; the pilot project yielded a profit of \$689.56 for the CY of 2012 while longer term testing is in progress for life cycle results of lead-acid batteries.

Cost analysis for a medium-sized building belonging to a public institute in Italy was carried out with different battery-based storage technologies under the local TOU charges. It produced long pay back periods (PBPs) of 40 years or more. The study deemed the application operationally feasible but financially non-viable; therefore, the authors suggested that more applications should be combined in order to aggregate benefits [51]. An Ontario, Canada study which studied a large scale CAES facility determined that it was not financially viable using current TOU rates in the region [35]. Since these studies were conducted, the cost of ESSs has dropped considerably; however, current TOU pricing arrangements in most cities are not favourable to ESSs' financial viability.

2.11. Demand charges

Electrical utilities' larger customers, such as industrial and commercial loads, identified by their energy requirement being greater than a certain threshold (e.g. 2000 kWh per month), will usually get charged separately for consumption and demand rather than a combined charge applicable to smaller loads. Demand is associated with the highest average

kW, for any 15 minute or up to 1 hour time interval [54] during the billing period that has been supplied to the customer [53, 75]. The demand charges for large industrial loads can be as much as 50% of their electricity bill, and extra charges may apply if the customer exceeds the contracted maximum demand [54]. According to [76], the demand billing is transitioning to demand being charged in kVA instead of kW, in order to include both active and reactive power required by large customers, since the size of the electricity grid must be adequate for delivering both powers.

Separate demand charges in electricity bills are warranted since they provide more equitable distribution of the costs introduced by customers with high demand from time to time. This occasional high demand requires electrical utilities to augment their grid assets and the system operator to increase the amount of costly standby reserves, for the purpose of serving a few instants of unexpected load [75].

Further, [14] reports that demand charges can vary under different circumstances, such as month of the year and hour of the day, according to the specifications set by the electrical utility. For instance, in summer on-peak hours, the demand charge is \$10/kW per month (applied to the highest on-peak recording), while during off-peak hours (e.g., night to early morning), a 'facility demand charge' is applicable and equals to \$2/kW per month (applied to the highest off-peak recording).

By using an ESS at the premises of the customer, and by following the sensible operating principle of charging during low load and discharging during peak load, a monthly benefit is expected to accrue from avoiding (or reducing) on-peak demand charges and incurring off-peak charges instead [53, 54]. When a PV system is combined with energy storage at the premises of a commercial load, the demand charges of the load can be minimised by using the PV generated power to reduce part of the peak demand. In the case of inadequate PV generation, the storage system will discharge to limit the peak demand (and therefore limit the charges) [19].

A comparison between a lead-acid and a vanadium redox (flow type) battery storage system was reported in [54], intended both for demand charges and energy consumption reduction for a large industrial load. The main study findings was that the battery technologies have similar performance, as they manage to reduce the electricity bill (demand and energy) by 4% and the demand charge by 8%. However, from a life cycle cost perspective, each battery technology has a different useful life; therefore, the number of

replacements of the battery up to the end-of-life of the application differs, affecting the life cycle cost.

In the demand charge management example of Fig. 6 [14], where local peak and off-peak periods are considered [77], the utilised load profile exhibits the highest demand over the billing period, and an 89% efficient storage has been considered. For the rated load power of 50 kW, which needs to be supplied by the ESS to the customer for a period of four hours, it has to charge for 4.49 hours the previous night. Further, the 15 minute time intervals between the 4 pm and 8 pm peak period (\$10/kW), which would be used in the absence of storage to determine the highest average kW, would have been replaced by the ones between 12 am and 4.30 am (\$2/kW).

Fig. 6. Illustrative example of ESS application for demand charge management.

An estimation of the expected customer benefit includes the demand charges when the ESS is absent and present. In the first case the demand charges are identified at \$500, whereas in the second case the demand charges are at \$100. The difference of the two leads to a gross benefit of \$400 per month, solely for demand charges, for a 50 kW customer facility.

Further demand response programs (DRPs) are discussed in [78]. One of them is the direct load control (DLC) mainly offered to residential and small commercial customers. The

program enables the ISO or the local service provider to turn off or cycle selected loads (e.g., the air-condition) on short notice [78], where in the absence of storage, it leads to a temporary compromise in the daily schedule of the customer economically incentivised.

A new demand response (DR) approach is proposed in [55] applicable to residential customers. This concept includes a residential energy management system (REMS) that controls the smart residence following DR incentives (\$/kW) and the TOU tariff (\$/kWh) sent to the REMS by the service provider, tackling high power demand and shifting energy consumption from the DR period to a more favourable period for the grid. Within the simulated scenarios was sole operation of the REMS or combined with an ESS existing at the premises. The shifting of energy and power is realised by delaying certain loads (e.g. clothes washer, clothes dryer, etc.) until the DR period is over. The resulted PBP in the case of sole operation of the REMS was in the range of one year, while in the case of the REMS combined with the ESS, the PBP was found in the range of 10 years. Although the PBP was improved compared to the 40 years presented in Section 2.10 (due to the combined benefit of the DR and TOU incentives), it is hard for the ESS to compete with low-cost DR approaches unless factors such timetable alternations of the end-users are valued.

2.12. RESs integration

The ability of a storage system (e.g., CAES or STATCOM combined with battery) to immediately respond to command signals, makes it the perfect match for renewables integration. Applications related to shifting - arbitraging, firming and smoothing of the intermittent output of RESs could result in higher absorption of their energy without impacting on the normal operation of the electricity grid. One further step is taken in [79], which suggests that after the reliability of RESs has been enhanced because of their coordination with ESSs, the role of the primary source of energy can be undertaken.

2.12.1. RESs shifting - arbitrage

Time-shifting of the output of non-dispatchable RESs can allow energy to be stored during surplus hours (e.g., night) where the excessive energy can be curtailed in the absence of storage, and if not curtailed, can cause terminal voltage rise, and the injection of the stored energy during peak periods related to high cost energy [1, 2, 4, 20, 22]. This operating principle not only prevents unwanted grid phenomena such as overloading of grid

components, but it also results in higher benefits for the ESS stakeholders, by selling more energy and at a higher price. Further, when there is insufficient renewable energy generated to fully charge the storage for the next day, additional energy can be provided by the grid [17] so the storage can be fully charged via a combination of renewable and low cost grid energy. In this way, the full extent of arbitrage can be performed during the high cost energy period [17]. The shifting of renewable energy from an unfavourable period for the load to a period of peak load, can also be seen as the matching of the load profile and the RESs profile [23]. For instance, in the case of a pumped hydro ESS (which is currently the most cost-efficient bulk ESS technology based on the comprehensive life cycle cost analysis performed in [80]), the surplus power generated by wind turbines (or low cost thermal energy) during the night hours can be employed to pump water from the lower reservoir to the higher reservoir, to be used during the next day's peak load period [40, 56].

