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REVIEW

Impacts of grid-scale battery systems on power system operation, case of Baltic region

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Abstract

Grid stability can be affected by the large-scale utilisation of renewable energy sources because there are fluctuations in generation and load. These issues can be effectively addressed by grid-scale battery energy storage systems (BESS), which can respond quickly and provide high energy density. Different roles of grid-scale BESS in power systems are addressed, following optimal operation approaches classification. Furthermore, integrating BESSs into distribution grids is discussed to manage challenges from distributed generation. BESSs aid in voltage control, enhance frequency regulation, and offer black-start services. Aggregating distributed BESSs can provide ancillary services and improve grid economics. For consumers, BESSs optimise energy costs, enhance reliability, and support self-consumption from renewables. Novel BESS services include congestion relief, system adequacy, and power quality enhancement. Moreover, the ancillary services provided in different European countries through BESS are analysed. Finally, a case study was conducted among three Baltic DSOs to analyse the required amendments to Grid Codes and Electricity Market Acts for the integration of grid scale BESS.

KEYWORDS

energy storage, power distribution control

1 | ROLES OF GRID-SCALE BESS IN POWER SYSTEMS

Grid-scale BESS can be utilised for many different purposes in electricity systems. At its core, BESS provides means to store electrical energy for later usage; large grid-scale storage can have a substantial impact on grid performance. This energy could be used to improve the grid reliability and power quality by providing ancillary services such as frequency regulation. Additionally, BESS can provide virtual inertia, which will become especially relevant in future largely RES-dominated grids. The stored energy can be used even out the daily power curve by reducing the peak power. Furthermore, it can enable renewable integration in current grids and postpone grid reinforcement that will inevitably be needed. In this section these roles have been studied further.

1.1 | Grid reliability and power quality impact

1.1.1 | Ancillary service provision

Ancillary services are supportive services that enable the transmission of electrical power from generation to consumption by ensuring that the grid parameters are kept in safe viable ranges. The term ancillary service can refer to a variety of different services but from the perspective of grid-scale BESS what are interesting and what are currently widely being researched are the frequency regulation, voltage regulation, and black start services.

The ancillary service market designs and product descriptions vary from country to country as illustrated by the ancillary services procurement and electricity balancing market design survey [1] conducted by the European Network of Transmission System Operators for Electricity (ENSTO-E). These discrepancies could stem from the historic development of ancillary service markets or the generation mix of these nations. However, the EU has moved towards harmonising the ancillary service markets with the energy balancing guideline regulation [2], which entails that at one point all of the EU member states should start to provide three balancing reserve products: namely the automatic Frequency Restoration Reserve (aFRR), manual Frequency Restoration Reserve (mFRR), that is, secondary and tertiary reserves respectively, and Replacement Reserve (RR). The provision of the primary reserve, that is, the Frequency Containment Reserve (FCR), has not been made mandatory; despite that many nations across Europe are voluntarily implementing it. An illustration of different frequency reserve products is given in Figure 1.

The purpose of the primary control reserve, that is, FCR service is to be the first response to the sudden occurrence of imbalance. Assets that provide FCR activate automatically within 30 s in the entire synchronous are. The activation signal for FCR does not come from the TSO, rather it is based on the continuous measurements of the grid frequency. Adjustments to the production and consumption of FCR providing assets are done proportionally to the grid frequency deviation from the norm. If the frequency deviation persists then the aFRR is subsequently activated [3].

The secondary reserve, that is, the aFRR service will begin to replace the FCR gradually 30 s after the imbalance occurs and reaches the full activation within 5 min. If the grid imbalance persists after 12.5 min of occurring then the mFRR service, that is, the tertiary reserve, starts gradually activating reaching the full activation at the 15-min mark and has a minimum delivery period of 5 min [3].

The last source of reserves, that is, the replacement reserve (RR) uses generators with longer start-up time to either complement the previous reserves or to release them back into their state of readiness. The RR has to reach full activation within 30 min of the disturbance and has a minimum delivery period of 15 min [3]. An alternative could be to instead use large grid-scale BESS. Battery storage can be a good alternative

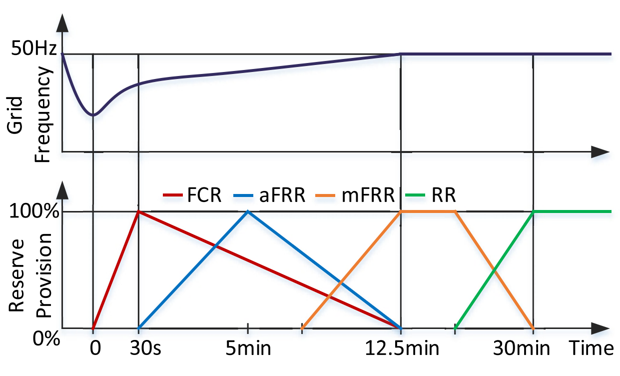

FIGURE 1 Illustration of frequency reserve product activations based on ENTSO-E grid codes.

due to its fast reaction speed, and environmental friendliness when used in combination with RES.

From the experience of the operation of Zurich 1 MW BESS that is used for FCR, peak shaving, and islanded operation; the main challenge for the provision of FCR is the management of the state of the charge (SOC) shifting, which is complicated by the internal losses of the battery and the activation signals that are generally not zero-mean [4]. The relation between the required energy capacity with respect to power capacity was found to be around 220 kWh per MW for FCR provision [5]. The effectiveness of BESS to provide ancillary services is investigated within the PRESTO (Primary REgulation of STOrage) research project [6], in particular by managing the storage SOC with variable droop control.

The profitability of grid-scale battery systems for purposes of Primary Containment Reserve (PCR), peak-shaving (PS), and Enhanced Frequency Response (EFR) was analysed in Ref. [7]. It was found that EFR purpose has the highest profitability of the three; however, combining EFR and PS applications improves the profitability even further.

Grid-scale BESS usage for FCR in a low inertia grid using grid-forming and grid-following methods was investigated in Ref. [8]. It was found that large-scale BESS can significantly improve system frequency containment, especially in the grid-forming converter control mode. Future smart grids will also inevitably encompass smaller distributed battery systems. The authors of Ref. [9] combined smaller BESS, RES, and flexible loads to create one large virtual energy storage system (VESS) for the purpose of voltage regulation. An overview of ancillary service provision with different types of ESS including BESS is given in Ref. [10], where it was found that the overall deployment cost of microgrids is reduced with the utilisation of ESS for ancillary services.

1.1.2 | Virtual inertia emulation

With the increasing RES penetration, the conventional synchronous generation is starting to be phased out. The future grids will undoubtedly have more converter interfaced generation which will result in the reduction of grid inertia. The grid needs to have an adequate level of inertia to maintain a stable grid voltage and frequency. With a low level of inertia, the imbalance between the generation and consumption will start to negatively affect the grid parameters much sooner than in the case with higher levels of inertia. Ensuring an acceptable balance will be even more difficult on a smaller microgrid scale. One novel technique to increase the grid inertia would be to perform virtual inertia emulation with large grid-scale BESS.

