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An international review of the implications of regulatory and electricity market structures on the emergence of grid scale electricity storage

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ABSTRACT

Energy storage systems (ESS) have the potential to make a significant contribution to planning and operation practises in power systems. While ESS can be used to provide multiple benefits in the power sector, widespread use has been restricted by high technology costs, lack of deployment experience, and the barriers and uncertainties caused by the present electricity market and regulatory structures that were designed for conventional electricity systems. This paper reviews countries with high renewable targets and with significant current or planned ESS deployments to ascertain the common problems affecting the use of ESS on the grid, and to establish where changes have been made or proposed to the electricity market and regulatory frameworks. Three major problems were identified as the undetermined asset class for ESS and unbundled electricity system limiting stakeholders from determining and realising multiple ESS benefits; low electricity market liquidity and changing market conditions; and a lack of common standards and procedures for evaluating, connecting, operating and maintaining ESS. Based on the established barriers, recommendations to update or create policies, regulation and market arrangements to increase the viability and wider use of grid level ESS are discussed. The three key regulatory and policy recommendations were identified as an alignment of renewable policies to that of ESS; creating a separate asset class for ESS and associated rules for regulated and competitive operations; and standardising assessment frameworks, connection and operational procedures for the use of ESS. Finally, three main electricity market recommendations include updating rules to support simultaneous ESS operation across wholesale, ancillary services and capacity markets; updating market rules to allow compensation for flexible and highly accurate responsive demand and generation technologies, such as ESS; and updating market ancillary services energy requirements.

Contents

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1. Introduction

1.1. The evolving power sector

Electricity is crucial to the development, progress, security and overall lifestyle in the global economy. Industrialisation led to the construction of large power plants in central strategic locations to generate and supply power through transmission and distribution networks (T&D) to consumers [1]. Globally there is at present a great reliance on these large fossil fuel or nuclear power plants to provide electricity needs [2]. The global power sector is facing or anticipating changes brought about by factors which include a growth in electricity demand; ageing electricity infrastructure; increase in the adoption of variable and flexible low carbon technologies (such as wind energy, solar photovoltaics, heat pumps and electric vehicles) and the need to integrate such schemes to the grid in moves towards decarbonisation [3]. Natural disasters have also influenced changes in some countries. For example, the Fukushima disaster in 2011 led to radical energy policy changes beyond Japan, where in Germany the government announced plans to phase out nuclear power completely between 2011 and 2022, and concurrently increase renewable energy source (RES) penetration [4].

Heightened concerns to reduce greenhouse gas (GHG) emissions, while improving security of supply, affordability and reliability has led countries globally to work towards developing a decarbonised power sector with smart grid infrastructure [3]. In Europe, there are plans to reduce emissions across the whole economy from 80% to 95% by 2050 compared to the levels in 1990 [5]. This target is expected to be achieved by increasing the electrification of energy intensive sectors and reducing the amount of coal power plants, with the decommissioned plants being replaced by variable RES, such as solar photovoltaics (PV) and wind turbines. An illustration of the growth in renewable energy sources for electricity (RES-E) for the European Union 27 (EU-27) member countries is shown in Fig. 1.

1.2. The effects of grid decarbonisation

The implementation of unconventional and decentralised generation technologies can provide technical, economic and environmental benefits to the power system, such as, loss reduction, improved system reliability and security, improved voltage profile, network upgrade deferral, reduced GHG emissions, reduced cost of fuel, and reduced T&D congestion [7,8]. But if not properly planned and managed, RES integration can also lead to negative secondary effects, both technical and economic that can affect the utilisation and performance of generation, T&D networks, and the electricity markets. Issues which include, bi-directional power flow at high voltage levels; unpredictable generation patterns and high daily peak demand due to increased low carbon technologies (LCT), such as solar PV and heat pumps; power system stability and power quality issues; voltage excursions; system stability and other factors discussed in [8–12] could arise. Of particular interest is the issue of balancing demand and supply caused by high levels of variable generation from RES. This can lead to both increased volatility of wholesale electricity prices and negative wholesale prices. For example, the latter situation occurred in Western Europe in 2012 as high wind power generation during mild weather conditions in the winter led to negative wholesale electricity prices lasting for hours in some Western European

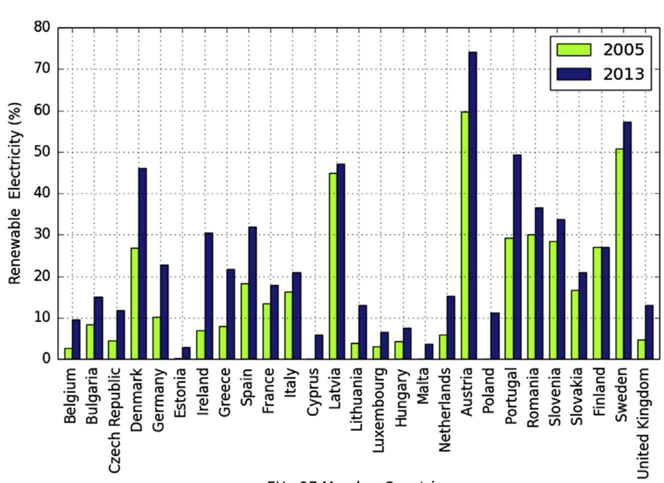

Fig. 1. Installed renewable electricity capacity for EU countries in 2005 and 2013. *Source*: [6].

countries [13,14].[1] Furthermore, there is the growing requirement to commission more flexible and back-up generation to balance the stochastic fluctuations resulting from increased RES. Contrarily, increased RES on the grid leads to a reduction in the hours of operation and resulting profitability of flexible and back-up generation [15]. In the distribution networks, significant changes are happening closer to the load centres due to increase in LCTs, energy efficiency, demand response (DR)[2] (meaning reducing energy consumption and shifting energy consumption respectively) and ESS are all key solutions that could be used in enabling LCTs. To minimise difficulties and make the most of the technical, economic and environmental benefits that can be provided by increases in RES and demand LCTs, it is likely that a combination of solutions such as flexible generation, DR, energy efficiency, ESS, and interconnections will need to be implemented [16]. Additionally, the present regulatory and market structures that were developed for traditional power systems will need to be updated in the years ahead.

1.3. Energy storage research landscape

Governments, utilities, regulators and other electricity stakeholders are all interested in the role of ESS in providing solutions in future evolving power systems due to its versatility in providing power and energy capacity.[3] As policies, electricity market and regulatory frameworks are constantly evolving, so is ESS, which is at its infancy but is expected to mature in the years ahead. It is estimated that the global demand for ESS will be £72 billion by 2017 [17], and in the UK for example, bulk ESS has been projected to provide annual benefits of £120 million by 2020, £2 billion by 2030, and over £10 billion by 2050 to integrate LCTs to the grid (with similar achievable benefits for distributed ESS) [16]. The investment potential in the UK can be applicable to power sectors in numerous countries facing similar issues.

Nevertheless, the unconventional operation and different functions of ESS complicates its operation under the current regulatory and market structures. This is because it is unique in its characteristics of providing generation and demand services and due to its flexibility, it can be used to provide various technical and commercial benefits to generators, network operators, energy suppliers, and consumers as summarised in Table 3.

Consequently, substantial research and evaluation has been completed or is being carried out globally to establish the feasibility of utilising ESS in future power systems. This includes key studies from the UK which assesses the role and value of ESS in the UK's low carbon energy future [16], and EPRI [18] which discusses the prospective breadth of values and applications for ESS in the US. However, while ESS is being considered as one of the possible solutions to grid and RES problems, there are also reservations. A study by Fürsch et al. argues that grid extensions are essential and preferred investments to ESS in a way forward for the European Union (EU) to achieve its targets for RES-E and GHG reductions [19]. Taylor et al. investigate the pathways for storage in the UK (with recommended institutional changes) via a coevolutionary framework and emphasise the risks policy makers and regulators will face if they develop strategies for ESS based on present market conditions [20]. Grünewald et al. discusses the uncertainties which negatively affect the uptake of large scale ESS in the UK [21]. Rangoni et al. look at the regulatory and market

[1] Countries affected were Germany, Denmark, France, Belgium, and the Netherlands.

[2] Demand side response and demand response are used interchangeably in this paper.

[3] Natural gas storage and thermal storage are beyond the scope of this paper, although the authors recognise their importance in the evolving power sector.

issues with using pumped hydro storage (PHS) for ancillary services in Italy and Spain [22], while Wasowicz et al. [23] and Pomper [24] examine general regulatory and market issues with using ESS in Germany and the US respectively. Bhatnagar et al. discusses the issues affecting utility owned ESS in the US [25], and the EU report by Vasconcelos et al. [26] discusses the experience of using ESS in the EU in contrast with the US and Japan, and the market design and regulatory barriers in the EU. Nekrassov et al. [27] and Krajačić et al. [28] evaluate how support mechanisms can promote the use of ESS much like renewables and the need to coordinate energy policy for ESS.

While an in depth analysis of the electricity markets and regulatory structures is beyond the scope of this review, this paper goes a step further from prior research in this area by investigating the underlying policy, regulatory and electricity market design issues limiting the use of ESS across the electricity system globally. This research is carried across a group of countries with high RES targets, substantial ESS deployments and/or with future plans for ESS deployments. Japan, United States (US), Spain, and Germany, and China were reviewed because of their significant contribution to the total worldwide installed capacity of ESS recorded as of 2013 [17,29]. The Electricity Advisory Committee report identifies the US, China, Japan, Germany, and the UK as top demand markets for grid scale ESS, expected to cover over two-thirds of the market by 2017 [17]. Other countries reviewed are Italy, where 463% growth in solar PV was recorded between 2010 and 2011; Brazil, where hydropower contributed up to 90% of electricity generated in 2011; Australia where there is an ambitious RES-E target of 20% by 2020; Norway and Denmark where a symbiotic relationship has been created with Norway providing storage using its hydropower capacity for some of the excess wind energy from Denmark [30–32]. Following this, the common problems that affect grid scale ESS implementation are deduced and recommendations are made for the required policy, regulatory and electricity market design changes that would support the feasibility of using ESS in an unbundled electricity system with a competitive electricity market.