Hydropower can be regarded as a renewable energy source and can also operate following the energy storage principle for further integration of other renewables. Therefore, significant interest is concentrated in pumped hydro ESSs and in the rehabilitation of old small-scale hydro plants. Advances in the field such as variable-speed pump-turbines and the development of computational fluid dynamics (CFDs) resulted in higher efficiencies under different operating conditions and plant components with better performance and lower cost – for instance, CFDs analysis can be used to compare old and new runners, improving the component's performance and also limiting the necessity of model tests. Nevertheless, factors such as the environmental impact of a hydro plant, the lack of appropriate regions where plants can be built as well as CFDs modelling scenarios with currently limited accuracy (e.g., turbulent flow for a wider discharge rate range), still pose challenges for hydropower [40].

The presence of storage can facilitate the shifting of renewable energy not only from one period of the day to another, as motivated by increased profits or less impact on the grid operation, but it can also be shifted from weekends to weekdays or from holidays to regular working days [10]. This principle would particularly fit industries with RESs at the premises, in the case where a five-day working week is maintained, and also during the standard holidays of the year.

Transmission line losses can be reduced by employing the local storage system to supply part of the local load demand (e.g., batteries have been charged from RESs surplus

and reactive power is controlled by the PCU), resulting in reduced current flow over long distances, thereby decreasing transmission losses [5, 20].

In residential renewable installations, such as PVs, where the end-users are to be billed by a TOU tariff, PV generated energy can be stored during the daylight hours, to be consumed during the evening peak period; therefore, expensive electricity can be avoided [19].

2.12.2. RESs firming

Wind turbines have to be stopped during stormy periods, and the power in the output of PV plants will be minimum during cloudy days [4, 20]. The presence of energy storage can minimise periods of low RESs generation by discharging energy stored during intervals of abundance; in this context, renewable energy becomes more 'firm'. The application of RESs firming has concentrated interest, and several experimental installations exist around the world with battery-based storage systems [6].

By using storage to backup renewable generation rather than increasing generation capacity reserves - which is typically what is currently practiced - generation costs should be more manageable (e.g., better fuel economy and reduced carbon emissions), which in turn, should reduce cost increases for the end-users [19].

Further firming of RESs can be achieved in the presence of storage during a grid fault. In the case of a grid short-circuit and the associated reduction in voltages, including high power variations, a neighbouring wind farm may not be able to inject power to the grid while the wind resource is high, leading to an uncontrolled increase in the speed of the wind turbines. In the presence of energy storage, and by its low-voltage ride-through (LVRT), and zero-voltage ride through [20] capability (e.g., STATCOM with P and Q or SMES), the wind-farm could experience fault and post-fault conditions, with significantly lower effects resulting in a firm presence of RESs during the fault and post-fault periods [2, 45].

2.12.3. RESs smoothing

Another application in which ESSs, such as CAES or STATCOM with storage, can be used is to smooth the intermittent output of RESs originating from wind speed variations [17] and affect the output power of wind farms and/or fast moving cloudy intervals above PV plants,

resulting in variations in their output power [4, 20, 57]. Smoothing the output of RESs can also be seen as a ‘filtering’ process which results in less fluctuating power output [6].

STATCOM coupled with storage can be employed both for the suppression of voltage fluctuations, and for the mitigation of output power variations resulting from PV generated power. Voltage improvements can mainly be achieved with reactive power, while power variations can be smoothed via active power. Smoothing RESs variations will also benefit the operation and maintenance costs related to generators used as ‘peakers’ – for example, by maintaining a more efficient operation with fewer start-stop actions [57].

A preliminary framework for calculating the additionally required energy storage capacity in western Europe (WEU) and other parts of the world is provided in [4], to accommodate the variable output power of projected renewable energy up to 2050. According to the calculations, for a 10-30% increase in wind energy, 40-100 GW of storage capacity is required to operate in WEU. Given that, 33 GW already exist predominately as pumped hydro, another 7-67 GW must be provided by 2050.

3. Criteria and process for selecting energy storage technology

Energy storage applications initiate from the top levels of the electricity grid and descend to the end-user level. For an application to be performed effectively, it is crucial that the right storage technology is determined. The storage selection process considers 14 characteristics, which can be customised for the application under consideration [6, 81-85].

A way to proceed in the selection process is to create a table with the necessary characteristics and record the values of the considered storage technologies for each characteristic. The selection can be realised by examining one by one the characteristics and comparing the recorded values. This comparison will eventually lead to the selection of the appropriate storage technology for the application under consideration, as demonstrated in [81]. A similar approach is described in [82], where the table with the storage technologies contains pros and cons; by comparing them, competent technologies are identified for further evaluation. In [85], a considerable number of characteristics is included, in turn, a discussion-based comparison is realised between the involved ESS technologies, leading to the selection of the appropriate technology. A combination of all of the above approaches is performed in [86], with tabulation of the values of the ESS characteristics, inclusion of

advantages and disadvantages, leading to a discussion-based comparison among the ESS technologies.

If a more precise selection process is required leading to a definite result, two approaches can be followed. These approaches include criteria that are customised for the application. In the case of [6], a radar chart is assembled with values from zero to 10, illustrating the extent to which each storage technology meets each criterion. In [83, 84], a decision matrix is created for each criterion, to grade the performance of each technology compared to another, and the grades are in turn summed. The selection process then continues by weighting each criterion, and after the weights have been defined, they are included in the calculations. The results establish a ranking of technology competitiveness factors (*TCFs*) – one *TCF* for each technology – and the first in the ranking is finally selected for the application under consideration.

The approaches proposed by [6, 83, 84], promote a more clear and precise selection process compared to [81, 82, 85, 86], because weights are included in order to relate the importance of each criterion to the application. In addition, the selection in [6, 83, 84], is achieved by identifying the highest *TCF*, which clearly indicates the appropriateness of the technology rather than realises the selection based on observation [81, 82, 85, 86]. Considering all of the above, the selection processes leading to the determination of the *TCFs* are compared in this section. They have been adapted in terms of utilised criteria, storage technologies, grid application and corresponding weights.

3.1. Criteria presentation and storage life consideration

To visualise the criteria (C_i) along with the storage technologies, which are considered in the selection process, Fig. 7 [6] is utilised. The values of the criteria corresponding to the technologies before the conversion to the normalised scale are available in [81, 87, 88]. After the normalisation, the highest criterion value can be 10 (C_{max}). The comparison is realised between Lithium-ion (Li-ion), Sodium Sulphur (NaS) and SMES technologies, because of characteristics such as high efficiencies, increased cycling capabilities, long useful life and moderate environmental impact, while Li-ion is well known for its energy density, NaS for its capital cost and SMES for its cycling capabilities.

Fig. 7. Criteria for comparison of energy storage technologies.

An alternative way to compare the performance of one type of storage technology with another, while taking a particular criterion into consideration, is to create a decision matrix and grade the performance. This process must be performed for each criterion. Table 2 [83] presents the decision matrix for C_1 , including the performance grading scale.

Table 2. Decision matrix for comparison of storage technologies in the context of C_1 , the grading is presented on the left.