Virtual inertia emulation works by imitating the inertial response of traditional synchronous generators (SG). The implementation of virtual inertia is based on the swing equation of SG that is incorporated into the inverter control so that the typical inertia less inverter could emulate the inertial characteristics of SG. It is considered "virtual" since the inertia is emulated without the utilisation of any rotating mass [11].

In general, the implementation models of virtual inertia emulation can be divided into three main categories [12].

- *Synchronous generator model* is based on operating inverters as synchronverters, that is, as inverters with similar dynamics to SG [13]. This is achieved by detailed modelling of electrical and mechanical parts of SG. Integration of this model into solar and wind production is explored in Ref. [14] and for a battery system in Ref. [15].
- *Swing equation*-based is based on operating inverters with only the swing equation of SG rather than modelling the entire electrical and mechanical parts. This method works by measuring the grid frequency and the active power output of the inverter. One well-known method for this is the Ise Lab's topology [16].
- *Frequency-power response* is based on the idea of emulating the ability of SG to respond to frequency changes. This approach is considered as one of the simplest methods of providing virtual inertia since it does not involve a detailed SG model. One well-known method in this category is the virtual synchronous generator (VSG) [17]. The main shortcoming of this method is that if the converter has to operate as a grid forming unit in islanded mode then it can't provide virtual inertia at the same time.

The impact of different levels of minimum inertia constraints with two decarbonisation scenarios was investigated in Ref. [18]. The authors concluded that setting minimum inertia levels may be useful during the transition phase to higher RES penetration levels, however, if not replaced in a timely manner they might end up impeding emission goals. Virtual inertia was used to suppress voltage fluctuations using a BESS in a DC microgrid with a large share of renewables in Ref. [19]. Optimal BESS sizing for virtual inertia emulation in islanded microgrid operation scenario was performed in Ref. [20]. The authors of Ref. [21] concluded that the problems of inertia and frequency stability of power systems with large-scale renewable generation could be addressed with wind turbine emulated inertia, integration of energy storage systems, and involving smart controllable appliances of prosumers.

1.1.3 | Peak power reduction

Peak power reduction, that is, peak-shaving entails a power reduction from the grid during morning and evening peak periods of consumption. During this period the power is supplied by a large energy storage system such as a BESS. The energy stored in the BESS is consumed during off-peak periods when the consumption is lower; at night time or during the daytime when the PV production is highest. With increasing renewable production, it will be crucial to have an adequate level of storage to shift the overproduced energy to mornings and evenings.

Compared to frequency regulation, which is a short-term power-intensive application, peak shaving is a more long-term energy-intensive application. Usually, the peak shaving process needs to be performed for the duration of 1–10 h [22], highlighting the need for large grid-scale energy storage. The main objective of reducing peak power is to alleviate the issues surrounding grid over-loading, reduce the ramp rate during peak consumption, and postpone the need for grid infrastructure reinforcement [23].

An overview of existing peak shaving implementation strategies and challenges based on energy storage systems (ESS), electric vehicles (EV), and demand-side management (DSM) has been given in Ref. [24]. It was found that challenges surrounding EVs are their availability, aggregated control, and lack of large-scale deployment. The challenges with EVs are regarding the customer willingness, presence of proper ICT infrastructure and the overall complexity of the system. Nevertheless, implementing peak shaving using BESS faces challenges of scheduling the optimum operation, optimal sizing, and high capital and maintenance costs.

A decision-tree-based peak shaving algorithm has been developed in Ref. [25] to mitigate peak demand complications in an islanded microgrid with a grid-scale BESS resulting in cost-savings from economic arbitrage, postponed system upgrades, reduced fuel consumption, losses, and carbon emissions. The authors expanded this research for a PV-BESS hybrid system in Ref. [26].

Currently, peak shaving using battery storage might be too expensive of an option, especially in places that are suitable for other large-scale storage systems such as pumped hydro or compressed air storage. However, BESS could be considered as an option in locations that lack the specific geographical features needed for those storage types [27, 28].

1.2 | Renewable energy integration

The ever-increasing renewable penetration has introduced challenges from the power system side that mainly stem from the intermittency and the variability of RES. These challenges have led to a growing need for grid-scale storage. The following BESS applications can further facilitate the integration of renewable energy [29]:

RES energy shifting addresses the intermittency of RES. This is because the most prominent renewable sources such as wind and PV are intermediate by nature and thus might produce at times when not needed or vice-versa. RES energy shifting entails incorporating BESS into the existing power system to store the surplus renewable energy. This can be especially relevant in PV-dominated grids that have high production peak during the daytime which might result in an overproduction that would otherwise be curtailed as illustrated in Figure 2.

RES variability smoothing tackles the variability of RES. Traditionally, renewable energy sources are considered non-dispatchable, meaning that their power output cannot be controlled by the operators dynamically. Although modern control rooms dispatch wind, this is more just limiting their output rather than balancing dispatch. Solar and wind power plants produce energy when the sun shines or when the wind

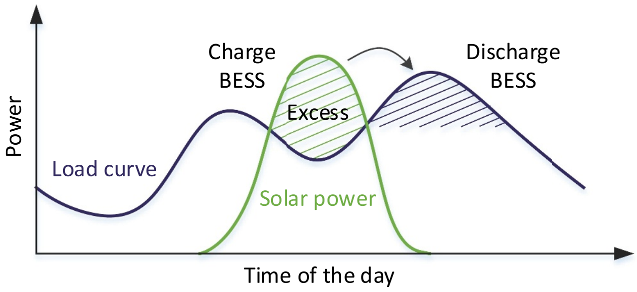

FIGURE 2 Daily excess RES energy shifting.

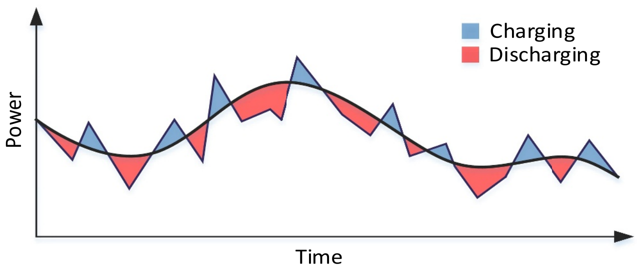

FIGURE 3 Short-term RES variabilitsy smoothing.

blows, but neither of those is guaranteed to be constant. Due to the stochastic nature of renewable sources, there is a need for short-term power smoothing that reduces the sharp ramping changes as shown in Figure 3. The sharp ramping rates are especially troublesome in the case when RES has a large contribution to the generation mix. Power smoothing requires far less energy storage than load shifting [29]; however, since it is a continuous process that is accompanied by frequent charging and discharging it results in faster degradation of BESS. A literature review of control strategies for wind power output smoothing with BESS has been given in Ref. [30]. A bibliometric review of articles related to renewable energy integration with BESS has been given in Ref. [31].