Section 2 provides a background on regulation of the electricity system and on the electricity markets. In Section 3, the types of ESS, their benefits across the power system, the statistics on worldwide deployment, and ESS business models for different stakeholders are discussed. Section 4 examines the policies, regulatory and market structures in the countries selected along with the changes that are being implemented or considered and Section 5 discusses the common barriers affecting ESS use and viability with the three key regulatory and electricity market barriers being:

- Unbundled electricity systems that lead to a lack of transparency in generation, supply and network activities. This affects assessing the full value of ESS across the electricity system. Moreover, the prevention of regulated monopolies from participating in the electricity market prevents T&D network operators from owning ESS that can influence the electricity market. This further limits avenues to recover the high investment cost in ESS competitively;
- Undetermined asset classification of ESS as it functions as generation and demand. Thus rules applicable to both functions applied individually to ESS will affect its viability;
- Difficulty in assessing value in the electricity markets due to the vertically integrated behaviour of supply and generation utilities affecting electricity market liquidity, and changing market conditions affected by external world events (such as natural disasters), changing policies, economics and operational factors. There is a lack of common standards and practices for new ESS technologies as a result of limited deployment experience.

Finally, Section 6 considers the reviewed policy, regulatory and electricity market updates that have been applied to provide recommendations on the changes that should be considered to enable wider ESS adoption in deregulated and unbundled power sectors. The three major policy and regulatory recommendations, and three electricity market recommendations are shown in Table 1.

2. Background on regulation and electricity markets

2.1. Regulation

In order to increase competitiveness, provide higher quality services to consumers and drive down costs in the power sector, the concept of deregulation was introduced for generation and supply functions [33]. In a restructured and deregulated electricity system, generation and supply functions are generally classed as competitive while the T&D networks are regarded as natural monopolies and are regulated [34]. Over the past 30 years, deregulation was introduced into the power sector starting with Chile in 1982 followed by England and Wales, and Norway in 1990 [35]. Unbundling brought about by liberalisation of the electricity sector offers a method of separating the activities of generation and supply from that of the national monopolies (T&D) and it facilitates regulation and control of the electricity sector. Regulation is necessary to curb organisational exploitation that could result from monopoly due to lack of competition for service provision and is employed in most countries to safeguard customers and other electricity stakeholders. Regulation is used as a tool to drive down the cost of electricity and ensure a low electricity tariff for customers, provide a return on investment for electricity network stakeholders involved with T&D, and provide incentives to T&D companies to improve both network and operating efficiencies to the benefit of customers.

Unbundling is considered a major step in the move towards developing a competitive electricity market [36]. Unbundling is a requirement in the EU as member countries have to follow the European directive 2003/54/EG, which states that grid utility ownership and operation must be regulated and separated from electricity supply utilities who can participate in the electricity market [37]. The deregulation of the power sector is increasing globally [38]. However, not all power sectors in developed

Table 1
Policy, regulatory and electricity market recommendations.

Policy and regulatory	Electricity market
Creating of a new asset class and set of associated rules for ESS used as a network asset or in the electricity markets.	Rules enabling the seamless simultaneous operation of ESS that is capable of providing serves in the wholesale, balancing and ancillary services, and capacity markets.
Standardising assessment frameworks, and connection and operational procedures for using ESS on the grid.	Creating adequate compensation measures in the ancillary services market for the accuracy, high ramp rates and responsiveness of ESS.
Alignment of ESS policies with that of RES, which should include incentivising RES owners to provide dispatchable energy.	Updating ancillary services market requirements to consider expensive ESS technologies that can provide system benefits but at a smaller bid size and shorter energy delivery duration.

countries are deregulated and unbundled, for example, in the US only 16 states and Washington, DC have completely deregulated utilities while states such as Florida are vertically integrated [39].

2.2. Electricity markets

Wholesale electricity markets usually operate as a centralised market (power pool) or decentralised market (bilateral contracts) [40]. The markets in a liberalised electricity system are futures, spot (day ahead and intra-day), balancing, ancillary services, and retail. In the wholesale forward market, short term contracts are carried out in the spot market (day-ahead and intra-day markets) and long term contracts are made in the futures market, which covers trades for a week up to a year. To maintain grid frequency and system stability, supply and demand has to be constantly balanced in real time due to the lack of storage capacity in power systems. System balancing is carried out via the balancing and ancillary services market to account for shortfalls in the spot market.

Liberalised markets have electricity prices with higher volatility due to the absence of regulation and reliance on competition [41]. Volatility increases because electricity market prices are determined by economic and operational factors, and in addition, supply and demand participants have a number of avenues for electricity trading [42]. Stan [43] discusses the impact of deregulation on increasing the volatility of electricity prices. Price cap regulation is used as a measure to reduce the impact of excessive volatility but this can have negative consequences as it leads to imprecise price signals which slows down market responses in short-term operation and affects long term investments [36].

The operation and structure of different electricity markets varies for different countries, some markets such as Germany's are liberalised, while others are partially liberalised, for example, China and most developing economies such as Brazil and India [44,45].

3. Energy storage and benefits on the grid

3.1. Energy storage types and benefits

The present power grid is expected to evolve towards a smart grid, which has the main aim of intelligently integrating the actions of all users, both generators and consumers to the grid in order to allow for a more sustainable, economic and efficient power system [46]. ESS can be regarded as a complementary tool in the future smart grid [47]. ESS stores electrical energy in different forms for later conversion into electricity. A variety of methods can be used to store (charge) and deliver (discharge) energy, allowing the ESS to serve as a load or generator. ESS technologies can be categorised into electrical, mechanical, chemical, electrochemical and thermal. The ESS technologies that have been tested or implemented globally are listed in Table 2. These technologies have different levels of maturity, applications and limitations discussed in [29,48].

The differences in properties and characteristics (such as power rating, energy capacity, discharge time, round trip efficiency) discussed in [48], make ESS more or less suitable for different applications. IEC [49] discusses the different technologies and applications with a detailed logarithmic chart illustrating the relationship with power output, energy capacity and discharge time for various ESS technologies. These parameters illustrate the applicability of ESS in high/low power or energy applications.

ESS can be used to resolve or alleviate the anticipated short and long term issues in power systems as discussed in [50]. The major applications, key stakeholders and resulting benefits of ESS implementation are described in Table 3, with ESS as a sole solution or in combination with other solutions such as DR, interconnections, peaking power plants, and conventional network upgrade or reinforcement. The viability of using ESS is determined by the technology cost and economics, regulations and policies in individual locations.

3.2. Worldwide implementation of energy storage

The implementation of ESS is relatively small but continuously growing with about 665 deployed projects recorded as of 2012 [17]. Worldwide ESS capacity shown in Fig. 2 was estimated at 152 GW (including projects announced, funded, under construction, and deployed), of which 99% is attributed to PHS and the remaining installations are new non-traditional ESS (such as batteries and flywheels) [17]. Fig. 2 illustrates a breakdown of worldwide storage capacity by region, which includes batteries, CAES, PHS, thermal energy storage, and flywheels.

3.3. Business models for using energy storage

A major issue affecting the wider implementation of ESS is the higher costs they add to the already expensive T&D networks or RES deployments, which often renders them uneconomical if used for a single application when compared against alternative conventional solutions. Thus, developing a viable business model for the provision of multiple functions is important for the success of ESS. The business models that could be applied for ESS depends on the target services required and the location on the grid [26]. It also depends on the market and regulatory structures which affects access to revenue streams and determines the ownership structure. Ponsot-Jacquin et al. discuss the impact of regulatory frameworks on successful business models for ESS [55]. Presently, viable business models to realise the multiple benefits of implementing ESS on the grid do not exist as they are challenging to implement. Island power systems have to be considered differently [55]. This deters investment in ESS and stalls development of ESS technologies.

In an unbundled power sector, ESS could be used (if regulation permits) for competitive (deregulated) services in the wholesale

Table 2
Energy storage technology types.

Storage technology	Technology type
Electrical	Superconducting Magnetic Energy Storage (SMES); Double-layer capacitors (DLC) or Super capacitor energy storage (SES)
Mechanical	Pumped hydro storage (PHS); Flywheel energy storage (FES); Compressed Air Energy Storage (CAES)
Electrochemical	Batteries (e.g., Lead-acid, Lithium-ion, Sodium–sulphur, Nickel–cadmium, Sodium–nickel-chloride (Zebra)); Flow batteries (e.g., Vanadium Redox, Zinc–bromine, Polysulphide Bromine)
Chemical	Hydrogen (H_2); Synthetic Natural Gas (SNG)
Thermal	Sensible heat technology (e.g. water, synthetic oils, concrete); Latent heat technology (e.g. liquid air, molten salt)

Table 3
Applications and benefits of energy storage on the grid [18,52–54].

Application	Stakeholder involved	Description	Benefit
Blackstart	Transmission and distribution	Set and control voltage and frequency in a power system during periods of partial or total T&D system shutdown.	Enable start-up of disconnected systems to allow reconnection back to the grid or for islanded operation. Thus improving reliability.
Power quality and harmonics	Transmission and distribution	Manage and reduce levels of harmonics by actively controlling the injection of current to the grid.	Provide power quality management to reduce or resolve issues such as harmonics, transients, voltage sags, swells, and flicker.
Reserves (spinning or non-spinning)	Transmission and generator	Manage system events on the grid by dispatching ESS in sub-hourly time periods.	Substitute the need for generators that provide this service.
Governor/inertial response	Transmission and generator	Provide governor/inertial response provided by synchronous generators during changes in system frequency.	Decrease the impact of the risks that may occur as a result of frequency excursions caused by system disturbances.
Voltage regulation	Transmission and distribution	Regulate voltage on the grid by sourcing or sinking reactive power.	Substitute or reduce the need for equipment replacement, and network upgrade or reinforcement to manage voltage and reactive power.
Frequency regulation	Transmission and generator	Manage imbalances on grid (load, generation, tie line power exchange) by sourcing or sinking power from the grid to stabilise frequency.	Substitute the need for slower or more expensive generation facilities providing frequency regulation.
Renewables smoothing dispatch and integration	Generator, transmission and distribution	Managing ramp rate and dispatchability of RES plants to reduce unpredictability of power generation.	Reduce volatility of spot market prices. Reduce levels of reserves (spinning/non-spinning) and frequency regulation required. Improve asset utilisation of RES, evening out fluctuations. Provide RES providers with flexible alternatives for participating in the electricity market.
Capacity management	Transmission and distribution	Power flow management through lines, cables, transformers and other network equipment.	Upgrade deferral of new lines, cables and substation equipment. Asset lifetime extension.
Increased asset utilisation and reduced losses by load levelling	Generator, transmission, distribution	Charging of ESS during off-peak periods (both centralised generation and RES) for discharge during peak periods.	T&D networks are designed to handle the maximum possible peak demand, even if this occurs for a few seconds. Therefore for the bulk part of operation of networks, there is underutilisation of generation and networks, which have a utilisation rate of 50% or less. ESS can increase the utilisation of RES and centralised generators. For the latter, due to lower night time temperatures, the generators used to charge ESS will operate more at night when fuel efficiency is higher and emissions output is lower. In addition, because energy to charge the ESS is transmitted at night when ambient temperatures, and transmission and distribution (T&D) loading are relatively low, T&D energy losses are reduced relative to those that would be incurred if the energy was delivered during the day.
Peak shaving/energy arbitrage	Transmission, distribution, generator	Capture energy during off-peak periods and sell during peak periods to reduce peak power requirements and the need for higher cost energy.	ESS can be used to increase the efficacy of the future electricity network by balancing supply and demand through charging ESS during off-peak periods and discharging during peak periods daily. Hence, the effective use of ESS would reduce the need for expensive peaking generation plants (e.g. gas fired combined cycle and gas turbine) which are run for short durations to provide capacity for excess electricity demand during peak times. It could also provide peak shaving for T&D network operators thereby leading to a deferral in T&D network upgrade.