Grading scale	C_1 - Energy density	Li-ion	NaS	SMES	G_{tot_1}
1 - Poor					
2 - Diminished	Li-ion		4	5	9
3 - Similar					
4 - Enhanced	NaS	2		5	7
5 - Superior					
	SMES	1	1		2

After the total of the decision matrices is in place, the total grade per technology can be determined for each decision matrix (G_{tot_i}) and, along with the maximum grade (G_{max}), they are weighted, in Section 3.2, to derive the $TCFs$.

At this stage, it is important to note that for certain battery technologies including Ni-Cd, Nickel Metal Hydride (NiMH), Li-ion, Lead-Acid Gel or Flooded type, the useful life of the battery is affected by a number of parameters, including temperature (T), DoD, discharge rate, time duration that the battery is subjected to low and high states of charge (SoC), as well as extent and frequency of overcharge [89-91]. Of the aforementioned parameters, [5] refers to the relation between the DoD and the cycle life of batteries in their generic form, while in [82], the technologies are specified, including NaS among others. The focus for the authors in [89] is not only on the cyclic capabilities as a function of the DoD, but also on the effect of the charge - discharge rate on Ni-Cd cells. The authors describe that as the discharge rate increases, higher stress occurs on the battery cell, which is likely to result in decreased useful life. Conversely, it is under research the effect of high charge rates on the battery cell, where no negative effects are expected on the useful life if occurring during low to mid SoC.

The curves of Fig. 8 [5, 82, 90], record the high dependency between the cycle life and the DoD, with EPRI [5], NGK [82] and VARTA [90] contributing the evidence. The figure shows that the higher the DoD, the lower the cycle life of the battery. For instance, if a Li-ion battery is operated at 90% DoD, it is expected to deliver 2000 cycles, on the other hand, if the DoD is shallower, such as 70%, the expectation is 2800 cycles.

During the selection process of the energy storage technology, the technical requirements of the application must be taken into consideration, as mentioned in Table 1, while they must be combined with Fig. 8 if batteries are concerned. In the case of SMES, the DoD has no effect on the cycle life.

Fig. 8. Cycle life as a function of DoD.

The above reasoning for the Li-ion battery can be continued by considering this technology to perform energy shifting - arbitrage. This application requires 250 cycles pa (from Table 1) while 90% and 70% DoD are examined. The cycle life of the battery for the deep DoD is determined to be 8 years. On the other hand, in the case of the shallow DoD, the cycle life equals to 11.2 years which is a considerable improvement compared to the initial expectation. The first interpretation from the above cycle life findings is that by decreasing the DoD, the storage medium may require to be replaced later during the lifetime of the application, resulting in fewer overall replacements and decreased associated costs. From another perspective, fewer replacements may occur; however, the energy capacity of the battery has to be increased [82], considering that the DoD is the ratio between the energy extracted from the battery over the rated energy capacity [91]. Hence, a higher capital cost is introduced, to be paid upfront by the investor.

3.2. Weights assignment and technology selection

During the discussion in Section 3.1 about the criteria and the effect of the DoD on the cycle life, energy shifting - arbitrage was considered as the application to be performed by the energy storage. In turn, this stage of the selection process includes a definition of the weights (w_i) for the application, and then substitution into Eq. (1), (2) [6] and Eq. (3) [83, 84]. The assigned values reflecting the weight for each criterion can be found in Table 3.

Table 3. Criteria weighting, customised for energy shifting - arbitrage.

Weight	Value	Weight	Value
w_1	7.5	w_8	5
w_2	7.5	w_9	9
w_3	7.5	w_{10}	7.5
w_4	7.5	w_{11}	2
w_5	7.5	w_{12}	9
w_6	7.5	w_{13}	7.5
w_7	7.5	w_{14}	7.5
Total	100		

$$App_{sum} = \sum_{i=1}^n w_i C_i, \quad n = 14 \quad (1)$$

$$TCF = \frac{App_{sum}}{\sum_{i=1}^n w_i C_{max}} 100, \quad n = 14 \quad (2)$$

$$TCF = \sum_{i=1}^n w_i \frac{G_{tot_i}}{G_{max}}, \quad n = 14 \quad (3)$$

Regarding the weighting presented in Table 3, operational constraints and safety (w_9), along with capital cost (w_{12}), receive 9, as a safe system with a low cost is the priority and should be encouraged. A series of other criteria maintain a weighting of 7.5, such as, energy density (w_1), specific energy (w_3), efficiency (w_5), cycling capabilities (w_6) and useful life (w_7),

which is above the equitable weighting value (i.e., 7.1429) in order to indicate their significance. In particular, energy density (kWh/m^3) and specific energy (Wh/kg) are representative of volume and mass; therefore, low spatial and mounting force requirements are rewarded. Conversely, low weights existing in Table 3, – for example, the value of 2 for the criterion of daily self-discharge (w_{11}) – is because of the 250 charging - discharging cycles pa required for the application, which is in the range of one cycle per workday of the year; hence, preventing from extensive self-discharge losses.

From the calculated *TCFs* and the subsequent ranking presented in Table 4, it is clearly indicated that the Li-ion technology is the most appropriate and therefore selected for energy shifting - arbitrage with 74.54% *TCF*, while the second and third are NaS and SMES with 60.69% and 52.59% accordingly, deriving from the selection process adapted from [6]. The result is as expected, as Li-ion meets to high extent criteria 1 to 5, which are weighted as important for this application. Further important criteria are 9, 10 and 12, where Li-ion maintains mid to high values, leading to domination of this technology over NaS and SMES.

Table 4. *TCF* and suitability per energy storage technology, for energy shifting - arbitrage.

Technology	<i>TCF</i>	Suitability	<i>TCF</i>	Suitability
	adapted from [6]		adapted from [83, 84]	
Li-ion	74.54%	1 st	70.3%	1 st
NaS	60.69%	2 nd	56.6%	2 nd
SMES	52.59%	3 rd	53.1%	3 rd

The selection process adapted from [83, 84] also maintains a similar ranking; however, the *TCFs* corresponding to Li-ion and NaS technologies are decreased – for example, for the Li-ion the 74.54% is replaced by 70.3% and 60.69% becomes 56.6% for NaS, indicating that the first and second technologies are less competitive and that they have descended towards SMES's *TCF* which is slightly increased. The aforementioned observation can be attributed to the limited steps of the grading scale, which have already been increased here by two compared to the original scale used by [83, 84]. Further, the process involving the decision matrices in [83, 84] is more subjective compared to the radar chart approach in [6], which is assembled based on actual values for each technology.

Lastly, based on the evidence provided in Table 4 and the subsequent discussion, it is deemed that both of the selection processes can be used to identify the appropriate energy storage technology for a specific application, with the process proposed by [6] being more just. The above described method will assist in selecting the appropriate energy storage technology from an increasingly complex suite of alternatives [92, 93].

4. Control structures

To realise the ESS applications described in Section 2, it is necessary to have full control of the active (P) and the reactive (Q) power capability of the ESS, which can be achieved through independent control of P and Q combined with 4 quadrant operation. This section describes and reviews the control structures that are capable of performing one or more of the above mentioned energy storage applications.