1.3 | Environmental impact

The applications of grid-scale BESS can have a positive effect on the environment. As discussed beforehand, grid-scale BESS can facilitate the integration of more renewable energy into the generation mix which would increase consumption of more environmentally friendly sustainable energy, while at the same time, the traditional generation would be phased out. The authors of Ref. [32] investigated the potential of grid-scale battery systems to replace combined cycle gas turbine (CCGT) plants in responding to variable peak demand in the UK. It was found in the future projection of 2035 that in the UK around 5.5 TWh of battery storage would be needed to replace the energy that would otherwise come from CCGT plants.

Utilising grid-scale BESS for the purpose of grid reliability and power quality can also have a positive impact on the environment by replacing the traditional fast-reacting peaking plants that are usually based on fossil fuels. An example of this would be the work of the authors of Ref. [33], who replaced diesel generators in a university campus microgrid with an unreliable grid power supply with a PV-BESS hybrid system that reduced peak-hour energy purchases from the grid significantly by phasing out diesel generators almost entirely. The authors also concluded that the transition to a PV-BESS hybrid system yielded substantial annual savings and calculated the payback period to be around 6 years.

Nevertheless, when dealing with large grid-scale battery systems the environmental impact of their production, transportation, and recycling needs to be accounted for. Other grid-scale storage types such as pumped hydro and compressed gas storage have comparably trivial environmental and health impacts [34] since they don't require the mining, refining, and recycling of potentially hazardous elements. A review of life cycle assessment (LCA) studies was conducted in Ref. [35] which found that producing 1 Wh of storage capacity is across all battery chemistries on average associated with a cumulative energy demand of 328 Wh and greenhouse gas emissions of 110 gCO_2eq. The potential end-of-life options for batteries could include reuse or repurposing for a "second life", recycling to recover materials, and disposal [36]. Presently less than 3% of lithium-ion batteries are recycled [37], however in the near future the increased demand coupled with restricted access to virgin materials is hoped to increase the recycling rate.

2 | OPTIMAL GRID-SCALE BESS OPERATION APPROACHES

The charging and discharging behaviour of BESS can be implemented with different approaches. Independent of the BESS size, small, medium or grid-sized, three basic operation approach categories need to be considered to determine the optimal method. The first category is conventional operation approaches that is based on traditional control methods, like droop control [36]. The second category is based on heuristic operation methods [37, 38]. These methods do not claim to be perfect, optimal or even rational. Instead, they try to present a practical and satisfactory solution for complex systems, like techno-economic optimisations [39]. The third category is meta heuristic approaches. Which is based on general applicable optimisation algorithms that might be tailored to the problem that needs to be solved, like particle swarm optimisation [40]. These three categories are discussed in more detail in the following subchapters.

2.1 | Conventional

Conventional operation approaches for grid-scale BESS are presented in several publications. These methods are often focused on basic control strategies to provide ancillary services. The comparison of different presented operation approaches is shown in Table 1.

The comparison shows that all the provided publications aim to provide ancillary services, especially primary reserve,

TABLE 1 Comparison of conventional operation approaches.

Publication	Method	Power/Capacity	Position LV, MV, HV	Cell technology	RES integration	DR integration	Geo location	Services
[36]	Droop control	–	MV	–	+	–	Milan, Italy	Ancillary (primary reserve)
[41]	Droop control	5 MW, 5 MWh	–	Li-ion	–	–	Germany	Ancillary (primary reserve)
[42]	Droop control	16 MWh	–	–	–	–	Baja California Sur, Mexico	Ancillary (primary reserve)
[43]	Droop control	200 MW, 100 MWh	–	–	–	–	United Kingdom	Ancillary (primary & secondary reserve)
[44]	Droop control	10 MW	–	Li-ion	–	–	Northern Ireland	Ancillary (primary reserve)
[45]	Model predictive control	20 MW, 80 MWh	–	–	+	+	–	Ancillary (primary reserve); operation cost reduction (real time price)
[46]	Droop control	225 MW, 175 MWh	HV	Lithium-Titanate-Oxide	–	–	Europe	Ancillary (primary reserve, restoration)

Note: + = considered/integrated; – = not mentioned/integrated.

with the conventional operation approaches for grid-scale BESS. Since this is directly related to frequency control, nearly all proposed methods are based on droop control approaches. As expected for grid-scale BESS, the power and capacity considered are in the MW/MWh range. Unfortunately, it is often not mentioned, on which voltage level the BESS is connected, but the two mentioned levels are medium- and high voltage levels. The popular battery cell technology is lithium-ion based. Eight of the 9 publications use simulations, whereas only 1 publication presents an experimental setup for research. Due to the droop control implemented in most of the publications, renewable energy sources and demand response are not directly integrated into most of the conventional battery operation approaches.

Apart from this scientific literature which is based mostly on simulations as the comparison shows, there are multiple TSOs and DSOs that started implementing large battery storage into their grids. Of course, based on the TSOs and DSOs main interests, these systems are controlled by conventional algorithms, like droop control, to provide ancillary services to the grid and improve the power quality this way. Examples for those implementations worldwide would be in USA [47], United Kingdom [48], Australia [49], Denmark [50], or Germany [51, 52].

2.2 | Heuristic

The most popular operation approaches for grid-scale BESS are heuristic methods. There is a wide range of publications that present different heuristic approaches to build a coordination framework not only for battery storage but often in combination with larger renewable generation sites. A comparison of different presented heuristic operation methods is shown in Table 2.

In heuristic operation approaches for grid-scale BESS, there are often multiple objectives that are considered. These include not just ancillary services but also economic, environmental and local power quality focused goals. For these goals, there are different approaches presented in every publication. These reach from energy market based control decisions to combinations with conventional approaches and prediction based models. Unfortunately, for some of these articles the grid scale BESS start at medium capacities, like 20 kWh, but most of them consider the MWh-range as expected. Like with the conventional methods, the preferred battery cell type is lithium-ion based. Due to the multi-objective orientation of these operation strategies, there is a direct integration of renewable energy sources and/or demand response into most of these control methods. Like the conventional methods, these operation strategies are simulation based as well.

2.3 | Meta heuristic

There are many publications that present different meta heuristic operation approaches for BESS, such as particle swarm optimisation [40] or discrete-time-gradient optimisations [59]. However, most of these publications present operation approaches in the framework of small or medium microgrids. In the context of grid-scale BESS the number of available

TABLE 2 Comparison of heuristic operation approaches.