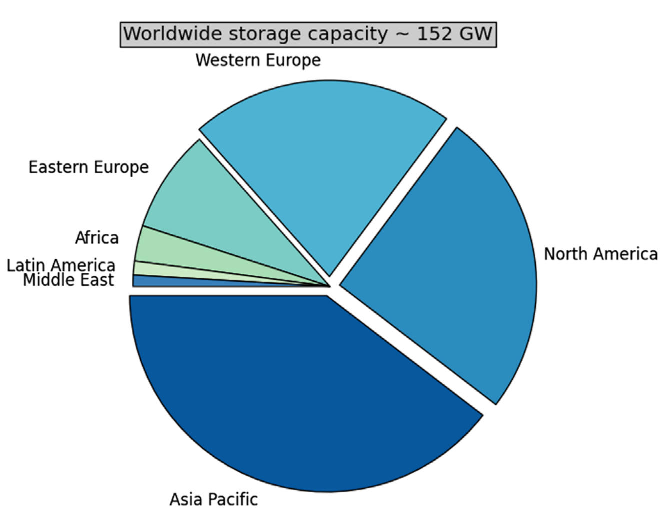

Fig. 2. Worldwide energy storage capacity by region, *Source*: [17,51].

energy market (day-ahead and intra-day), balancing and ancillary services markets, and capacity markets to maximise value across the electricity value chain. According to Pomper [24], ESS owners and providers can be categorised into six types as presented in Table 4. The ownership types, regulatory frameworks and location of the ESS would influence the business model, which can either be regulated and/or competitive. Additionally, the regulation in place would determine the owner of the energy absorbed or injected into the grid from the ESS. In essence, the energy stored in the ESS could be owned by the ESS owner or by other stakeholders on the grid.

ESS used under the regulated business model would provide a guaranteed revenue source as this would be fixed based on contractual terms for services provided or if owned by a regulated network operator, would lead to a guaranteed cost recovery. This guaranteed source of income makes value quantification easier. The extra energy capacity left from providing regulated services can be used for competitive schemes in the energy market if permitted by regulation. However, as the control and priority over use of the ESS for regulated services on the T&D network

Table 4
ESS ownership types [24,26].

Owner type	Description	Revenue stream
Merchant providers	RES and non-conventional generation providers or ESS owners who provide storage services based on market prices or power purchase agreements to different customers.	Use ESS for competitive operations. Services provided based on market prices to different customers.
Transmission system operators	Owners and operators of transmission infrastructure. They may provide transmission only services (regional transmission operators in the US) and/or transmission services and market based services (national grid in the UK).	Use ESS to assist and improve transmission services with costs recovered based on regulatory conditions. Depending on regulation, they may or may not be able to use ESS to provide services in the electricity market.
Distribution system operators	Owners and operators of distribution network infrastructure.	Use ESS to assist and improve distribution services with costs recovered based on regulatory conditions. Also depending on regulation, they may or may not be allowed to provide services in the electricity market.
Customer group	Electricity suppliers or ESS providers who use a collection of end-user ESS (via contractual arrangements) to provide cost savings to customers, and for grid/market related services.	Utilise aggregated ESS from customers or other stakeholders to provide electricity market services or regulated services to T&D network operators.
Contract storage operators	Third parties that only lease ESS services to generators, T&D operators, suppliers or consumers. They do not control the operation and its use on the grid. Operates is carried out based on the clients instruction.	Provide ESS facilities based on instructions from clients for regulated or competitive services with revenues derived from contract agreement.

is relinquished to the regulated party during the contract period, the availability for competitive use by the owner would not be assured.

Conversely, the deregulated or competitive business model can be used to participate competitively in the electricity markets and can additionally be used to provide regulated services without major interference [24,26]. But the downside of this model is the uncertainty of revenue streams due to economic uncertainties that affect electricity market prices. Vasconcelos et al. discuss the impact of economics, regulation and policies on electricity price spread [26]. The resulting price evolution caused by changing price spreads, further compounded by the growth in RES, will affect the price of ESS services in the electricity market and this will lead to issues with quantifying values for investors. Other problems that may result from this model are the difficulties in calculating ESS value due to complexities in the mixture of regulated and deregulated income streams. Furthermore, difficulties may arise in realising the value of the remaining ESS capacity to earn money via a regulated stream due to energy capacity limitations.

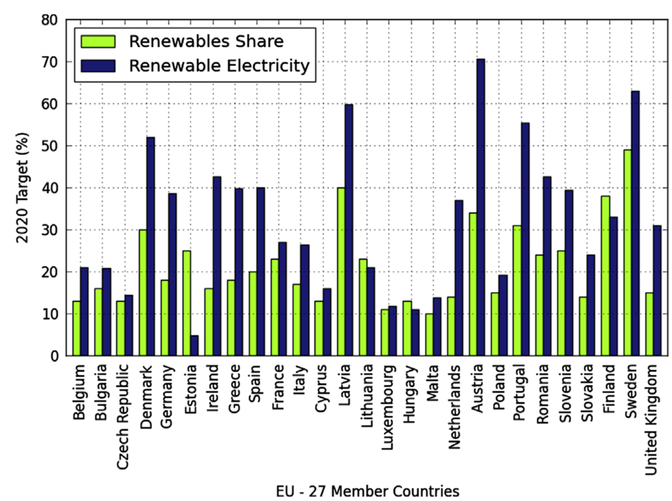

Fig. 3. 2020 Renewables targets for EU countries showing both shares for all energy and only electricity.
Source: [6].

4. Review of policies, regulation and electricity market arrangements supporting storage

4.1. European perspective

ESS investment in Europe covers over 20% of the ESS market worldwide [17,51,55]. The European Commission (EC) developed a strategy energy technology Plan (SET-Plan) for developing and implementing an EU energy technology policy for the transition to a low carbon economy [53]. The aim of the SET-Plan is to change the EC's approach towards investing in research, development and demonstration (RD&D) activities for a low carbon economy and it includes materials for ESS [53,56]. The roadmap identified insufficient performance of ESS technology and high costs as the main issues affecting ESS deployment. It highlights the maturing of ESS technologies and subsequent mass commercialisation as the main priority to widen the use of ESS [56]. Finally, the roadmap emphasises increasing research and demonstration activities to meet technical performance objectives related to ESS materials and the overall costs.

In the European legislatives for the internal market for electricity there is no reference to the use of ESS to provide system flexibility and security of supply [57]. This can be attributed to the yet developing landscape of ESS technologies with high energy capacity, except PHS which has been widely used in the electricity system with implementations dating back to the 1960s in Italy and the UK. As a result, PHS is grouped alongside other traditional generation technologies in the present regulatory frameworks, which disregards the flexibility options it can provide [22]. In contrast, legislation for the internal market for natural gas includes gas storage [58]. Gas storage is necessary because of the price volatility of gas in international markets and the high demand peaks, in such situations, gas storage is used as a physical hedge [59]. Similarly, electricity storage will become increasingly important as the electricity markets become more volatile due to increasing deployments of RES and varying prices of fossil fuels for electricity generation.

In the National Renewable Energy Action Plans (NREAPS) published by member states of the EU, targets were set by most EU-27 countries to increase PHS installed capacity by 40% between 2010 and 2020. In addition, in the environmental legislation, Directive 2009/28/EC clearly mentions the use of ESS in future electricity networks to support RES integration in T&D networks [60]. The inclusion of ESS is to help in meeting the high renewables targets by 2020, illustrated in Fig. 3. Further on in Article 16 of Directive 2009/28/EC, strong support is provided by the following statement "*Member States shall take appropriate steps to develop transmission and distribution grid infrastructure, intelligent networks,* storage facilities *and the electricity system, in order to allow the secure operation of the electricity system as it accommodates the further development of electricity production from renewable energy* *sources[…]"*. But generally, there are no established plans for storage capacity from non-traditional ESS [6,61].

The requirements for legal unbundling based on EU Directive 2009/72/EC prevents T&D network operators from controlling power generation and supply, to prevent anti-competitive behaviours in the electricity market. This prevents the network operators from investing in ESS as a network asset [62]. The European network of transmission system operators for electricity (ENTSO-E) draft network code on requirements for grid connection and demand connection code defines ESS generating electricity as a *Generation Unit* and ESS consuming electricity as a *Demand Unit* but exempts PHS plants that generate and store electricity [63,64]. This prevents investment by Transmission System Operators (TSOs) and Distribution System Operators (DSOs) in ESS assets. Therefore, TSOs and DSOs who require ESS services the most are impeded from being key players in advancing and implementing the use of ESS on the grid. On the other hand, ESS can be used by generators or suppliers for grid support and competitive services [65].