4.1. Independent active and reactive power control

Control structures that are well known in the literature [94-98] for controlling power electronic topologies in the absence of a considerable amount of storage (e.g., low amount of stored energy in the dc-link capacitor), have been adapted to handle considerable amounts of active power stored in means such as batteries and supercapacitors [99-102].

Control structures that include grid synchronisation, which is achieved by using a phase-locked-loop (PLL), as well as transformation from a stationary reference frame, abc , into a synchronous reference frame, dq , and vice versa, are shown in Fig. 9. This figure has been adapted from power control diagrams provided in the literature [99-102]. A complete control structure combines two linked levels namely the external, and the internal, with the division into levels introduced by [103, 104]. In the external level, measured quantities are supplied and compared with their corresponding references. The differences are then regulated and transformed into two reference current components, id^* and iq^* , which are fed into the internal level. In turn, id^* and iq^* are compared with the measured id and iq , and the errors are controlled and transformed into two corresponding voltage components, vd and vq , after cross-coupling compensation has been realised [95]. Differences in signs that are represented by the colour grey in Fig. 9, results from the different definition of the positive current direction. Finally, a dq to abc transformation is performed, or a conversion from Cartesian to Polar coordinates, leading to the modulation command.

Fig. 9. Illustration of control structures, grid synchronisation, and reference frame transformation in a generalised form.

The control described above has been implemented with four regulators in [99-101], while in [102] it has been realised with only two for a system that is easier to tune and with reduced complexity. However, in the latter approach, a slight coupling has been detected and discussed by the author, which does not considerably affect the independent PQ control according to his demonstration. The aforementioned control processes, involve the transformation of the measured voltages and currents from abc to dq [94, 98]. Although this transformation introduces higher complexity to the process, it is necessary in order to achieve independent control of the required system variables (e.g., ω and V), and in turn, to control the active and the reactive power accordingly. Further, the $abc \rightarrow dq$ transformation, results in zero steady-state error in the case where proportional plus integral (PI) regulators have been used. On the other hand, when a stationary reference frame (e.g., $1-ph$ or $\alpha\beta$) is maintained, a proportional plus resonant (PR) regulator must be used instead of the PI. As described in [105], PI regulators produce no steady-state error when sensing dc quantities, while PR regulators eliminate the steady-state error when sensing ac quantities. Further, if the application includes fundamental frequency changes, the resonant frequency of the PR controller has to be adjusted to meet the current fundamental frequency.

The PLL's tracking capability is used to extract the grid angle δ and the frequencies f and ω . Then δ and f are utilised in the aforementioned reference frame transformation to maintain synchronisation with the grid [94, 97]. Further, δ and ω can be used for a comparison with the reference values in the external level of the control structure in P terms. This is because δ is related to the power transfer between the ESS and the grid [106], and ω is indicative of the loading of the system as discussed in Section 2.3.2. In both cases of grid-connected and islanded micro-grid operation, P supply is vital in order to maintain ω within proximity to the nominal value [101].

4.2. Voltage balancing capability under unbalanced load conditions control

The control structures presented in Section 4.1 are mainly intended for balanced systems because of lack of conversion of their measured quantities (e.g., unbalanced voltages) into symmetrical components. Nevertheless, in the presence of an unbalance, they maintain a moderate response, as remarked in [102] and demonstrated under grid fault conditions in [99, 100].

According to [107], the transformation of an unbalanced system from its stationary reference frame, abc , into a rotating reference frame, $dq0$, results in two dc components including an ac oscillation on each. Further, the 0 in the aforementioned reference frame transformation is of non-zero value, which was the case for a balanced system (and therefore it was omitted), but it appears as an oscillation and must be included in the control process.

Fig. 10. Illustration of a control structure with symmetrical components in a generalised form.

The presence of the ac component on the dc quantities contradicts the dc signal requirement of the PI regulators. To produce no steady-state error, conversion of the unbalanced quantities (i.e., voltages and currents) into three symmetrical components – that is, positive (1), negative (2) and zero (0) sequence. Fig. 10 has been adapted using sources provided in the literature [107, 108]. Because of the restored symmetry of the abc

values on each component, the subsequent transformation from $abc^p \rightarrow dq^p$, $abc^n \rightarrow dq^n$, $abc^0 \rightarrow dq^0$ results in dc components that can be effectively regulated by the PIs.

It should also be taken into consideration that the conversion described above can be utilised in its entirety solely by four-leg voltage source converters (VSCs) because it requires a path for the zero sequence current, which is provided by the neutral wire connecting the fourth leg of the VSC to the star point of the load, eventually leading to the ground. This is because the zero sequence current flows only through the neutral wire to the ground [109]. In the case of three-leg VSCs, the positive and negative sequence can be used due to the absence of the fourth leg and the path to the ground. An example of such a control structure is available in [110].

4.3. Association of control structures with ESS applications

The control alternatives A1 to A5 discussed above are related to ESS applications based on evidence found in the literature of Sections 4.1 and 4.2 and they are presented in Table 5. In the case of a lack of evidence, expected compatibility between control structures and ESS applications is discussed based on the capability of the control structure and the description of the applications in Section 2. Further, control reference parameters (i.e., P^* , Q^* , V^* , δ^* and ω^*) are examined depending on the application under consideration.

When the ESS is intended to facilitate the integration of RESs in terms of smoothing power fluctuations and performing voltage support, such as in [99] (Table 5), the power quality is enhanced. In terms of external control, A1 has been considered with references being the active (P^*) and reactive (Q^*) power, as these applications require these quantities to be controlled because P^* is related to the average wind power and Q^* with the deviation of the terminal voltage from its nominal value.

For firming the presence of RESs in terms of LVRT, according to [100], as reference can be considered the terminal voltage (V^*), and after it has been compared with the measured quantity, the appropriate Q^* is generated. By providing the necessary Q to the RES facility during the grid disturbance, which could originate from a grid fault, the facility can ride through the low voltage period without disconnection and experience a smoother post-fault period. In terms of P^* , it aims to limit the power variations at the terminal where the RES facility is connected – that is, the point of common coupling (PCC) – and it is generated by

comparing the terminal voltage reference angle, δ^* , to the angle during the grid disturbance following the external control in A2.

If the arbitraging of energy (i.e., buy low, sell high) is the objective of the ESS, combined with selling ancillary services to the grid, such as spinning reserve, then the external control should be associated with A3, as realised in [101] (Table 5). The angular frequency of the grid, ω , extracted by the PLL; and the measured terminal voltage V are the inputs to be controlled. In turn, these measured quantities are compared to the nominal values of angular frequency, ω^* , and voltage, V^* , and the residuals are supplied into droops for the generation of active and reactive power commands (i.e., P^* and Q^*).

To prevent the overloading of transmission lines, the A4 control structure can be employed as suggested in [102]. The references that have been considered (i.e., P^* and Q^*) are directly related to the congestion problem which depends on the power-flow. As the power-flow approaches the load carrying capacity of the transmission line with an expectation of exceeding it, then it becomes an issue, according to the discussion in Section 2.7. In terms of the determination of P^* and Q^* , they can be fixed by the user depending on the loading level that he or she wants the equipment to be subjected to, up to the capacity limit.