Publication	Method	Power/Capacity	Position LV, MV, HV	Cell technology	RES integration	DR integration	Geo-location	Services
[53]	Setpoint adjustment, over fulfilment, use of deadband, use of gradient	5 MW, 5 MWh	MV	Lead acid, Li-ion (LMO, LFP)	–	–	Germany	Ancillary (primary reserve)
[54]	Real time- (TSO/DSO frequency signal based), predictive (feed-in-tariff based) control	20 kWh	LV	Li-ion	+	+	–	Ancillary (primary& secondary reserve); increased self-consumption; operation cost reduction (demand response)
[39]	TSO/DSO frequency signal based, intraday energy market (15 min based), peak shaving (monthly & daily model)	1 MW–5 MW, 1 MWh–30 MWh	–	Li-ion	–	–	Germany	Ancillary (primary reserve& secondary reserve); peak shaving; black start
[55]	Decision-based control algorithm with optimisation	5 MW, 5 MWh; upscaling to > 50 GWh	–	Lithium-manganese	+	–	United Kingdom	Ancillary (secondary & tertiary reserve)
[56]	Techno-economic model based algorithm	>1 GWh	–	Li-ion	+	–	United Kingdom	Ancillary (secondary & tertiary reserve)
[57]	Multi-objective optimisation, energy market based (day-ahead),	<200 kW, <200 kWh	MV, LV	Li-ion	+	–	–	Economic optimization; peak shaving; increased self-consumption;
[58]	Corrective voltage control	>300 MW	-	–	+	–	–	Local reactive power control; local voltage control; local power/voltage control

Note: + = considered/integrated; – = not mentioned/integrated.

publications is reduced to a few relevant ones. A comparison of the presented approaches is shown in Table 3.

As mentioned before, the number of meta heuristic operation approaches for grid-scale BESS is more limited than the other approaches. The presented methods implement a general optimisation technique in the control strategy, namely particle swarm-, discrete-time-gradient- and generic optimisation algorithms. However, the capacity considerations for those methods seem to be set between medium and grid-scale level. This is also shown in the presented voltage level connection. Many publications show smaller sized BESS of less than 100 kW with meta-heuristic operation approaches. This indicates a higher popularity of these methods on microgrid-scale to primarily achieve an optimised operation for a private investor or customer rather than the DSO or TSO. As with the two previously discussed methods, lithium-ion cell technology is preferred as well as simulations instead of experimental setups. All methods integrate only renewable energy production and do not consider demand response methods. The focus of these publications is, as expected for medium scale BESS, on microgrid services, like increased self-consumption and operation cost reduction. Ancillary services are not considered at all.

In summary, the three different operation approach categories are oriented at specific goals. While conventional approaches are focussing on ancillary service provision, heuristic and meta heuristic approaches are tailored to provide maximum cost reductions with multiple objectives. Based on that, it can be concluded that heuristic and meta heuristic grid-scale BESS control is most suitable for private investors, as their goal is cost saving and quick return-of-investment. For TSOs and DSOs, conventional control methods are the best fit, as their primary goals are grid stabilisation, reliability, and power supply security. This is confirmed by the examples of practical implementations of TSOs and DSOs with grid-scale BESS which are all based on conventional operation methods.

3 | PARTICIPATION OF GRID-SCALE BESS GRID SERVICES TO OVERCOME POWER QUALITY ISSUES

All electrical devices require the voltage level to remain within a certain magnitude and parameters. The required voltage levels and parameters are determined with European Standard EN 50160 [68]. The standard defines, describes, and specifies the voltage regarding its frequency, magnitude, waveform, and symmetry of the line voltages and is addressed as power quality in the professional literature. Voltage related power quality events (power surges, sags, transients, momentary interruptions, etc) are usually caused by external events that is, weather (high winds, lightning), starting and stopping heavy equipment (motors driving mechanical processes, utility switching), circuit overloading or system failures (short circuits, fault clearings, wrong dimensioning of system). If previously most of the power quality issues could be omitted to consumers and power electronics driven non-linear loads [69–72], then in the past years, growing concerns regarding the electricity consumption and production's impact on the environment have introduced a new set of sources for power quality issues – low carbon technology. The European Green Deal [73], The 2030 Climate and Energy Framework [74], and the 2050 long-term strategy [75], have the aim of the EU to become climate-neutral by 2050. To accomplish this, governments are creating different incentives for energy end-users and producers to invest in low carbon technologies, that is, photovoltaics (PV), wind energy (WE), electric vehicles (EV), battery energy storage systems (BESS), and similar. As the load demand keeps growing and the integration of stochastic

TABLE 3 Comparison of meta heuristic operation approaches.

Publication	Method	Power/Capacity	Position LV, MV, HV	Cell technology	RES integration	DR integration	Geo location	Services
[40]	Particle swarm optimised fuzzy control	110 kW	LV	Li-ion	+	–	–	Increased self-consumption
[59]	Multi-timescale and discrete-time-gradient optimisation	>100 MW	–	–	+	–	–	Operation cost reduction (day-ahead & 15 min); balance RES & load
[60]	Genetic algorithm	200 kWh–700 kWh	MV	Li-ion	+	–	–	Operation cost reduction (day-ahead)
[61–67]	Genetic algorithm, artificial bee colony, grey wolf, particle swarm, wild horse;	<100 kW	(LV)	–	+	+/–	–	Increased self-consumption, operation cost reduction

Note: + = considered/integrated; – = not mentioned/integrated.

generation increases, new challenges arise in the power system operations.

3.1 | Power quality issues caused by stochastic loads and generation

Although renewable electricity generation from weather-influenced sources introduces uncertainties on the generation side, the load side can introduce similar uncertainties due to market price-driven demand-side management actions. Coinciding stochastic events on both the generation and consumption can lead to voltage and frequency events as described in Refs. [76, 77]. Another issue that might arise in power systems with high penetration of renewable generation is the increased need for ancillary services to mitigate the possible stochastic generation down curtailment and the corresponding loss of energy, as discussed in Refs. [78, 79].

3.1.1 | Stochastic loads

Authors in Ref. [80] prove with numerical simulations that the stochastic nature of the load can suddenly make the system lose its voltage stability. According to Ref. [81], residential loads are subjected to variations that are biased with the household's inhabitant's lifestyle. The latter can help classify household loads according to its inhabitant's lifestyles and level out specific stochastic characteristics, but eventually, a certain amount of unpredictable variability remains. Furthermore, with the increasing share of renewable electricity generation assets and deregulated operation of the energy markets, novel services (i.e., demand-side management) introduce yet another level of variability to the load that is hard to forecast to a certain magnitude. Economics-based shifting of loads can accumulate unwanted power quality parameters to limited periods where otherwise evenly distributed power quality phenomenon is magnified to an unaccepted level, putting additional strain on the distribution network. Most electricity consumers with integrated renewable energy sources are connected to the low-voltage distribution system. This system already includes a high number of single-phase loads, and together with the distributed generators (DG), they could cause unwanted effects in distribution networks, as discussed in Ref. [82].

The majority of residential electricity consumers are single-phase loads and together with uneven loading of the phases causes an existing voltage to unbalance phenomenon in the distribution grid. Single-phase PV-s, residential battery energy storages, and home electric vehicle charging stations could further increase the voltage unbalance in the network. According to scientific literature [82, 83], voltage unbalance causes issues with induction motors as it raises the temperature, increases losses, and lowers their efficiencies. Additionally, the voltage unbalance is often accompanied by negative sequence voltage that causes negative sequence current, which does not do any useful work and contributes to energy losses and decreased transmission capacity in the distribution lines. From the perspective of the load, the most important factors are the load power variation speed and its magnitude, as described in Ref. [76]. Such variations, for example, could be introduced by plug-in electric vehicles [84, 85], as every different car plugged in for charging could introduce different load profiles depending on the manufacturer, battery capacity, charging technology, the initial state of charge, ambient temperature, etc.