There is currently no market framework or regulation supporting investment in ESS and there is a general lack of harmonisation on policies for ESS. Other notable challenges are:

- Lack of a common European electricity market and balancing market which will affect the use of ESS across EU countries due to different market rules that prevents the beneficial interaction between markets [66];
- Capacity mechanisms are considered in most EU member states for peaking power plants and not for other flexible forms of generation like ESS [67];
- From article 16 of the Directive 2009/72/EC, priority is given to renewable generators regardless of their effect on the grid and electricity market. Hence compensation has to be provided to RES owners for curtailing renewables to reduce bottlenecks on the network and the need for network upgrade or reinforcement. Events of huge compensation paid by TSOs to RES owners to curtail excess energy have been recorded in the UK and Germany [68].
- RES-E providers are paid using generation based price driven incentives (such as Feed in Tariffs and price premiums). These factors provide no incentive for RES-E providers to invest in ESS to provide dispatchable energy.

As discussed in [26], there is no agreed method to evaluate the regulated (grid support) services ESS can provide due to the limited transparency of pricing mechanisms and lack of data for the different services. This causes difficulties in calculating the value for different applications ESS provides, thus affecting use in a regulated business model. This effect does not apply to deregulated business models which rely on the energy, balancing and ancillary services markets. Vasconcelos et al. assert that inconsistencies in regulation of ESS in the EU could lead to competition problems and inadequate ESS resource distribution and allocation [26].

4.2. United Kingdom

The UK is considered a pioneer in the regulation of the electricity sector with the RPI$-X$ (retail price index minus efficiency savings) model implemented in a deregulated electricity system in 1990 [69]. The UK government has a 15% renewables target by 2020 and plans for the increased electrification of transportation and heating by 2030 [70]. Thus the government has identified ESS, interconnection and DR as crucial in enabling the UK to reach its targets for transforming the electricity system by the year 2050 [70].

4.2.1. Challenges

There are negative perceptions lingering from unsuccessful ESS projects in the UK, a pilot flow cell battery trial was launched in 2001 and was stopped in 2003 due to technical difficulties [71]. There is no clarity on the future role of ESS in the UK and consequently no specific regulation for ESS. There are no specific licence conditions for ownership and operation of ESS, which functions as a load or generator. At present, ESS is considered as a generator under licence conditions [66]. Therefore, as part of the licence agreement, the ownership of ESS by T&D network operators will be restricted to smaller storage devices with a maximum power capacity of 10 MW or up to 50 MW if the declared net capacity[4] is less than 100 MW [72]. However, this is subject to generation licence exemption approval by the government. A report by Taylor et al. [53] lists the limitations for using ESS in the UK for balancing and system reliability in the transmission network as high capital cost; low RES penetration; high grid charges (T&D) for ESS regardless of their contribution to improving network operation. Also, according to ERP [73], the spot market gate closure time is narrow and the T&D networks are currently robust enough, so at present the viability of using ESS is limited to small areas with specific issues in the UK. There is no incentive for investing in ESS as Renewable Obligation Certificates (ROCs) and Feed in Tariffs (FITs) reward renewable generators based on electricity output notwithstanding the impact they have on networks or the electricity market. They also have priority access to the grid [53].

In distribution networks where high amounts of distribution generation (DG) are anticipated, distribution network operators (DNOs) will need to curtail DG, upgrade or reinforce their networks to maintain quality and security of supply. At the same time, under the security of supply standards (ER P2/6), DG is considered to be a non-network solution that contributes to system security [74]. On the contrary ESS, which is generally considered as a possible solution to increase DG proliferation and improve quality and security of supply, is not recognised for its contribution to system security. Other challenges ESS faces in the UK are competition with other cheaper established fossil fuel based technologies, e.g. gas peaking power plants, for providing balancing and other ancillary services. In the electricity market, different contracts have to be agreed upon for the balancing and different ancillary services; this means ESS owners need multiple contractual agreements to derive maximum benefits [71]. There are also issues with long payback times when participating in the unpredictable electricity market. The two aforementioned factors complicate the evaluation by ESS owners and other stakeholders of the multiple benefits that can be provided. Baker et al. discusses the issues with bilateral trade agreements carried out by generation and supply businesses behaving like vertically integrated utilities that leads to reduced market liquidity [75]. This complicates participation in the wholesale energy market by large or small scale ESS owners. Moreover, as ESS is not considered an asset for network or system operators, they cannot recover the investment costs for ESS as a regulated asset if used on their networks.

The System Operator (National Grid) is responsible for balancing demand and supply, this limits DNOs who cannot actively manage the regional distribution networks or provide DR [76,77]. This can represent a conflict as LCTs go into the distribution networks and this is where distributed ESS could aid the uptake of LCTs by reducing network impacts.

Outside of regulation and electricity markets, challenges include the conservatism of power sector stakeholders and the

[4] Maximum power capacity of the installation after energy storage system efficiency losses and consumption of auxiliary components.

possibility of competition between the TSO, DNOs and suppliers when contracting for services provided by ESS to manage the grid [76].

4.2.2. Policies, regulation, electricity market changes and future plans

A capacity market with transitional arrangements for ESS and DR separate from generation technologies has been created to work alongside wholesale and balancing markets to ensure security of supply. It has been established that ESS can be involved in this market to provide capacity for system reliability with a fixed revenue stream [78].

The Office of Gas and Electricity Markets (Ofgem) who regulate the UK power sector has developed a new regulatory framework for network operators. The new framework called Revenue set with Incentives for delivering Innovation and Outputs (RIIO) has been introduced for T&D network operators with a strong emphasis on long term planning, increased flexibility, and innovation in a move towards a smart grid [79]. It is expected that the RIIO framework will foster the implementation of innovative solutions, such as ESS, to improve cost efficiency.

4.3. Other EU countries considered

4.3.1. Denmark and Norway

Electricity production is almost fully renewable in Norway with up to a 99% contribution from hydropower plants, varying year-to-year based on changes in precipitation [80]. Norway runs an open and integrated electricity market with other Nordic countries (Finland, Denmark, Sweden, Estonia and Norway) through the Nord Pool market (Nord Pool Spot AS), which is one of the most liquid wholesale electricity markets in Europe [81].[5] In Denmark, The Danish electricity market is made up of Eastern and Western markets which are both integrated into the Nord Pool. In order to improve energy security, the Danish government is moving towards a green growth economy and establishing electricity, heat and transport systems to be run on 100% renewable energy by 2050 [82]. ESS has been identified as a pivotal element in the Danish 2050 energy vision [83].

The hydroelectricity capabilities of Norway are used as storage for interconnected Scandinavian countries, Germany and the rest of continental Europe and Russia via the Nordic power exchange [84]. The relationship between the Norwegian and Danish electrical system is strong and this allows for the high amount of wind penetration in Denmark, with excess energy exported for storage in Norway [31,85]. However, this is limited by transmission constraints between both countries [86]. Hence, with their biggest challenge by 2020 being the storage and distribution of wind power, the Danish government has plans to further expand interconnections between Denmark and Germany, Norway and Sweden [87].

4.3.1.1. Challenges. The present regulation in Denmark treats ESS as load, hence ESS is liable to grid charges for load. In Norway, there are grid charges for PHS as load or generator with an additional charge for energy consumption during peak periods [66].

4.3.1.2. Policies, regulation, electricity market changes and future plans. There is no specific regulation or electricity market change for ESS in Norway and Denmark [66]. There are however future plans for using storage. In Norway, there are plans to use hydrogen for energy storage and for transportation, to reduce GHG emissions [88]. The Norwegian government plans to produce hydrogen via electrolysis using hydropower electricity (power to gas) for use locally or to export to other European countries [85,88]. In the Danish future plans, there is an indifference towards ESS technologies, but the approaches to using ESS that were considered for further investigation are [53]:

- Creating hydrogen gas from excess electricity from wind power generation and storing it using the nation's natural gas infrastructure for later distribution and use for electricity generation;
- Creating schemes for large scale district heating systems to store heat converted from surplus electricity by heat pumps.

4.3.2. Germany

Germany's electricity market is Europe's largest [89]. At present 20% of the gross electricity consumption is from RES with targets for 50% and 80% to come from RES by year 2030 and 2050 [23,90]. RES integration to the grid has resulted in generation curtailment and requirements for infrastructure upgrades, which has led the government to consider using ESS to meet its renewables targets [23]. ESS is considered to be a key component in the country's move towards a reliable, economically stable and efficient power system. Studies carried out by the German Energy Agency (DENA) on the changes required on the grid to allow for increased RES penetration concluded that under the current unbundled network arrangement and current technology costs, the expansion of the transmission network provides a better solution than the deployment of ESS [91]. DENA however recommended incentives to encourage ESS stakeholders to coordinate with grid operators to alleviate congestion on the transmission network and reduce total system costs [92]. DENA also determined that after 2020, ESS would be more affordable and useful in Germany for peak shaving, load following, power balancing and system flexibility applications.

4.3.2.1. Challenges. A report on European regulatory aspects for electricity storage [65] concluded that the lack of regulations, opportunities and mechanisms to support the competitive use of ESS is affecting the uptake of ESS in Germany. At present, PHS owners operating in the market have issues with finding the best split of ESS capacity for use in the spot and reserve markets based on market prices [26]. The present regulation treats existing PHS facilities as load, liable to pay grid charges [90,93]. There are challenges on how to develop and support the use of ESS by all power system stakeholders under current regulation. The strengthening and restructuring of the electricity market to quicken the adoption of ESS is seen as a major issue [90]. There are also no incentives in the market premium scheme for demand oriented dispatch of renewables [94], this limits the amount of investment directed to ESS.

4.3.2.2. Policies, regulation, electricity market changes and future plans. New PHS plants, expansions, and other ESS are exempted from grid tariffs for 20 years [90,93]. The Energy Act was updated to allow all ESS technologies to participate in the control energy (reserves) market [90,93]. ESS providing electricity from stored RES is exempt from electricity consumer taxes and grid system operators are obligated to remunerate participants who feed stored power from RES to the grid in line with mandated renewable energy tariffs [23,65].

In the short term, subsidies have been provided to support the development of ESS use in small to medium sized PV (up to 30 kW) connected to the grid [95]. These subsidies were provided because of the FiT scheme and decreasing solar panel prices. It is aimed at increasing the adoption and development of storage batteries in Germany which has the largest amount of PV with

[5] A liquid market is a market with many bids and offers, low spreads and volatility.