When the balance between the grid voltages is an issue resulting from load unbalance, the A5 control structure of Fig. 10 can be employed as it is performed in [107, 108]. Its capability of regulating the total of the symmetrical components results in a voltage balanced system. Balancing is achieved by setting the positive sequence voltage reference, vd^* , equal to the required voltage magnitude for the system, while the rest of the references are kept to zero. The reason for the zero values is mainly the elimination of the negative and zero sequences towards a balanced system.

In the context presented in Sections 2.2 and 2.5, the ESS can be considered to supply capacity to the system additional to the existing one, and also to defer an infrastructure upgrade at the T&D levels. In the first application, the central station generators produce both P and Q , according to the power-flow solution [66]. In the second application, the load carrying capacity is associated with P and Q [111], as the previously mentioned power-flow is transferred from the power plant, and across the levels of the electricity grid to the loads. Therefore, the A1 and A4 structures can be regarded as potential controls for the applications. As an example of reference generation when additional generation capacity is

required, the forecasted load (S^f) can be utilised, compared to the central station generation capacity (S^c), such that $S^* = S^f - S^c$, and thereafter, $S^* = P^* + jQ^*$ to determine the active and reactive power references for the control structure.

Table 5. Reported control structures associated with ESS applications.

Application	Control structure	Application	Control structure
Energy shifting - arbitrage	A3 [101]	Service reliability	A3 [101]
Spinning reserve	A3 [101]	TOU energy charges	A3 [101]
Voltage support	A1, A2 [99, 100]	RES firming - LVRT	A1, A2 [99, 100]
Frequency regulation	A3 [101]	RES smoothing	A1, A2 [99, 100]
Congestion relief	A4 [102]	Power quality - PF correction	A1 [99]
Power quality - Voltage balancing	A5 [107, 108]		

The application of load following, responds to the difference between the system's load and generation by performing load following up or down as described in Section 2.3.1. As this difference is reflected in the system's frequency, a control such as the A3, which takes into consideration the measured ω and compares it with ω^* , can be employed. As the load demand is also related to Q [66], monitoring the system's V and comparing it to V^* would result in the provision of reactive power to the load. As load following requires a response every several minutes (Table 1 and Section 2.3.1), the response time of the ESS, which is in the range of a few cycles, is more than adequate to carry out the task. The response time of the ESS, which is within a few cycles, can be seen in the responses to the system changes in [99, 100]. Further, the frequency regulation service described in Section 2.3.2 maintains an operating principle similar to the load following service, with however a faster response requirement, for example 30 seconds to one minute (Table 1), which is still well above the response time of the ESS. It is deemed that frequency regulation can also be performed when the A3 control is concerned.

Another ESS application with potential financial benefits is RESs shifting - arbitrage, following the description in Section 2.12.1. Via this application, more renewable energy can

be absorbed (e.g., wind energy during the night), and it can be injected into the grid at selected time intervals with high cost per kWh. Alternatively, stored renewable generation can be used for a customer's own consumption combined with the TOU market framework presented in Section 2.10. The A1 control structure can be charged with the aforementioned task, and accordingly instruct the ESS in terms of P , which has a more direct link with financial benefits, and Q , which is controlled for grid support reasons or to reduce the demand charges for commercial and industrial customers (Section 2.11).

5. Implementation considerations

There is a number of drivers for ESSs deployment, with the bold being RESs diffusion targets – set by governments – to lead them. On the other hand, there is still a range of technical, operational, market and societal impediments to widespread ESSs integration. The following sections discuss some key implementation considerations for the successful widespread deployment of ESSs.

5.1. ESSs for higher and effective RESs integration

Because of the dispatchability offered by the ESSs to the RESs, renewables can potentially become a primary energy source in the electricity grid. Surplus renewable generation can be absorbed by the ESS, without threatening the secure operation of the electricity grid, and it can be discharged during peak demand periods to alleviate part of the grid's burden. This energy shifting is also an arbitraging action where energy is treated as a commodity that is sold when market conditions are favourable. Following the RESs shifting-arbitrage principle both profits are maximised, and higher RESs absorption is achieved, aligned with environmental concerns and RESs aims.

Further, dispatched renewable energy can substitute a portion of the power requested by the remote generators; hence, reducing the transmission losses, as the power is generated and consumed locally. For companies with a RES facility at the premises, energy generated over weekends and public holidays, can be shifted to regular weekdays, thereby reducing energy consumption and demand charges.

The presence of RESs, affects the generation capacity reserves, which are increased as the RESs penetration increases. For every 10% increase in wind penetration, another 2-4% of the wind power capacity is required from regular generators, to maintain the balance and

the stability of the system. The increased requirement for spinning reserve can be replaced by an ESS located in the vicinity of the RESs. This will ensure that during periods where there are sudden fluctuations in generation (such as clouds or sudden loss of wind), the ESS will be able to supply the gap of the anticipated power.

RESs smoothing is one of the most important applications the ESS can undertake, resulting in a vast improvement in the quality of power supplied to the end-users, as voltage fluctuation and swelling are significantly mitigated. RESs smoothing also promotes a more economic and with reduced GHG emissions grid operation, as thermal generators can maintain constant operation, at the operating point where they are most efficient; since the counteractions ('filtering') to the intermittent power generated by the RESs, are performed by the fast-acting ESS. Further, less costly generators can be employed (i.e., the faster the generators can change output power, the more expensive the fuel they consume), resulting in generated electrical energy with lower cost for the electricity customers.

5.2. Grid segment peak load growth considerations

In the case of an ESS intended for T&D upgrade deferral, a low peak load growth would fit better from a financial point of view. This is because the addition of new storage capacity is required less frequently, compared to a grid segment with high peak load growth. The shape of the future load profiles, particularly in respect to peak load growth will determine the sizing, location and ESS configuration. Each segment of the grid will require power modelling to be completed and a customised ESS solution recommended. Further, If there are multiple critical segments in the grid, then multiple ESSs may be selected.

When the electricity customers maintain a time-wise energy consumption, the peak load decreases – for example, in the state of Queensland, from summer 2009/2010 to summer 2013/2014, the peak demand was gradually decaying with the average rate of - 1.33% pa [68, 69]. However, factors such as population increase, income growth, as well as additional industrial activity, eventually will lead to higher load demand.

For transmission network service providers (TNSPs) and distribution network service providers (DNSPs), the deferral of costly grid upgrades – that remain underutilised for years – results in the large capital to remain at their disposal, the associated financial risk is minimised, and ultimately the electricity customers have to pay less additional cost in the price of electricity.

5.3. ESSs in the wholesale energy market

The wholesale energy market principle is based on day-ahead and real-time auctions, where the ISOs operating under this principle, aim to obtain the necessary energy to supply the load. Once the auctions are completed, the generators are optimally dispatched and the LMP (or RRP) is determined for each of the HV reference terminals. ISOs (or RTOs) operating under this principle include, PJM, AEMO, CAISO, NYISO, Midwest ISO, ISO-NE, to name a few.