According to numerous tests carried out on 68 different EV models in Refs. [86, 87] the charging capacity amongst different EVs can remain between 27 and 205 kW (average 92 kW), whilst the duration remains between 18 and 51 min (average 32). It should be noted that the charging experiments were carried out in public fast-charging facilities, meaning that such large variability in duration and capacity is stochastic and could occur in the system any time of the day. Although the energy consumption remains relatively stable (47 kWh on average), the load variation speed and magnitude can change significantly. According to the International Energy Agency's report [88], the global electric vehicle market has doubled roughly every 2 years. With the rapid changes imposed by stochastic charging activities, such a trend inevitably increases the difficulty of keeping an acceptable voltage profile in the distribution systems [89]. Fast-changing loads with high magnitudes could cause over- and under voltage events since the dedicated system elements (i.e., transformer on-line tap changers or reactive power support devices) have an unavoidable delay in adjusting to the new system state. The growing number of electric vehicles and home chargers contribute to the voltage drop and the total harmonic distortion (THD) that could exceed the set boundaries by standards in the low voltage distribution networks as discussed in Refs. [82, 90]. Additional THD sources are power-electronic devices that are widely used in home appliances for example, TV sets, personal computers, compact fluorescent lamps, LED lamps, and similar. The concurring harmonics increase losses (similarly to the negative current components) and deteriorate equipment life span due to additional heat dissipation [91]. The large increasing share of power-electronic driven electric vehicle home chargers and time shifting of loads could eventually lead to a situation where the THD of the low voltage distribution network exceeds the safe and recommended operational values. A study [91] showed that when electric vehicle penetration reaches 70% (with three-phase rectifier chargers), the fifth order harmonic level in the distribution network is doubled. Another study [92] indicated that low voltage distribution networks could have issues with transformer capacities and low voltage line thermal ratings when the electric vehicle penetration in the grid reaches 40%.

With the paradigm shift currently occurring in the power industry, it is essential to develop the energy demand and supply domain and manage and develop the control and hardware of the physical system. Without the integrated approach, considerable challenges hinder reaching the climate neutrality target. In future distribution grids, the following five aspects need to be addressed regarding the impact of stochastic loads on power quality:

1. The capacity of transmission/distribution equipment
2. Harmonic distortion
3. Voltage unbalance
4. Overvoltage
5. Undervoltage

3.1.2 | Stochastic generation

Mainly two factors pose challenges for grid integration of renewable systems: the variability and the decentralisation of energy generation. For example, the variability of solar power occurs in two stages: the first stage is variability over day and night, the second stage is due to solar irradiation fluctuations caused by intermittency of clouds. Similar variability can be omitted also to wind power as described in Refs. [76, 92, 93]. The reliability of the electrical grid is endangered by the high penetration of such volatile energy sources, causing problems in balancing supply and demand, voltage instability and power quality [94]. Decentralised energy generation mitigates problems in transmission grids, for example, reduced line losses, but can induce new problems in distribution grids, such as overvoltages, and requires new operation strategies [95]. Another aspect to consider is that traditionally the low voltage distribution grids have been unidirectional regarding power flows – usually towards the loads. As the distribution networks were initially designed to serve loads, the high penetration of local renewable energy production can lead to network congestions as coinciding generation peaks tend to occur irrespective of the residents' lifestyles.

Authors in Ref. [89] discuss that the stochastic nature of weather dependant renewable energy sources pose challenges for the currently used voltage management devices, that is, online load tap changing (OLTC) transformers, voltage regulators (VR), or shunt capacitors and reactors. While the weather impacted generation can have sudden changes in power output in a matter of seconds, then the voltage regulating devices tend to have longer reaction times due to their mechanical switching nature. From one side, this causes excessive wear and tear on the voltage regulating devices resulting in a shorter lifespan but, in worst cases, can lead to generation curtailment or even switch off due to network protection algorithms. In addition to sudden voltage changes, the high penetration of distributed energy resources can also impact the power quality on several levels [83]. Rapid voltage changes might lead to varying light intensity, also perceived by the human eye, known as flicker. Single-phased PV-s can lead to and contribute to unallowed voltage unbalance. According to Ref. [82], a high number of single-phase low carbon technologies (PVs and electric vehicles) can increase the voltage unbalance in single nodes and the entire low voltage network. The stochastic nature of the PV-s output can increase the voltage unbalance fact in the distribution system during specific periods of the day if compared to a system without PV-s installed.

Since small-scale renewable energy sources are coupled to the grid through power electronic devices, they tend to impact the harmonic distortion in distribution systems. With the large-scale integration of low carbon technology to our low voltage distribution grids, it is becoming more challenging to satisfy the required level of power quality [96]. In future distribution grids, the following five aspects need to be addressed regarding the impact of stochastic generation on power quality:

1. The capacity of transmission/distribution equipment
2. Harmonic distortion
3. Flicker
4. Voltage unbalance
5. Overvoltage

3.2 | Battery energy storage systems for power system services

BESS-s are an important enabler for the integration of stochastic and renewable generation installations not only on grid level, but also near prosumers. BESS-s increase flexibility in balancing supply and demand but can also increase safety, reliability, and quality of distribution grids by performing ancillary services for frequency stability, voltage stability and availability of energy and power reserves for balancing. As European Union is parallelly promoting the transition of the traditional generation-centric ancillary services energy market towards a market with an increased role also for prosumers [97], participating in ancillary services provision could make the investment in BESS-s economically more feasible [78] and at the same also enhance the possibility and performance of demand-side response.

BESS-s have the possibility to provide a variety of ancillary services. More generic ancillary services today mainly focus on voltage regulation [98–100] or frequency regulation [101–109]. The following table (Table 4) adopted from Ref. [110] and modified according to ENTSO-E and European Union terminology summarises the traditional ancillary services that could be delivered with battery energy storages to different target groups. The target group includes three main fields of activities: system operators (also including transmission system operators, distribution system operators and any other operational forms, that could be present), utility companies (mainly owners of assets, including generation, storage, lines, etc.), and electricity consumers (residential, industrial, commercial, etc.).

3.2.1 | BESS services for the TSOs and DSOs

Authors of Refs. [98, 99, 107] discussed advanced methods in voltage control strategies to meet the challenges that arise due to the large amount of distributed generation penetration into the distribution grids. The idea of using BESS for voltage

TABLE 4 Battery enabled traditional ancillary services, their definitions, target groups and coverage in scientific literature.