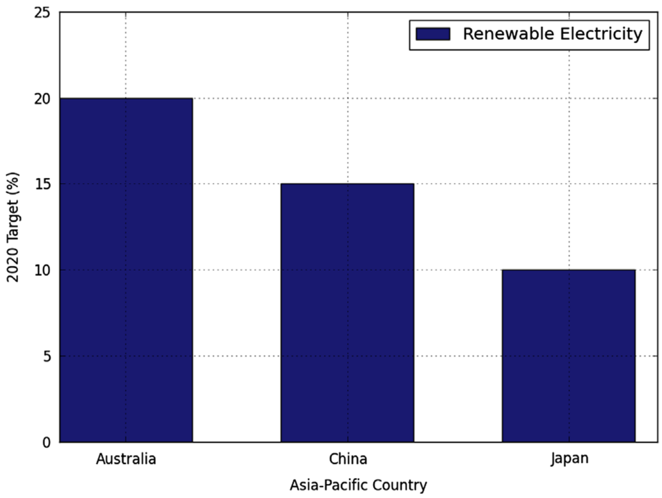

Fig. 4. RES-E 2020 percentage targets for energy consumption in Australia, China and Japan.
Source: [102]

residential storage in the world [96]. Incentives have been provided for biogas installations to integrate intermittent wind power to the grid [90]. In the medium to long term, the potential of PHS in Germany and coordinating use of other EU storage facilities is being explored [90].

4.3.3. Spain and Italy

Spain has RES targets of 20% by 2020 and in 2010, 13.8% of electricity consumed was provided by RES [97]. Italy on the other hand has a lower RES target of 17%, but it is one of the countries in the EU with a significant increase in RES within distribution networks [6,32]. There was a phenomenal growth of 463% in PV contribution to the grid in Italy in 2011 and in that year 28% of electricity was produced from RES [32].

4.3.3.1. Challenges. There is no specific regulation for ESS in Spain and legislative initiatives have been restricted to the Canary Islands where compensation is realised through regulated capacity and energy payments [22]. ESS use by TSOs is restricted to the canary Islands as regulation following the draft EC bill 2009/72/EC on the internal energy market limits the TSO Red Electrica de Espana (REE) from operating storage facilities except for pilot projects in the islands with a capacity equal to or lower than 5 MW [22]. A major challenge in Spain is recovering the investment cost for ESS, which comprises of mainly PHS. PHS is liable to grid charges for generation and demand while compensation for capacity is provided and guaranteed for the first 10 years of installation [22,66].[6] Rios et al. conclude from their study that greenfield PHS sites are unable to recover fixed costs solely from energy arbitrage in Spain [98].

4.3.3.2. Policies, regulation, electricity market changes and future plans. In Italy, the rapid increase in RES led to new legislative initiatives and proposals to be passed [22]. The Legislative Decree 28/11 implementing directive 2009/28/EC calls on the Italian TSO (Terna) to identify network reinforcements, including ESS, to enable energy from RES to be fully dispatchable [22]. In essence, the TSO (Terna) is meant to follow the EC legislation on unbundling, but the subsequent Legislative Decree 93/11 stipulates that TSOs and DSOs can own and control dispersed ESS (including batteries) with careful consideration given to the most financially feasible solution to solve problems identified on their networks [66]. Conversely, the TSOs or DSOs are not allowed to receive compensation from ESS implementation greater than the cost of an alternative solution. And the decree further states that construction and operation of PHS in the TSO's network development plan should be competitively contracted under regulation to guarantee deployment and utilisation for grid security and effectiveness of RES integration to the grid [22].

4.4. Asia Pacific

4.4.1. Australia

The National Electricity Market in Australia operates five interconnected regions in Australia and is it is one of the world's longest interconnected power systems [99]. Australia has high carbon emission reduction targets as the country has the highest per capita GHG emissions in the OECD and one of the highest globally [100]. There is currently a target of 20% electricity production from RES by 2020 as illustrated in Fig. 4, this is expected to help reduce GHG emissions by 5% [101–104]. Nonetheless, the increase in RES has not brought about an interest in ESS, which currently does not participate in the energy market. The government, regulators, ESS providers and network operators are not certain of the future role and amount of ESS required.

4.4.1.1. Challenges. Marchment Hill Consulting [105] discuss how the uncertainty of the government's RES targets affects the uptake of ESS and highlight the lack of economic grounds for implementing energy storage in the present electricity system. There is a lack of experience of using ESS on the grid as the majority of ESS trials and deployments are for remote systems. Hence, due to the lack of support, experience and uncertainty of its future role, utilities do not include ESS in network plans and are unsure on how to recover costs for investing in ESS. The use of ESS in the balancing services market is not deemed profitable because of low prices for such services caused by surplus amounts of generation on the grid, which are running at low capacity factors, and high power system stability as generation and demand is evenly distributed geographically. Furthermore, there is a fuel tax credit for diesel used for fixed and stationary generators that are used to provide flexible and backup generation, limiting the deployment and success of ESS and RES in Australia [106]. The other challenges faced with using ESS in Australia are [45,105,107]:

- There is no set framework for connecting distributed generation (DG) to the electricity network. There is a lack of technical standards for DG connections, which has created uncertainties and difficulties in deploying DG. These factors will affect ESS implementation;
- The networks are unbundled, preventing utilities from owning or using generators for grid support services;
- Generators rated below 5 MW cannot participate in the electricity market and provide ancillary services for grid stability. This will affect independent ESS owners with smaller ESS. However, this limitation can be exploited by aggregating ESS;
- There is a lack of transparency towards the problems T&D network operators are facing. This also ties into a high threshold set for T&D network operators to request tenders for solutions to resolve network constraints.[7] This limits the participation of smaller ESS technologies;

[6] Compensation is provided at approximately £16,800/MW.

[7] The minimum threshold for requesting tenders is £6 million.

- Finally, there is a wholesale electricity price cap which could potentially limit ESS investors interested in making profits via energy arbitrage.[8]

4.4.2. China

The Chinese electricity sector is vertically integrated with state owned monopolies but there are currently plans to reform the power sector by unbundling transmission and distribution and deregulating the electricity market [108]. The electricity market in China is the world's second largest behind the US [44,108]. The Chinese electricity grid is expected to become the largest in the world by 2015 based on installed generation capacity and electricity production [109].

China currently has the largest installed capacity of wind power in the world and has the highest investment target for RES with plans to achieve 200 GW by 2020, and a projection for wind generation capacity to reach 533 GW by 2035 [110,111]. There are targets for electricity production from RES to constitute 11.4% of primary energy source by 2015 and 15% by 2020 [109]. The market for ESS use is motivated by the need to increase the efficiency of the grid by the integration of RES. Presently 17% of wind generation is curtailed as a result of network bottlenecks [112]. Thus, the need for ESS will become increasingly apparent as installed capacity grows. Another major driver for ESS is the requirement for energy security and flexibility due to the increasing industrial and domestic energy consumption in China [113].

4.4.2.1. Challenges. As the Chinese electricity market is not competitive, policies would be the main drivers for developing ESS. However, the current lack of national policies supporting ESS is a major barrier to the national uptake of the technology [92,113]. The stakeholders in the electricity system are not investing in ESS because of the high capital costs, concentration on ultra-high voltage grid expansions, and the low capital costs for dispatchable conventional generation technologies such as coal power plants [114].

4.4.2.2. Policies, regulation, electricity market changes and future plans. The government has budgeted for numerous ESS demonstration projects as part of a smart grid development plan between 2011 and 2015 [92]. Local municipalities have also set out some policies to promote the development and deployment of energy storage [111].

4.4.3. Japan

The power generation and retail sectors of the power industry are liberalised and controlled by ten vertically integrated power companies [115]. The aftermath of the Fukushima nuclear power plant disaster led the Japanese government to put forward a Strategic Energy Plan to reduce the reliance on nuclear power generation by increasing RES penetration [116]. One of the new incentives was the setting up of one of the highest FiT's in the world for solar PV, this was introduced in 2012 to drive increase in RES-E [117]. After the nuclear disaster, the government's interests have increased in the use of ESS in providing security of supply. In terms of experience with ESS, large battery demonstrations using Sodium Sulphur (NaS) batteries were initiated in the 1990s for managing demand on the grid and in 2010, NaS installations in Japan made up an estimated 82% of the 365 MW of worldwide installed NaS [47].

4.4.3.1. Policies, regulation, electricity market changes and future plans. There is a short to medium term target for 15% ESS capacity to be deployed on the grid [47]. The government is currently promoting the use of residential ESS for use with solar PV, and there is an expected targeted increase in capacity from 3.68 GW in 2010 to 28 GW by 2020 [53,118,119]. High performance power storage and hydrogen storage were identified as one of the cross cutting technologies to aid the Japanese Government's goals to reduce GHG emissions by up to 70% in 2030 [120]. A roadmap for ESS between 2010 and 2050 was established and two pathways were identified, with one supporting the use of storage facilities in electric vehicles (EV) and the other geared towards stationary applications of ESS for RES integration, load levelling, power quality improvement, and local level energy management systems [121].

There are currently subsidies in place for battery storage connected to the grid with limits on compensation based on the storage capacity installed [119]. Regulation requires guaranteed and dispatchable wind generation, and to support this, the Japanese government provides subsidies covering one-third of the cost for renewable generators to use ESS [122,123].

4.5. The Americas

4.5.1. United States of America

The US has goals of 80% renewable energy by 2050 [124]. Presently, 29 of the 50 states in the US have a Renewable Portfolio Standard (RPS) that requires a 10–40% electricity contribution from RES [125]. The investment in ESS is growing and is encouraged by the Energy Independence and Security Act of 2007 which identified the use of advanced electricity storage and peak shaving technologies as a means of modernising the grid in the US to maintain reliable and secure electricity infrastructure and to meet growth in demand [55,126]. The North American electricity market consists of vertical market segments and an open-bid market for centralised independent system operator (ISO)[9] ancillary services, which is accessible to ESS [127–129]. Studies have shown regulated revenue sources as the highest for ESS in the US [26].