The LMP is paid by electrical utilities or load serving entities, to buy electricity in the ISO market, and in turn, the ISO pays the LMP to the generators for their production. The selection of HV reference terminals, and the determination of one LMP for each terminal, is realised for equitable pricing of the electrical energy. The LMP contains the marginal cost of the generators as well as the transmission losses, from the generation site to the reference terminal; therefore, it is affected by the region. Further, in the case of congestion, the generators most economical dispatching cannot be realised as it will exceed the load carrying capacity of the congested equipment. Considering the above, re-dispatching is required, which involves different generators to be utilised, with higher marginal costs, situated in different regions. This way, the congestion problem is resolved; however, higher LMPs are recorded. An ESS placed downstream of a transmission line/transformer expected to face congestion, alleviates the problem and most importantly, allows the first and most economic dispatching to be realised. Therefore, the LMPs with which the load serving entities purchase energy from the ISO are lower, leading to lower electricity cost for the end-users. ESS applications that can be monetised under the LMP principle, treating the ESS as a generator of the system, include, energy shifting-arbitrage, T&D upgrade deferral, frequency regulation, generation capacity reserves, etc.

Generally, during the discharging stage, the ESS can be considered as a generator of the system; therefore, paid by the LMP for its energy production. To the contrary, when the ESS stores energy, it is charged by the LMP, such as a load serving entity purchasing energy from the ISO market.

For applications monetised by the LMP, such as energy shifting-arbitrage, sensitivity analysis is required to find out the effect of mass scale ESS deployment on the price of electricity. This is because, a considerable reduction of the peak load would result in a

flattening of the electricity price, which would in-turn, reduce the economic viability of the ESS investment.

Both an energy payment and availability payment would still be required for ESSs when employed for applications that are required infrequently, such as the ones included in the generation capacity reserves and the black start (e.g., called upon approximately 10 times pa, Table 1). The availability payment is made to bridge the gap of revenue loss due to the infrequent calls for the generators to deliver energy. This is realised, because solely the energy payment is low, appointing the application financially unattractive; while, with the availability payment, the total revenue is increased, restoring investor's financial interest in this particular application.

The transmission access charges are applied from the TNSP to the DNSP, for the use of the electricity grid in transmission level, to transfer power from the generators to the distribution level. The charges are location-specific, and they are determined for a HV reference terminal, reflecting the use of the upstream apparatus. In the absence of RESs, the operation of an ESS will result in a decrease in the demand-based component of the charges, while the energy-based component will be increased, depending on the efficiency of the ESS. To the contrary, when RESs are combined with storage, both the demand and energy-based components of the access charges will be reduced, as less power flows across the transmission level. Further, the use of additional local generators, by the TNSP, is avoided, as the storage provides the additional power that exceeds the load carrying capacity of the transmission grid. A future scenario where there are high penetrations of distributed RESs, 'firmed up' using ESSs, has the potential to significantly reduce the revenue of the TNSP under current market arrangements.

5.4. ESS in the retail energy market

Residential electricity customers subjected to a TOU tariff, in the absence of storage, should amend their energy consumption pattern, to offset much of the charges from the on-peak period to the off-peak. To the contrary, in the presence of storage at the premises, and by following the TOU buy low sell high principle, the electricity customers can maintain their regular energy consumption profile, by consuming during the on-peak period, the energy that has been stored during the off-peak. Further, in the presence of a rooftop PV installation, the ESS is charged with a combination of low cost energy from the grid, from

the previous night, along with PV generated power, during daytime hours when the residents are usually at work.

From the literature (Sections 2.1 and 2.10) it was revealed that a storage system operating solely for retail energy shifting (i.e., TOU) or wholesale energy shifting (i.e., LMP) applications was found financially non-viable due to long PBPs; whereas, the ESS participation in the wholesale energy market yielded more revenue. Section 2.11 records a basic example involving aggregation of benefits from TOU tariff and DR; the example leads to a PBP of 10 years indicating that the aggregation of benefits is the pathway for ESSs economic viability.

Industrial and commercial electricity customers are often faced with both a consumption and demand charge (e.g. for peak demand in a specific period) component. An ESS provides a significant opportunity for these customers to reduce the peak demand component by releasing stored power during peak periods. Further, the demand charges in the near future will be based on apparent (S) power; therefore, both P and Q capabilities of the ESS, will contribute to the reduction of the demand charges.

5.5. ESS control with PI or PR regulators – balanced system

The independent control of the system variables, and the subsequent independent control of the active and the reactive power of the ESS, is realised through the transformation from the stationary reference frame (i.e., abc) to the rotating reference frame (i.e., dq). The decoupling is achieved, via the separation into a d and a q component, where P is often associated with d , and Q is often related to q . Further, the transformation $abc \rightarrow dq$, results into two dc signals which can effectively be controlled by the PI regulators; hence, zero steady state error can be achieved between the reference and the measured quantity. PI regulators have been extensively used in the literature, and their robust performance has been demonstrated.

In the case the recorded quantities are maintained in a stationary reference frame (e.g., $1-ph$ or $\alpha\beta$), then PR regulators must be used instead of the PIs. This is because, the PR controller is in a stationary reference frame; hence, the signals fed to the controller must be in a similar reference frame (ac signals), for zero steady-state error to be achieved. When there is a change in the system frequency, the resonant frequency of the PR regulator should also be amended, to meet the system frequency.

5.6. ESS control – unbalanced system

Moving from a stationary reference frame to a rotating reference frame, results in pure dc components when the 3-*ph* system is balanced. When the system is unbalanced, the $abc \rightarrow dq$ transformation, results in an oscillatory component in addition to the dc signals. This contradicts the PI requirement for pure dc input signals; hence, the steady state error is non-zero. To restore the balance, analysis of the signal into symmetrical components must be performed. This is achieved by converting the abc measured quantities (voltages and currents) into abc^p , abc^n and abc^0 , which are further transformed into dq^p , dq^n and dq^0 . This intermediate step increases the complexity and the computational effort of the control process; however, it is necessary for the generation of pure dc signals, as inputs to the PI regulators, leading to zero steady-state error.

Full extent utilisation of the symmetrical components can be realised, solely in the presence of a four-leg VSC. This is because, the 4th leg of the converter is connected to the load via the neutral conductor, and in turn, the path leads to the ground. Therefore, this type of converter is capable of controlling the current to the ground. When a three-leg converter is available, only the positive and negative sequences can be controlled, preventing from controlling the ground component – which is present in the case of a line-to-ground fault – therefore; part of the unbalance is still present.

6. Aggregated ESS applications

Reported studies on existing ESS pilot projects having focused on a single application for the ESS device indicated they were not yet financially viable in normal market conditions. However, an ESS coupled with the appropriate controls, and due to its fast-acting capability to P and Q commands with relatively high conversion efficiencies at different output power levels, enables it to undertake multiple applications simultaneously. Thereby, operational and monetary benefits can be aggregated towards the enhancement of its grid support role and the improvement of its financial viability as an investment.