Service name	Definition	Target group	Papers
Load-frequency control and regulation reserves	Mechanism used to restore the balance between load and generation within a control area to maintain the power frequency in the desired range to avoid grid instabilities.	System operators	[79, 101–109]
(Spinning) energy reserves	Generating capacity that is either online (spinning) and instantaneously available or available in the matter of minutes (usually <15 min) and can provide output in response to contingency events (e.g., generation or interconnection trip).	System operators	[78, 101–109]
Voltage support and regulation	Mechanism that ensures the voltage level in the power system is kept within acceptable operations range and to avoid system wide incidents that is, voltage collapse, or inefficient operation conditions.	System operators	[98–100]
Black start capability	In the event of total system failure that causes grid outage, the ability to bring a regional part of the grid back online without external grid connection.	System operators, utility companies, electricity consumers	[111–114]
Energy cost optimisation	Also known as energy arbitrage or storing power purchased at off-peak times and selling it on-peak	Utility companies, electricity consumers	[78, 79, 94, 97, 115–120]
Increased distributed generation self-consumption	Minimising the export of stochastic and distributed renewable generation produced electricity from a region during low consumption periods and utilising it during high consumption periods.	Electricity consumers	[100, 115–120]

regulation lies in the controlled charging and discharging of the BESS according to the operation of distributed generation and the corresponding voltage level fluctuations in the distribution system. Additionally, the authors of Ref. [100] bring out that the integration of BESS into the voltage control strategy in distribution systems could increase the life expectancy of on-load tap changers and step voltage regulators that otherwise would suffer from the increased workload and shorter lifespan due to the additional work cycles caused by the distributed generation.

Authors of Refs. [101, 104, 108] discuss the challenges posing in utilising batteries for frequency regulation. A special control system could also overcome the issues associated with more frequent usage of BESS for frequency regulation that increase the operating costs or decrease the battery lifetime. The authors of Refs. [102, 103] on the other hand discuss and validate the possibility to use distributed BESS-s to provide FCR (or primary reserves, as usually referred to in specialised literature) in Germany. The importance of the pilot project lies in the fact it successfully demonstrated the possibility of a distributed storage capacity successfully providing services that were previously provided by large conventional power plants. Authors of Ref. [105] discuss about the suitable dimensioning of the BESS unit for FCR provision in wind dominated power systems, Brogan *et al* in Ref. [106] analyse the minimum requirements for BESS to participate in frequency control activities and during a high and low rate of change of frequency events. The author of Ref. [109] brings in yet another aspect that BESSs could be suitable for that is, distributed control of BESS to prevent under-frequency load shedding. All the previously mentioned papers bring out the challenges of large-scale renewable energy penetration and the lack of ancillary services from a conventional generation that is being actively phased out due to the changing energy policy and increasing share of renewables.

Additionally, BESS-s combined with weather impacted generation could provide a viable alternative for black start ancillary services that are currently provided with conventional generation units. Authors in Ref. [111] discuss the possibility to combine wind power plants with energy storage systems to provide black-start power. If traditionally the black-start power is provided with thermal, nuclear, or hydropower, then the instability of the output of the wind power plant is one reason that these assets are seldom used as a black-start power resource. The paper proposes a method of energy storage configuration to enable this possibility with wind power plants. Similarly, to wind power plants also PV-s is neglected when discussing black-start capability. Authors in Ref. [112] discuss the challenges to combine BESS-s with PV installations to provide black-start capability. The key challenge is caused by the random output of the PV installation and high variability of power and energy during black-start events that could lead to either over-charging or over-discharging of the BESS. With suitable control and optimisation algorithms, these issues can be overcome and could provide a valuable alternative source of black-start capacity. Authors of Refs. [113, 114] discuss about the possibility to use the BESS to provide black-start capability for the distribution system with either a single unit or with a multi-energy storage power system. Generally, all authors come to the same conclusion that BESS-s are a universal asset that can extend the black-start capability of a variety of technologies. More than that, in order to enhance power system resilience, battery energy storage systems (BESS) play an integral role in addressing power system events and outages. In these scenarios, BESS operation involves rapid response to imbalances in supply and demand, frequency deviations, and voltage fluctuations. To maintain grid stability during sudden load changes or power outages, BESS can quickly inject or absorb power. Backup power from BESS can ensure essential services are maintained during longer outages. Having fast response capabilities and flexibility, BESS can mitigate the impact of power system disturbances, ensure uninterrupted power supply, and contribute to overall grid resilience.

In addition, the versatility of BESS cab be further increased through the aggregation of distributed battery assets. This way even the distributed BESS-s could be used to provide similar services as large-scale bulk energy storage units, as discussed in Ref. [121]. The aggregation of distributed BESS assets in distribution grids are suitable for providing ancillary services meanwhile also increasing their economic performance. With the increasing share of stochastic renewable energy production, the planning and maintaining the main grid becomes ever more challenging and with higher operational cost. BESS, both on distributed and centralised levels, could be one possible solution to help transform the energy sector to a more decentralised and less carbon-intensive without compromising the security of supply or making it too expensive to hinder its further development. BESSs could be the versatile link to speed up this process, due to it possibility to cope with many of the existing issues starting from localised problems (voltage quality, congestion relief, etc.) to a more centralised alternative to traditional generating capacity provided services (frequency, control, voltage control, asset adequacy, etc.).

3.2.2 | BESS services for consumers

BESS are mainly marketed for their energy cost optimisation through retail energy time shift, peak shaving, and increased self-consumption from distributed generation through behind-the-metre solutions as discussed in Refs. [79, 100, 115–120, 122]. Also, the power reliability can be increased through BESS usage in weak grid locations to cope with voltage sag ride though and provide back-up power and even island solutions [123]. Although these services are mainly targeted at residential customers, then as discussed before, with coordinated control these BESS units could be used also for ancillary service providers, and thus increase the added value created by BESS units for both their owners and the society. Otherwise, the market prices are not favourable to make the BESS economically viable for all residential customers as discussed in Refs. [115, 117, 120]. Other aspects that hinder the benefits from increased self-consumption are location-based limitations to distributed renewable generation as discussed in Refs. [116, 119], making it even clearer that BESS systems should combine different services provision (e.g., ancillary services) to make them economically viable. The increasing demand for electricity and substituting traditional generation with stochastic technology also increases the strain on the physical network. Novel solutions are needed to cope with both operational and planning challenges of the power system. Both, the consumer and power and utility companies, can benefit from it though increased socioeconomic welfare.

3.2.3 | Novel services with BESS

Novel ancillary services from BESS-s include congestion relief [124–128], transmission/distribution system adequacy related services [127, 129–131], and power quality-related issues [98, 132–138]. Authors of Ref. [124] describe a case study where the battery located at a congestion point can provide backup energy storage during a contingency event to relieve thermal overload, thereby allowing the transmission limit to be increased. Although not specified, authors of Ref. [125] discuss the distribution system level optimisation of different assets (including energy storage) to avoid congestion during intraday operation. Authors of Ref. [126] propose to include the energy storages as service within a sharing economy concept to relieve transmission congestions by utilising the idle capacity on the open market for a fee, while in Refs. [127, 131] the authors propose a similar solution but instead with the energy storage capability of electric vehicles. Also, the possibility to utilise energy storage to defer upgrade of the existing electric grid infrastructure is introduced in Refs. [127, 129–131]. The latter one could lead to reduced cost for utility ratepayers and prolong the usage of existing infrastructure while maximising its utilisation factor.