4.5.1.1. Challenges. Because ESS does not fall under the conventional functions of generation, transmission or distribution, the Federal Energy Regulatory Commission (FERC) individually addresses issues with the classification of ESS for use on the grid [130]. A major challenge for FERC is developing and adapting markets in deregulated states and creating proper evaluation frameworks in regulated states, to allow ESS technologies to have economic value for the range of benefits that they can provide [25,131]. In addition, there is a degree of ambiguity in the jurisdiction of FERC and the State Public Utility Commissions (PUC) regarding ESS interstate wholesale transmission [25].[10] This affects the ability to recover costs for ESS providers if there are different jurisdictional rates for charging and discharging an ESS when involved in a FERC jurisdictional wholesale transaction or PUC jurisdictional retail transaction [24]. The differences in rates could lead to a profit or loss for the ESS providers and this blurs the assessment of ESS value by ESS providers, utilities and state regulators.

Pomper et al. indicate that a lack of liquidity in the balancing markets affects ESS participation [24].[11] In New York, ESS is used in the Limited Energy Storage Resource (LESR) market for short duration frequency regulation [52,132].[12] In this market, the energy

[8] The current electricity price cap is set at −£600/MWh and £7600/MWh.

[9] The ISOs control, supervise and manage the electrical power system in individual or multiple states in the US.

[10] The State PUCs regulate the generation, transmission and distribution provided by utilities except interstate transmission markets which are handled by FERC. They also regulate retail electricity prices.

[11] This is a small scale market with limited market participants and restrictive bidding requirements.

[12] According to New York Independent System Operator [133], "*a LESR is characterised by its ability to provide continuous six-second changes in output coupled with its inability to sustain continuous operation at maximum energy withdrawal or maximum energy injection for an hour*".

requirement is removed allowing regulation to be considered for sale as an individual product. But ESS, like other traditional regulation service providers, is paid for actual energy discharged to the network and not for the total energy consumed and injected, termed "*mileage payment*" [92]. ESS is compensated like conventional regulation providers, with no consideration for fast response [92].

Finally, there are few deployments and a range of pilot and demonstration projects, which has led to lack of proof on the long term benefits of ESS. Lack of experience coupled with the unwillingness to change the status quo and invest in risky infrastructure, limits the adoption of ESS in the US [25]. Other challenges are [25,111]:

- Funding complications for ESS demonstrations or deployments stemming from issues with determining the cost recovery from providing regulated services due to different accounting and reporting requirements and jurisdictional uncertainties when using ESS for different services;
- Large-scale development of PHS hindered by increasing regulatory, environmental and site location challenges;
- Effect of policies for other competing technologies or solutions which potentially inhibit the need for ESS, e.g. DR, network upgrades and peaking power plants.

4.5.1.2. Policies, regulation, and electricity market changes and future plans. ESS has been approved by FERC to provide transmission support services, participate in the wholesale electricity market, by providing time shifting services to improve generation efficiency, and to provide ancillary services. The key legislation and policies supporting ESS are [25,92,111,128,134]:

- FERC Order no. 719 updates FERC regulations to improve the operation of the wholesale electricity markets, including pricing and DR in periods when there is a shortage of operating reserves;
- FERC's Order no. 755 requires RTOs and ISOs to develop two tiered rates (payment for capacity and performance) for frequency regulation services, with the payable rates determined by the market;
- FERC's Order no. 784 allows ESS owners to participate competitively in the ancillary services market and expands on Order 755 to ensure payment for performance based on speed and accuracy for providing regulation and frequency response services to utilities. This enables ESS developers to take advantage of the high ramp rate and fast responsiveness of ESS. The order will also enable utilities to obtain cost recovery from revising accounting and reporting requirements for ESS operations.
- FERC Order no. 890 requires non-generation resources (which include ESS and DR) to be considered along with generation resources for various transmission services on the grid;

The US Department of Energy (DoE) established the energy storage technologies programme to develop and improve the functional capabilities of the US grid [135]. Bills have been proposed in Congress to create tax incentives for ESS investments that increase reliability, allow renewables integration and increase grid efficiency. The bill proposes a 20% investment tax credit for new grid connected ESS (at least 1 MW/1 MWh), and a 30% investment tax credit for new onsite storage (at least 4 kW/20 kWh) and new residential storage (at least 500 W/2 kWh) [111,136].

At state level, the California government, motivated by 33% RPS target for 2020, passed an assembly bill AB 2514 directing Californian utilities to define feasible and economic targets for implementing ESS to stabilise the grid [92,137]. Furthermore, a mandate was approved by the California PUC which establishes the policies and mechanisms for the procurement of ESS. The mandate specifies targets for the three biggest utilities in California to procure an estimated 1.325 GW of ESS over the next 10 years from 2014 [138]. In Texas, the Senate bill 943 permits ESS to participate in the wholesale electricity market. In addition, the bill requires the state PUC to classify some ESS assets as network facilities or generation assets thereby allowing ESS to be eligible to also provide ancillary services in the ancillary services market, interconnect to the grid, and obtain returns for providing transmission services [139]. Other changes approved are [17]:

- Settlement rule for ESS resources that allow ESS to be settled as a generator when charging and discharging. Previously ESS was settled as generator when discharging and load when charging.
- Exemption from fees and charges for retail load, and transmission costs.

The New England ISO (ISO-NE) changed market rules to allow services from non-conventional regulatory service providers to be used in order to support ESS. A pay for performance structured incentive for generators providing faster response to regulation signals was also introduced as required by the FERC order 755 and 784 [52,92]. PJM, an RTO that runs the world's largest competitive wholesale electricity market, permitted LESR to participate in the market for frequency regulation, and from January 2011, pay for performance was initiated [140,141]. ESS is defined here as a fast response device of mainly battery or flywheel technologies and they are placed on the same level as PHS [92]. And lastly, the Mid-West Independent System Operator (MISO) following from the FERC ruling created a frequency regulation market tariff for stored energy resources. This allows ESS operators to compete with other fossil fuel generation regulation providers [142].

4.5.2. Brazil

Brazil has the largest electricity sector and hydropower resource in Latin America where hydropower is the main electrical energy resource [143,144]. The electricity mix has one of the highest percentages of renewables in the world with hydropower making up to 78% of the countries installed generation capacity [30]. In 2011 hydropower contributed 90% to the electricity produced [30]. An increase in generating capacity is required to meet the increase in electricity demand spurred by the government's plan to increase electricity consumption per capita[13] [145]. Renewable energy policies have been put in place through a scheme called the programme to foster electric power alternative sources (PROINFA) [115]. Consequently, the government set targets for 16 GW of wind, 13 GW of biomass and 117 GW of hydropower (from 84 GW in 2011) up to the year 2030 [146].

4.5.2.1. Challenges. The two challenges facing the Brazilian energy sector are balancing the vast hydropower plants with alternative energy sources, i.e. both thermal generation and renewables; and maintaining security as the electricity consumption increases due to its growing economy and the government's 10-year plan to increase electricity consumption per capita [147]. In terms of storage, the Brazilian hydropower plants have large storage reservoirs with storage capacity that can store up to half of the country's annual electricity consumption [145]. The National interconnected System (SIN) enables use of the storage potential as it connects the four regional subsystems with their geographically

[13] Electricity consumption is expected to grow by up to 52% between 2010 and 2020 based on an annual average growth rate of 4.8%.

dispersed hydropower plants. This enables the use of the storage reservoirs with hydrological diversity brought about by different weather patterns where the hydropower plants are installed to balance changes in electricity demand and rainfall across the North and South regions throughout the year [145,148].

Over reliance on hydropower has led to power shortages in the past, this was the case in 2001 [145,149]. In addition, there are geographical and political limits that affect exploiting 70% of the remaining hydropower potential in Brazil to meet increasing electricity demand [30]. These limits on hydropower resources have led to the government developing run-of-the river hydropower plants, which lack storage [30]. However, Soito et al. discuss how the availability of current hydropower plants with storage reservoirs would provide a means storage (virtual reservoir) for the new run-of-the river hydro plants and other intermittent renewables that are expected to be deployed on the grid [150].

4.5.2.2. Policies, regulation, electricity market changes and future plans. While there are no policies promoting the use of ESS, the government wants to avoid power shortages caused by over reliance on hydropower, geographical and political limits. It is suggested that solar and wind can be used as complementary resources to balance the impact of dry seasons and drought on hydropower generation, as higher irradiation and wind speeds occur in the dry season [151]. The government is diversifying the countries energy mix to balance the hydropower resources [145,152]. Consequently, The use of renewables comprising of wind, solar, small hydropower, along with thermal generating plants (fossil fuel, biomass and nuclear) are being promoted and implemented to complement hydropower resources.

5. Regulation, electricity markets and their impact on storage implementations

As most countries move towards decarbonisation and increase the amount of generation contributed from RES, the distinction between generators and consumers will change, with the latter being able to generate and inject power to the grid. Consequently, current regulatory and market arrangements will be challenged and will need to be updated. The increase in RES and LCTs will affect conventional operation and performance of T&D networks and creates the need for alternative solutions such as ESS and DR. But the regulatory barriers restricting the uptake of ESS are to a large extent dependent on the extent of unbundling practised. Unbundling of the power sector was conceived to drive down consumer costs by increasing competition and ensuring utilities deliver secure and reliable power supply in an economical manner. In countries where unbundling has not been fully realised and there is vertical integration, it is easier for utilities to deploy ESS across the power system to support the grid and to also use ESS commercially in the electricity market. This is due to the transparency of requirements from generation down to the customers, which allows the utilities to decide on the best ESS investment strategies to meet their operational and profit goals. On the other hand, in an unbundled system, the benefits derived from implementing ESS are more challenging to determine and accomplish because there are multiple actors involved from generation to consumers with different goals, practices and regulation systems in place. However, the EU report [65] infers that the benefits of ESS in providing competitive services are better realised in an unbundled power sector.

Currently, most ESS technologies are expensive when compared to conventional solutions for utilities. Without the right policy, regulatory and electricity market changes, investment in them will lead to higher costs for consumers. This goes contrary to one of the goals of unbundling, which is to drive down consumer costs. Overall, there is limited operational experience of ESS, apart from PHS on the grid. Ergo, this had led to inconsistencies or lack of policies supporting the use of ESS and few changes to the regulatory and market frameworks that deter the use of ESS.