Table 6 outlines four groupings of applications that can operate in a non-conflicting way even benefiting one another following the individual application requirements detailed in Section 2. These four grouping examples are not intended to be limiting, but more to

illustrate some potential near-term aggregation opportunities, that can be achieved with current ESS technology.

Table 6. Aggregated ESS applications summary.

Applications grouping	Energy shifting-arbitrage	Frequency regulation	Spinning reserve	Non-spinning reserve	Supplemental Reserve	Voltage support	Distribution upgrade deferral	Transmission access charges	Congestion relief	Service reliability-UPS	Power quality	Time-of-use energy charges	RESS shifting - arbitrage	Transmission losses
Group 1	X					X	X	X	X					
Group 2						X	X	X	X				X	X
Group 3										X	X	X	X	
Group 4		X	X	X	X									

6.1. Group 1

Following the operating principle of storing thermally generated energy from the grid, during off-peak periods, in order to inject it back during on-peak periods, a single ESS owned by the electrical utility can perform the following applications:

- Energy shifting - arbitrage to achieve an economic benefit
- Distribution upgrade deferral to achieve an economic benefit
- Transmission access charges to achieve an economic benefit
- Congestion relief to achieve an operational/economic benefit
- Voltage support to achieve an operational benefit

The application of energy shifting-arbitrage decreases the peak power experienced by the grid equipment, thereby also achieving some degree of congestion relief. Further, this process supports the deferral of grid upgrades for a number of years, as it tackles the main reason forcing grid upgrades, which is the annual peak load growth.

In parallel to the energy shifting, voltage support operation can also be maintained by the ESS. Loads such as fluorescent lamps and induction motors, require a high amount of Q

from the grid, leading to additional loading in the transmission lines and voltage drops. The provision of Q by the ESS, both supplies part of that reactive power demand leaving a greater margin for active power, and improves the voltage profile across the feeder. For voltage support to be performed, the rated power of the PCU has to be greater than the rated power of the storage unit, depending on the support requirement.

In terms of transmission access charges, they are composed by both demand and energy components, paid by the DNSP to the TNSP. By charging the ESS during the off-peak period and discharging it during the peak period, there will be a considerable reduction in the maximum demand of that period, thereby reducing this charge component. To the contrary, the energy component of the transmission access charges will be increased, depending on the efficiency of the ESS. For a thorough economic study both the effect on the demand and energy components of the access charges have to be examined.

6.2. Group 2

PV generated power from rooftop installations can be utilised to charge the ESS during daytime hours. In turn, the ESS is discharged during the on-peak period, resulting in distribution upgrade deferral and congestion relief. In the case where the anticipated PV power is inadequate to charge the storage, energy from the grid can be stored during the partial-peak or off-peak period, to be injected during the on-peak hours. Further, the transmission lines and transformer loading during these periods, is below the rated; hence, the power-flow does not threaten the thermal limits of the equipment.

Absorbing PV generated power during the day, and injecting it when it is needed the most by the grid, allows for significantly more renewable energy to be consumed than the case of not having ESS, without adversely impacting the qualitative operation of the electricity grid. It is also aligned with the aim for higher RESs penetration levels. Further, higher integration of renewables coupled with ESSs, means both higher revenues for owners of these distributed systems but also lower life cycle ownership costs for grid assets. The Group 2 applications, from the perspective of the electrical utility, are presented below:

- RESs shifting - arbitrage to achieve an economic benefit
- Transmission losses to achieve an economic benefit
- Transmission access charges to achieve an economic benefit

- Distribution upgrade deferral to achieve an economic benefit
- Congestion relief to achieve an operational/economic benefit
- Voltage support to achieve an operational benefit

The combination of RESs and ESSs placed in proximity of loads, results in reduced power transfer requirements over long distances (i.e., from the remote generators to the loads), which leads to transmission losses reduction. Further, when the ESS charging is realised with locally generated energy, both the demand and the energy components existing in the transmission access charges are reduced. This is because the highest demand with which the TNSP charges the DNSP is decreased, by shifting part of the peak demand to the off-peak period. Regarding the reduction of the energy component, it is also decreased, as the energy requirement from the remote thermal generators is diminished; however, energy is still being bought from the local RESs.

6.3. Group 3

Considering the trend for reducing the feed-in tariff for renewable generation during daytime hours, an ESS coupled with a RES offers boundless opportunities to reconfigure the electricity market arrangement and empower customers. From the perspective of the customer, the scenario of having widespread penetration of RESs coupled with ESSs, will deliver the following aggregation of applications:

- TOU energy charges to achieve an economic benefit
- RES shifting to achieve an economic benefit
- Power quality to achieve an operational benefit
- Service reliability to achieve an operational benefit

Provided that the electricity customer is subjected to a TOU tariff, the high cost energy can be avoided, by shifting the PV generated energy from the off- or shoulder-peak periods to the on-peak period. Hence, high cost energy can be avoided, while the user can still maintain their preferred energy consumption profile, which usually exhibits high consumption between 4 pm and 8 pm.

The RES shifting operation mitigates the voltage rise problem, primarily at the premises of the end-user. It also benefits the power quality for the rest of the terminals existing in the feeder. The reliability of service is also facilitated, as in the case of a power outage, the

electricity customer will be able to limit or ride-through the outage period, depending on the severity of the incident and his stored energy.

Power quality is another benefit delivered by the ESS, as it decreases the exposure of sensitive equipment to grid disturbances (e.g., overvoltage), therefore; avoiding the decrease in the useful life of the equipment that would occur without a power quality compensation mechanism.

The combination of an ESS with a gen-set can be employed when service reliability is of immense importance (e.g., hospital). For instance, in the case of a power outage, the ESS can supply for a brief period of time the load, until the gen-set takes over.

6.4. Group 4

Ancillary services are required to maintain the normal grid operation, in the presence of smaller or larger disturbances. As a small disturbance, load variation can be considered, while frequency regulation is employed to equalise load and transmission losses with the generation. In the case of a larger disturbance, such as, the loss of a thermal generator, the generation capacity reserves are employed, to restore the grid operation to normal conditions.

Considering that the ESS can respond faster than thermal generators and that generators working at part load are less efficient, resulting in more fuel consumption per MWh and higher GHG emissions, a portion of the ancillary services can be assigned to storage. The applications that are grouped below can be performed by a single ESS:

- Frequency regulation to achieve an economic/operational benefit
- Spinning reserve to achieve an economic/operational benefit
- Non-spinning reserve to achieve an economic/operational benefit
- Supplemental reserve to achieve an economic/operational benefit

The capacity (MW) requirement for frequency regulation has been identified as 1% of the load as it varies during the day. In terms of generation capacity reserves, they should account for 125% of the 1st largest contingency, assigned to spinning and non-spinning reserves, while 50% of the 2nd largest contingency is assigned to the supplemental reserve.

The ESS along with the other generators in charge of frequency regulation should vary power output by following the positive/negative ACG signal, sent by the ISO every 4

seconds. These regulating actions, aim to maintain the system frequency within the range of 50.1 Hz to 49.9 Hz, as defined by the AEMO.