Power quality issues due to stochastic generation and load are becoming increasingly important, as discussed in the Sections 1.1.1 and 1.1.2. The mentioned power quality issues (voltage unbalance, voltage variations, harmonic distortion, and flicker) can be successfully managed with BESS-s as discussed in Refs. [123, 139, 140]. Especially important power quality issues are the transient voltage variations and harmonic distortion of the network voltage due to the frequent starting and stopping of distributed generation as discussed in Refs. [98, 132]. Authors in Refs. [133, 135] bring out that a variety of power quality issues in microgrids (i.e., element failures, voltage swells and sags with short transients and high frequencies) are ideal to be met by energy storages with high ramping capability. Authors in Ref. [134] introduce a hybrid energy storage system that includes in addition to a battery also superconducting magnetic energy storage to compensate long and short-term voltage fluctuations to extend the lifetime of the battery. Authors in Refs. [136, 137] give a comprehensive overview about research regarding energy storage capabilities and summarise that an energy storage system can cope with most of the possible power quality-related issues. Ref. [138] summarised that voltage quality improvements are complementary otherwise to the load shifting application performed by the energy storage system.

The following table (Table 5) adopted from Ref. [110] and modified according to ENTSO-E and European Union terminology summarises the novel ancillary services that could be delivered with battery energy storages to different target groups.

3.3 | Application of grid scale BESS in different countries

In the 2020 ENTSO-E carried out a survey on ancillary services procurement and electricity balancing market design

TABLE 5 Battery enabled additional ancillary services in the future, their definitions, target groups, and coverage in scientific literature.

Service name	Definition	Target group	Papers
Resource and reserves Adequacies	Incrementally defer or postpone investments in peak load capacities on inertia reserves by utilising (battery) energy storage assets.	System operators, utility companies	[101–109]
Distribution/Transmission system adequacy	Incrementally defer or postpone investments in grid to meet peak load capacities by utilising (battery) energy storage assets.	System operators	[127, 129–131]
Transmission/Distribution congestion relief	Utilisation of (battery) energy storages to minimise the congestion on transmission/distribution lines during congestion hours	System operators	[100, 124–128]
Power quality services	Power quality maintenance and backup power for electricity consumers.	Electricity consumers	[98, 132–139].

amongst TSOs [141]. 47 countries (53 TSOs) were involved in the survey, and 30 (33 TSOs) of them provided answers. The TSOs were asked to answer questions of five topics: imbalance settlement, ancillary services, demand-side response, voltage control and black start. From the survey, we see that ancillary services are provided mainly via five assets: generators, demand-side response, pump storage, distributed generation, and batteries. The following table (Table 6) summarises the analysis regarding ancillary services and possibilities to provide it with BESS assets.

It should be noted that countries who stated that "All possible options" are accepted for different frequency regulation services were considered to accept services also from BESS units. Italy also stated in the survey that one significant/important change that is being implemented regarding the ancillary services is to involve low-consumption resources such as batteries coupled with PV in the ancillary services provision.

Regarding voltage control all the answered TSOs (100% from the ancillary services group) and additionally Luxembourg considers voltage control as an ancillary service. Only three TSOs (Finland, Germany, and Slovakia) consider storages as voltage control service providers. Since the survey does not specify the types of storages it consider, the authors assume that it also includes BESS. Other parts of the survey did not cover storages as assets for services.

Although ancillary services are a vital part of services that could be provided with BESS-s the future outlook forecasts that by 2030 the global grid-related annual deployment of energy storages will be focusing on capacity management, energy shifting, transmission and distribution management, and PV-s combined with storage applications in various sectors [142].

4 | CASE STUDY: BALTIC REGION DSOS

Increased integration of BESSs into distribution systems requires amendments to Grid Codes and Electricity Market Acts (EMA) to ensure their safe and fair operation. To identify possible issues and improvements into existing regulations, a case study was conducted among three Baltic DSOs: Elektrilevi OÜ of Estonia, AS Sadales tīkls of Latvia and Ignitis Group of Lithuania. The study was conducted during autumn 2021 and winter of 2021/2022.

The study was carried out in the form of an interview with Elektrilevi OÜ and in the form of e-mail exchange with AS Sadales tīkls and Ignitis Group. The interviewees of Elektrilevi OÜ were the Head of Market Relations and the Head of Technology. The method of the interview was semi-structured, where the discussed topics were known to the interviewees beforehand, and the interview results were followed up with internal discussions and manifested in a structured and reviewed interview protocol document. The interview was carried out in the national language to avoid miscommunication regarding legal and technical terms. The e-mail survey was composed of eight questions, some of which were complemented by one to three follow-up questions (a total of 20 individual questions). The communication with AS Sadales tīkls was relayed through Riga Technical University, who also provided relevant translations of their responses. The communication with Ignitis Group was conducted with their Head of Innovation and carried out in English.

The study focused mainly on two aspects regarding behind the metre energy storage systems: regulatory and technical. A summary of the DSO responses is provided in Table 7. All Baltic DSOs stated that they are not allowed to own or operate ESSs, which will change when the current EMA amendment draft enters into force. The EMA draft amendment states that grid operators can own, develop, manage, and operate ESSs when they are considered as fully integrated grid components, or they are required to enable efficient, reliable, and safe operation of the grid and not used for buying or selling electricity. The aim is to clearly separate grid operations form other processes involving ESSs, which is a similar approach as used for distributed generation. The described approach emphasises the involvement of private capital, rather than relying on strategic National investments for the large-scale integration of ESSs into the power grid.

All DSOs stated that they are currently unable to procure ancillary grid services. The reasons for this are limitations in regulations and the lack of service providers. However, the Lithuanian DSO has indicated that they are currently working towards a set of flexibility procurement rules, while the Estonian DSO has suggested that they support an exception to the grid tariff structure, where such ESS that are used to provide ancillary grid services are excluded from (some) tariffs. Matters become complicated when the purpose of the ESSs is not fixed to either energy management or network services, for example, mixed generation, load and storage assets

TABLE 6 List of countries who accept ancillary services (mainly frequency related) amongst other assets also from batteries.