The underlying general market systems and regulatory barriers to the deployment of ESS in the countries reviewed are:

5.1. Storage regulatory barriers

5.1.1. Renewables integration policies

Bidirectional power flows and excess power on the grid caused by the changing generation mix, comprising centralised and decentralised generation with renewables, will lead to network capacity overload and voltage control problems discussed in [11,12]. This currently requires curtailment or grid expansion by network operators. ESS could be used to store excess energy from RES and substitute for grid expansion. However, there is little incentive for investment in ESS because of the high priority and financial compensation provided to renewable generators to curtail excess energy. The guaranteed high tariffs which are in place to increase and promote RES penetration reduce the incentives to firm the capacity of RES using ESS. To solve RES intermittency, ESS is expected to be located close to the RES to improve dispatchability but this may not be the optimal position on the grid to relieve congestion problems [23]. Finally, the extra expense on grid access tariffs for connecting ESS to the grid would increase the start-up costs for renewable energy generators, further dissuading them from using ESS.

5.1.2. Transmission and distribution use charge, tax exclusions and renewable energy subsidies

Regulation determines whether T&D use of system charges should apply to ESS used to provide services on the grid, and if ESS is liable to these charges, there is contemplation on whether to charge ESS as a generator or consumer. Presently, ESS used on the grid is subject to T&D charges as a generator, consumer, or both, depending on the country. If charges do apply, the lack of transparency in calculating them, which is a current problem in the EU affecting DG, will also affect ESS [23].[14]

In most countries electricity consumers have to pay electricity taxes, however, due to the undetermined legal classification, it is unclear if ESS when used as a load, is to be included in this tax payment. Consumers also pay for the cost of renewable energy schemes that are being implemented, for example, this is carried out in the EU via renewable energy subsidies. The determination on whether ESS should be included in these payments as part of the renewable energy scheme or under a specific ESS scheme is uncertain. Likewise, there is an uncertainty in determining if ESS should benefit from the subsidies attached to RES schemes. Given that ESS is considered a possible solution to increase RES penetration, this could be considered an integral part of the scheme.

5.1.3. Undetermined asset classification

Current regulation for ownership and operation is applied based on the function of devices in the power system [18]. ESS is multifunctional and can serve as a generator, transmission or distribution asset, or as an end user, depending on the required end goal. Consequently, ESS asset classification is undetermined under present regulatory. For example, the laws in the EU as stated in [37] prevents grid operators from participating in the electricity

[14] Types of charges include deep charge (DG covers all expenses), shallowish charge (DG pays for connection and reinforcement) or shallow charge (DG only pays for connection and maybe a transformer).

market and as a result they cannot directly utilise ESS to recoup cost of investment by providing competitive services when it is not being used for grid support operations. In order to classify a device under a particular asset type, the operational uses and goals need to be clearly understood and defined by the regulators. Due to the varied characteristics and types of ESS devices, this is not currently fully understood. The undetermined asset classification directly affects eligibility for ESS asset ownership, grid tariffs, and cost recovery for regulated assets.

5.1.4. Lack of framework and incentives for storage service provisions to transmission and distribution network operators

Economic incentives supporting the use of ESS by network operators to maintain efficient operation of their networks are lacking. As more RES is added to the grid the power quality will deteriorate, especially with PV and other microgeneration schemes on the distribution network. There are no incentives or rewards in place for improved power quality and power quality benefits are difficult to quantify [153]. The benefits ESS provides by improving capacity utilisation of the grid and increasing efficiency of centralised generators is also difficult to quantify. Furthermore, the return on investment for network operators to invest in ESS is questionable due to the high levels of risk and uncertainty caused by current regulatory and electricity market systems. This is not the case for conventional network expansion where revenues are guaranteed, and thus discourages investment in ESS.

5.1.5. Regulatory frameworks that have caused unwillingness to take risks or innovate

The conservative nature of current regulatory frameworks in most countries leads to network operators, generators, and other stakeholders being cautious in moving towards technologies that are novel and not technically and commercially proven. Although some ESS technologies are established, most technologies (other than PHS) are still developing for use on the grid. Hence the lack of experience and high investment costs makes it a risky venture.

5.1.6. Lack of standards and practices

Most ESS with the exception of PHS are relatively new and developing technologies (e.g. compressed air energy storage, hydrogen storage) with minimal deployments. This has resulted in the lack of necessary standards and practices to carry out thorough economic assessment, system design and deployment.

5.1.7. Policies for other competing technologies or solutions

Policies being put in place favour established technologies (e.g., interconnections, gas peaking power plants) over the use of ESS which has limited operational experience. This limits the growth of ESS implementations.

5.1.8. Investment dilemma

Under regulatory rules, all stakeholders that benefit from ESS are meant to pay for the solutions the ESS implementation provides them. The difficulty in determining the wide range of benefits across the grid makes it difficult to quantify the overall value of an ESS investment. This affects the profitability of investing in ESS, and is especially the case for independent ESS owners.

5.1.9. Energy storage not being considered as part of RES under RES targets

The production of electricity from ESS connected to the grid may or may not be from RES. This creates a conflict in trying to classify ESS under RES. According to Krajačić et al. [61], a guarantee of resource origin would be a suitable way for ESS to be considered as part of a countries renewable generation mix to meet RES targets.

5.1.10. No benefit for controlled and dispatchable RES

Generally, generation based support mechanisms (market premiums or feed-in-tariffs) and priority dispatch are part of regulatory frameworks and policies to increase the uptake of RES. However, these mechanisms do not include and compensate for the controlled dispatch of renewable energy to meet demand and supply variations on the grid [65]. This may influence traditional generators to invest more in RES where revenues are guaranteed. Thus, RES owners are not incentivised to participate in the reserve or ancillary services markets, which traditional generators participate in for extra revenue.

5.2. Storage market design barriers

5.2.1. Limitations on market participation and use for grid support services

Under present market rules in some liberalised electricity markets, the ancillary services market is more attractive for ESS owners as it provides opportunities to earn more from providing reserve services [22,154]. In the reserve market, generators are expected to provide the reserve capacity they are contracted for, under any conditions and this is required close to real time. ESS owners may be unclear of the state of charge of the ESS when they are participating in the balancing or reserves market. This may prevent ESS owners from being involved in the spot market and in providing grid support services because it would be impossible to guarantee use in the balancing or reserves market if the ESS is used for other operations. A study carried out by Wasowicz et al. [23] shows that revenue increases from 6.2% to 19.2% were realised for ESS owners when grid support activities were provided along with reserve services. Hence, it is apparent such a limitation will affect the profitability of an ESS investment.

5.2.2. Lack of market liquidity

A liberalised electricity market that promotes competition favours a liquid wholesale market [155]. However, bigger generators engage in bilateral contracts to mitigate issues that arise as a result of volatile prices in the spot market, this is currently affecting DG operators in the EU [156]. This leads to low electricity market liquidity which is an entry barrier for ESS owners because it will limit ESS operators from getting access to the wholesale electricity market and provides an unreliable market that is unsuitable for new entrants to sell or purchase power [155]. In power sectors that are not unbundled, the bigger vertically integrated utilities with economies of scale and larger influence can hinder market access for smaller ESS owners as is the case with DG in the EU [157].

5.2.3. Market operation requirements and market fees

Satisfying the requirements of the spot market could be difficult if ESS is also being used in other energy markets based on the business model in place. Confirmation is required close to real time for the provision of balancing and other ancillary services, this however conflicts with wholesale market requirements, which involves participants confirming their position ahead of real time (based on defined market gate closure periods) in futures, day-ahead or hour-ahead markets. Regulated actors (T&D network operators) may impose a guaranteed reservation due to their control and high priority on ESS capacity for use in providing operating reserves and regulation services. This can lead to underutilisation of ESS by affecting its participation in the spot market. There is also the issue of high fees for trading in the wholesale or retail market (based on ESS location) for charging and discharging the ESS, which currently affects DG [68].

5.2.4. Decline in spread of peak and off-peak energy prices

The spread of energy prices during peak and off-peak periods provides an avenue for ESS owners to gain revenues from energy arbitrage. ESS is mostly deployed in countries with a huge price spread [29]. The price of peak and off-peak electricity and resultant spread is affected by factors including, the demand and generation mix which changes over time due to policies and regulations, and unpredictable fuel and carbon dioxide (CO_2) prices affecting base and peak load generation [158,159]. Miller et al. reviewed wind integration studies carried out in the US and Canada over a 6-year period and a major deduction was that the increase in wind penetration led to a reduction in electricity spot prices, especially during high wind and low load scenarios which led to greater spread in peak and off-peak prices [158]. However, the spread has been seen to reduce due to excess PV or wind energy during peak periods, consequently decreasing the profits that can be realised from arbitrage. For example, the spread was reduced in the German electricity market between 2010 and 2011 when the contribution of energy to the grid from PV was high; this led to lower midday peak energy prices, which reduced the PHS margin in 2010 [93]. This drop in price spread in Germany is also discussed in [23,159]. In addition, the electrification of transport and heating in the move to decarbonise these sectors could also nullify the increase in price spreads because heating and charging of EVs will substantially occur at night. This would increase the off-peak electricity prices and hence reduce the price spread [158].

5.2.5. Unfair advantage provided to regulated utilities

The use of ESS by natural monopolies could complicate electricity market operation as it can provide the regulated network operators with a way to influence the electricity market price and provide a biased advantage, which goes against the principles of unbundling. This would in turn reduce the prospective revenue that independent ESS owners could derive from participating in the wholesale markets.

5.2.6. Market price control mechanisms

Price control mechanisms enacted in different countries may affect the revenues ESS can make from arbitrage. The fixing of prices in balancing markets as discussed in [26] can affect the compensation from providing balancing services as payment is not made on marginal prices but on average or pay-as-bid prices.[15] Also, the introduction of price caps, which is used as a measure to curb high volatility, could potentially affect the success of ESS. Such measures have been put in place by the UK's electricity regulator (Ofgem) in the past [160]. In 2001, the US FERC enacted a price cap to reduce rapidly increasing wholesale electricity prices; this led to the bankruptcy of a power company in California [66,161]. As ESS may often operate for shorter periods during the year, compared to conventional generation, the opportunity to recover investment costs during periods of volatility in the markets is important. A price cap will create uncertainties that will significantly affect the business case for investing in ESS.