In the case where sustained under-frequency is sensed (e.g., for a few seconds), it means either a contingency, or inadequate generating capacity, so spinning reserve should be deployed. If the engagement of the first reserve does not manage to restore the system frequency, then the non-spinning reserve should also provide power. If one of the reserve generators fails to pick up load, then the supplemental reserve replaces that generator. The ESS that is considered as a generator of the system and has been included in the ISO's planning; can be called to replace portion of the aforementioned reserves by utilising portion of its capacity which was reserved for such an incident.

7. Future research directions

A future where ESS becomes an integrated part of the electricity grid is starting to take shape; however, there are a number of hurdles to overcome before we will see the current rate of ESS diffusion accelerating in advanced economies. Many of these hurdles relate to the current outdated paradigm of electricity grid governance, regulatory and market frameworks, which are undoubtedly inhibiting investment in ESS deployment. Other impediments are more technical, relating to a lack of understanding of the technical benefits of integrating ESS into the grid at various segments and with different combinations of applications and control. Also, to bridge the gap between the micro technical and the macro governance hurdles, we must attempt to quantify the life cycle economic benefits of various smart grid 'futures' scenarios having different aggregated ESS applications within the network. Finally, the current momentum of battery technology research needs to continue, but be more mindful of the complex interrelationship between ESS cost, life span, fitness-for-purpose for aggregated applications requirements, reliability and safety.

Current energy markets and regulatory frameworks must facilitate greater ESS participation in the ISO markets. The US energy market has taken some reform steps, with the Federal Energy Regulatory Commission (FERC) order 784, enabling non-generation units to participate in the ISO market. Aligned with the FERC order, CAISO's regulation market, allows limited energy storage participation. FERC and CAISO policies' should be considered in other countries. These new policies should not only include the availability and energy component payment, but they should also incentivise units that maintain higher efficiencies

and rapid response times. Creating an open market enabling ESS deployment but specifying certain 'grid' objectives from any such deployments would drive the necessary competitive market pressures to innovative current ESS technologies.

The number of medium and larger scale ESS projects being implemented globally is increasing, each providing greater insight into their benefits and the revelation of issues to be resolved. While lessons are being learnt and benefits quantified, there are still far too few demonstration projects; many are concentrated in the US and in Western Europe with only a few of these actively participating in a refined wholesale ISO market. Moreover, these ESS projects are in their infant years with few long-term examples of multi-application ESS functioning within the electricity grid. As discussed in this paper, there is a significant lack of empirical evidence on how ESS can be implemented to achieve multiple applications. Also, the life cycle benefits accrued from multi-application ESS installations for both existing and Greenfield electricity distribution systems must be determined, along with the associated life cycle economic assessments to demonstrate that the economic benefits of ESS (e.g. network augmentation deferrals, peak demand reductions, etc.) outweigh the additional costs on a net present value basis. The authors are focused on conducting such studies in the future. Such evidence will undoubtedly heighten confidence that ESS can deliver operational benefits, while reducing the long-run marginal cost of electricity provision.

Because of the widespread utilisation of power electronics in a wide range of applications (e.g., solar inverters, AC/DC/AC converters in wind power applications, electric vehicles, etc.), high efficiencies have been reached (e.g., 96%) for many applications. Conversely, power electronics and battery technologies associated with ESS are still in a relatively immature stage of development; the research and commercial opportunities in this area are vast and deserve urgent attention. For instance the battery technology of lithium cobalt oxide (LiCoO_2) which is usually found in applications that require low power and high energy can be replaced by the lithium iron phosphate (LiFePO_4) technology when the application requires high power for short-term and long cycle life. Additionally, improvements in pump hydro energy storage (PHES) technology can be achieved by further advancing the existing computational fluid dynamics (CFDs), leading to individual components with better performance and increased overall installation efficiency. Intelligent algorithms and decision support systems utilised in current ESS technologies are relatively simple with ample room for improvement to handle increasingly complex

distributed grid arrangements, and the current suite of ESS control systems are not presently ideal for achieving the mutually interdependent goals of multi-applications.

8. Conclusions

An energy future where renewables are effectively integrated into the grid requires the coupling of sufficient ESS for the shifting, firming and smoothing of their fluctuating output power. An optimally combined RES with ESS will ensure a more economic grid operation either by reduced spinning reserves or by making use of TOU tariffs and demand charges. In all of the above cases, electricity customers are benefited by direct or indirect reductions in their electricity bills.

In terms of monetisation of the plethora of the ESS applications; this can be realised through the retail or wholesale energy markets. Particularly for the wholesale market, the ESS can be regarded as a generator within the system and it can be dispatched accordingly. The selling or the purchasing of energy can be realised based on the LMP; therefore, reflecting marginal costs and transmission losses. For applications that are called infrequently, it is important that both the availability payment and the energy payment are received by the ESS; a practice followed for the conventional generators.

The selection of the appropriate ESS technology is another important dimension that has to be explored during the planning stage, as it significantly affects the effectiveness, the useful life and the lifecycle cost of the application. Selection criteria such as energy density and power density signify the space requirements of the ESS technology. Specific energy and specific power represent weight requirements of the storage technology. When space and mounting force are critical, these selection criteria become important hence are weighted accordingly. The daily self-discharge is another criterion that receives its weight depending on the application. For instance, in the case of energy shifting-arbitrage, the daily self-discharge rate is weighted with the least important parameters due to the frequent call of the ESS to perform the application. Here, 14 selection criteria are involved in the *TCF* determination; a factor that clearly indicates the appropriateness of the storage technology for the required application.

For the ESS applications to be realised, application-specific control methods are required in order to control the appropriate parameters (e.g. P , Q , V , δ and ω). The independently controlled variables such as ω and V are usually attached to the d and q

components of the synchronous reference frame due to their relation to P and Q . Furthermore, for elimination of the steady state error, dc input signals must be fed to PI regulators while ac input signals are appropriate for PR controllers. When an unbalance is present, the aforementioned dc input signals contain an oscillatory component that makes PI compensators unable to completely eliminate the steady state error. Therefore, the unbalanced abc signals have to be converted using the symmetrical components, in turn, the abc signals of each sequence are transformed into the synchronous reference frame resulting in pure dc signals that are effectively controlled by PI regulators. It should be noted that the 012 sequences can be used to the full extent solely in the case of 4-leg VSCs due to the additional degree of freedom of the neutral current path.

ESS deployment will be accelerated when the benefits of sophisticatedly controlled ESS for serving multiple grid applications can be properly understood and verified. This paper illustrates the non-conflicting aggregation of four groupings of ESS applications with control (e.g. Group 2 included the following applications: RESs shifting – arbitrage; transmission losses; transmission access charges; distribution upgrade deferral; congestion relief; and voltage support). Extensive field implementations of ESS with appropriate control methods, together with aligned cost-benefit assessments, are needed to validate the potential aggregated benefits owing to properly controlled ESS in the grid.

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