	Frequency containment reserve		Frequency restoration reserve (automatic)		Frequency restoration reserve (manual)		Replacement reserve	
	Capacity	Energy	Capacity	Energy	Capacity	Energy	Capacity	Energy
All possible options	Belgium, France, Germany, Netherlands, Switzerland	France	Belgium, France, Germany, Netherlands, Switzerland, Slovenia	Belgium, France, Germany, Netherlands, Switzerland, Slovenia	Belgium, France, Germany, Netherlands, Switzerland, Slovenia	Belgium, Estonia, France, Germany, Italy, Netherlands, Switzerland, Slovenia	France, Switzerland	France, Italy. Switzerland
Generators + batteries	Austria, Czech Republic, Hungary	–	–	–	–	–	–	–
Generators + demand-side response + batteries	Denmark, Sweden, Finland	Sweden	Czech Republic	Czech Republic	–	–	–	–
Generators + demand-side response + pump storage + batteries	Ireland, Northern-Ireland	Ireland, Northern-Ireland	–	–	Czech Republic, Ireland, Northern-Ireland	Czech Republic, Ireland, Northern-Ireland	Ireland, Northern-Ireland	Czech Republic, Ireland, Northern-Ireland
Generators + batteries + distributed generation	–	–	Hungary	Hungary	Hungary	Hungary	–	–

TABLE 7 Summary of survey results carried out among Baltic DSOs.

Category	Estonia	Latvia	Lithuania
DSOs and ESS ownership	The EMA amendment draft states that grid operators can own, develop, manage, and operate ESSs when they are considered as fully integrated grid components, or necessary to enable efficient, reliable, and safe operation of the grid and not used for buying or selling electricity	Existing legislation prohibits DSO to operate and maintain EES for their own needs. A draft EMA amendment provides DSOs the possibility to own and operate ESS with permission of the regulating body.	Current legislation prohibits DSOs to own, develop, or operate energy storage facilities. There is an exception, which allows for DSOs to own ESSs in cases where they can be considered as an integrated grid component.
Grid connection requirements for ESSs	When a storage unit is behind a single inverter, the technical specifications are solved through manufacturer requirements. Most technical aspects regarding ESS integration to the grid are derived from the requirements identified for generators.	Current connection regulations of the Public Utilities Commission (PUC) do not separate or stipulate the connection process of EESs from producers and consumers. It is considered that since EESs are inverter-based generation units, the connection requirements must be similar to (micro)generation units. Therefore, the EES connection process depends on generation capacity.	ESSs are treated as generators and their functionality and protection requirements are same as for PV systems. The connection of ESSs is handled case-by-case. The technical connection conditions should include capacity (consumption and generation), while relevant technical characteristics of should meet generator grid code requirements (e.g., frequency and voltage protection, ramp rates, remote control, reactive power support etc.)
Grid tariffs for stored energy	Although network charges do not apply for produced energy, there is a separate statement in the draft EMA amendment regarding stored energy: no network charge is applied when returning stored energy to the network. This clause is aligned with the current situation, where distribution fees do not apply for generated electricity.	No special distribution tariff for ESS charging and discharging cycles and no actual plans to create such tariffs. The Latvian DSO supports the opinion that customers who offer the DSO services through ESSs must be proportionally remunerated for their services.	No special grid tariffs for providing energy to the grid from ESSs.
Perspective and planned changes in grid tariffs	The Estonian DSO suggests transitioning from mostly energy-based network charges to more capacity-based network charges, resulting in a larger revenue base from grid availability.	The Latvian DSO states that it is exploring a new tariff structure. Due to the reduction in distributed electricity (due to increased distributed generation), it is likely that the new tariff structure will have the fixed (capacity) component with a higher weight than the variable (electricity) component.	The Lithuanian DSO indicates that there is an ongoing study aiming to provide regulatory guidelines, including recommendations for grid tariffs, for the regulating body.

installed behind the metre. Additionally, there is a consensus of vision among Baltic DSOs, where they see a transition from mostly energy-based network charges to more capacity-based network charges, resulting in a larger revenue base from grid availability.

In terms of technical aspects, the integration process of ESSs into the power grid is currently analogous to electricity producers. Most technical aspects regarding ESS integration to the grid are derived from the requirements identified for generators. Although it is a resource efficient approach, it is recommended to state separate technical procedures and requirements for the integration of ESSs into the larger grid to account for the full extent of their flexibility. Additionally, the Estonian DSO recognises that it is possible that there are less sophisticated solutions currently connected to the grid that the DSO is unaware of and that for the differentiation of ESSs, they propose four options, which are based on:

a) capacity – similar to classifying (distributed) generators;
b) purpose – identify the use of the ESS, for example, strictly for influencing behind-the metre assets, energy trading, provision of network services, etc.;
c) control – which control functions are required from the perspective of the grid and the device;
d) dimensioning of protection equipment – what is the size of the necessary relay protection equipment required by the ESS.

5 | CONCLUSION

With the rapid development of technology, union policies with incentives, and a corresponding decrease of low carbon technology prices, more consumers connect PVs, BESSs, and EVs to the low voltage distribution grids. With the required infrastructure for public EV charging and demand-side management activities, the challenges for the system operators increase. The stochastic nature of the weather-impacted generation and new stochastic loads (e.g., EV charging) introduces challenges in voltage control and power quality assurance. The distribution grid needs to cope with bidirectional power flows and possibly amplified issues related to poor power quality caused by the scheduling of stochastic (and possibly non-linear) loads. Although PV systems can help mitigate some voltage magnitude and unbalance issues, the untimely scheduling of non-linear loads can cancel those effects. Grid stability can be affected by the large-scale utilisation of renewable energy sources because there are fluctuations in generation and load. These issues can be effectively addressed by grid-scale battery energy storage systems (BESS), which can respond quickly and provide high energy density which were thoroughly discussed in this paper.

Despite the fact that Battery Energy Storage Systems (BESS) offer effective solutions for managing power quality issues in the grid, their operation can also introduce harmonics. This incident occurs as a result of BESS' connection to the grid through inverters using Pulse Width Modulation (PWM). While BESS can reduce voltage fluctuations and improve power factor, PWM-based inverters can inadvertently generate harmonics, which can negatively affect grid power quality. Therefore, harmonic mitigation strategies must be carefully considered to minimise adverse effects when integrating BESS.

A case study was carries out in to analyse impacts of grid scale BESS on the Baltic DSOs and possible requirements to change their grid code. To summarise the survey case study results, the following conclusions can be drawn.

- Baltic DSOs will have the possibility to own and operate ESSs in case they can be considered as fully integrated grid components.
- Currently, there are no dedicated requirements for connecting ESSs to the grid and requirements for generators are commonly applied.
- Currently, there is no standard procedure for connecting ESSs to the grid and they are handled case-by-case, but procedures similar to connecting PV inverters to the grid are envisaged by the DSOs for the future.
- No special tariff or exemption is neither applied nor planned by the Baltic DSOs for stored energy.
- All DSOs have shown interest in using ESSs for grid services and the procurement of such services from respective service providers. As grid services are not supported by current legislation, the specific application of such mechanisms remains to be determined.
- It is deemed likely that current grid tariffs in the Baltic States are subject to change, mainly to adjust to the decrease in distributed energy and increase in distributed generation.

AUTHOR CONTRIBUTIONS

Freddy Plaum: Data curation; investigation. **Tobias Haring**: Formal analysis; investigation. **Imre Drovtar**: Investigation; methodology. **Tarmo Korotko**: Formal analysis; funding acquisition. **Argo Rosin**: Data curation; investigation.

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The authors declare no conflicts of interest.

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No sensitive data used.

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