5.2.7. Wholesale and retail price market distortion

The issue of wholesale and retail price mix-up was identified in the California Rule Making for Energy Storage AB2514 [25]. This involves T&D operators distorting the electricity market by participating in the wholesale and retail markets while obtaining regulated revenue on the ESS, which is a network asset, thus placing them at an advantage against other ESS or generation owners. This is further compounded if an ESS asset is charged by purchasing energy at wholesale prices and selling at retail prices without adequate coordination of the electricity markets [25]. However, this would be based on the contracts a regulated utility has in place for charging and discharging ESS if they are allowed to participate in the electricity market.

5.2.8. Low remuneration for reserves and other ancillary services

Insufficient remuneration for reserves and ancillary services will affect the large scale investment in ESS, this is currently the case in the EU [29]. ESS is compensated in the same way as traditional regulation service providers despite the additional benefits that their accuracy, high responsiveness and rapid ramp rate can provide. This was also a limiting factor in the US until new legislation was passed in 2013 requiring payment for performance to be considered.

5.2.9. Penalties for not meeting scheduled energy dispatches

Using storage under a business model where it provides regulated and competitive services would be difficult to control. This is crucial as based on market rules there will be financial penalties if ESS is contracted to provide reserve services or electricity in the wholesale market but does not have enough available energy due to it being used for other grid support services. This will be a major barrier in implementing multi-functional ESS without appropriately designed markets and rules in place.

5.2.10. Value assessment from market operations

The method of assessing the potential revenues from ESS providing services in different electricity markets is complex because of the associated risks and uncertainties of changing market conditions. These are caused by changing economic factors such as the varying world prices of oil and gas, and changing regulatory frameworks and policies, which could be influenced by among other things, changing governments, political conflict and natural disasters. This makes it challenging to quantify the potential long term revenues for using ESS both competitively and for regulated services.

5.2.11. Sizing requirements for ancillary services markets

There are limitations placed on the minimum duration and size of generation that can participate in providing regulation services, in the EU, the minimum power capacity is limited between 1 and 5 MW, and it is 5 MW in Australia [67,105]. There are also limitations on the energy capacity in reserve markets. This limits participation from investors with smaller sized ESS on the network.

6. Recommendations

6.1. Policies and regulatory frameworks

6.1.1. Alignment of RES policies with that of ESS

The development of RES requires government intervention and a move away from relying on the current liberalised electricity markets which were designed for central dispatchable fossil fuel power generators [162]. In order for RES to grow and compete with these central conventional generators, policies had to be introduced and regulations had to be amended. However, the policies and regulatory changes for RES do not support ESS development as they are currently being developed as a

[15] For pay-as-bid pricing, payment is made to the generator based on amount placed in a submitted bid and for marginal pricing, payment is determined based on the most expensive scheduled generator.

stand-alone application. Indeed they may not apply to ESS, for example, if an ESS charges using power from fossil fuel sources. Hence, the government and regulators should ensure that policies and regulation for ESS are aligned with that of RES. A combination of direct and indirect methods of support used for RES as discussed in [163] could be used to support ESS uptake. However, because of the difficulties in quantifying all the benefits that an ESS investment may provide other than its primary functions, it is recommended primarily direct methods of support, mainly subsidies and tax incentives, are put in place for new ESS investments.

The implementation of ESS for renewable capacity firming should be considered as a major tool for meeting RES targets and as part of this recognition, regulations and incentives should be put in place for RES owners to provide dispatchable energy with benefits such as quicker access to the grid and reduced network connection charges. This would drive RES providers or other third parties to invest in ESS and reduce requirements for other flexible back-up capacity (from peaking generation plants) on the grid to manage RES intermittency. Further, as discussed in [28], renewable energy policies should be revised to provide two tariffs for RES owners providing intermittent energy and dispatchable energy from ESS. This is current practice for island power systems in Greece [28].

The move towards increasing LCTs, which are located closer to customers in the distribution networks, will affect the operation and maintenance requirements for distribution networks. ESS is seen as a possible solution yet most policies being updated or created are mainly applicable to large scale ESS. Future policies need to also consider distributed and community ESS and the wider benefits they can provide on distribution networks as discussed in Table 3. Accordingly, once the contribution of ESS to the security of supply in distribution networks is better understood, the security of supply standards for distribution networks, such as the ER P2/6 standard in the UK [74], which recognises the contribution of DG to system security should be amended to recognise ESS as a valid tool to maintain or improve security of supply on the network.

6.1.2. New asset class and regulation for ESS

Regulatory changes should be made that allow for the creation of a separate asset category and rules for ESS because of its dual generation and demand function. These rules should enable the effective utilisation of ESS to allow for a more accurate tariff charge and compensation mechanism based on the operational efficiencies ESS provides under different applications. This should remove regulatory issues encountered when considering ESS as generation or load when used in T&D networks as it would lead to the creation of an ESS use of system methodology and charging scheme, which should recognise the contribution of ESS to system security, loss reduction and the provision of other ancillary services on the T&D networks. Furthermore, this new asset category would encourage investment by unbundled operators who are prevented from owning generation. If this is not feasible, ESS should be exempted from grid tariffs for load and generation. If that is not achievable, a recommendation made by the EC funded project on grid reliability and operability with DG using flexible Storage (GROWDERS) for incentives in the form of subsidised grid connection charges should be provided to ESS owners operating to provide grid support services [65].

6.1.3. Floor market price for carbon

A carbon price floor such as that introduced in April 2013 by the UK Government[16] should be considered to reduce uncertainty of the carbon market price, in countries that have an emissions trading scheme. The introduction of a price for carbon, which is necessary to curb GHG emissions, will increase the economic feasibility of LCT implementations. Consequently, this will increase the need for flexible demand and generation solutions such as ESS and DR to handle future peak demand and the unpredictable generation from these LCTs, but will discourage the use of carbon intensive technologies such as peaking power plants [164]. ESS participation in the electricity market, along with DR can reduce the peak capacity requirements on the grid and the resulting need for peaking power plants, which produce GHG emissions. Peaking power plants will increasingly become more expensive and unfavourable in the future as gas prices and volatility increases, while RES capacity with low marginal cost of operation increases, potentially resulting in relatively lower electricity prices,

6.1.4. ESS ownership by regulated monopolies

TSOs should be allowed to own and operate ESS as part of transmission network assets if it provides a better solution than conventional methods. DSOs, who play a more passive role (for example, in the UK), should be allowed by regulation to manage the distribution networks in an active manner. This can only be accomplished by the TSOs dispersing some regional balancing duties (ancillary services) to DSOs. This should enable DSOs to own and operate ESS as a network asset. Both the TSOs and DSOs would then be able to recover the investment cost of ESS as it becomes a regulated network asset. However, the TSOs and DSOs should be regulated on the commercial activities and remuneration they can get from using ESS. TSOs and DSOs planning for their networks to accommodate high RES penetration levels should be advised under regulation to consider ESS with other alternative technologies if their potential in T&D networks has been justified.

6.1.5. Standardise evaluation frameworks, connection and operational procedures

The total lifecycle impact of implementing various ESS technologies on the grid needs to be understood by regulators and other stakeholders in the power sector as this will dictate operation and maintenance strategies. This can only be accomplished through amassing experience from the rational roll out of ESS when viable and by continued research, development and evaluation on more ESS schemes for pilot and actual operations across the generation, and T&D networks. This will enable a better understanding of the technology so that procedures for evaluating ESS and alternatives as discussed in [25] could be developed and adopted by regulators and used by the T&D operators as part of a new or updated regulatory framework.

As the experience from live deployments increases, this will enable a standardisation of methods for evaluation, connection, operation, maintenance, and disposal of ESS technologies used on the grid. This would help in reducing the risks and uncertainties of investing in ESS. Based on the standards of assessment, it is recommended that all beneficiaries of the ESS operation contribute towards the cost of the ESS investment, i.e. based on the benefits the stakeholders get. This should help in determining the contribution of ESS for regulated utilities and the amount of support or remuneration they should realise from such an investment.

6.1.6. Roadmap for ESS deployment on the grid

If ESS is considered as a potential solution, it is important that plans, targets and goals for the use of ESS (much like that

[16] The carbon price floor is a regulatory policy in the UK that sets a minimum market price for carbon. This policy was created to counter the low carbon prices in (*footnote continued*) the EU emissions trading scheme caused by the economic recession and over supply of permits [164].

implemented for RES in the reviewed countries) are established for the use of large, distributed and customer ESS implementations on the grid to provide the applications such as those shown in Table 3. This will reduce uncertainties in assessing the viability of ESS in the medium to long term and thereby spearhead investment, development and experience of using ESS technologies.

6.1.7. Reduce curtailment of RES by investing in ESS

The amount of money spent on curtailing excess energy from RES that causes bottlenecks on the T&D networks can be invested in ESS solutions for RES capacity firming, which would defer or reduce the need to carry out expensive network upgrades or reinforcements.

6.1.8. Reuse of electric vehicle batteries for grid storage applications

As battery technologies continue to develop, so does the viability of EVs replacing conventional internal combustion engine vehicles and this may lead countries to move towards deploying more EVs on the grid. While there is the possibility of utilising the storage potential of EVs for grid applications once vehicle to grid (V2G) infrastructure is in place, there are technical, social, political, economic and cultural barriers as discussed in [165]. In considering other ways to use the storage potential of deployed EVs, Patten et al. [166] highlight that up to 50% of initial battery capacity remains at the end of a battery's technical life in EVs. This provides another avenue to take advantage of EV deployments as old EV batteries that have reached their lifetime in a vehicle could be reused for grid storage applications before they are disposed or recycled. For example, Patten et al. propose a concept to use recycled batteries for an additional 10 years after their use in EVs to increase the renewable energy portfolio in Michigan, USA [166].

Using the second life of EV batteries provides the advantages of reducing the environmental impacts that disposing these batteries would present, especially when there is a significant EV uptake. Furthermore, reused batteries could provide a discount on capital cost of energy capacity when compared to new batteries, thus increasing the economic viability of using batteries for grid storage applications.

6.2. Market frameworks

6.2.1. Electricity market rules for simultaneous operation of ESS

Presently in most countries reviewed, ESS can be used in the wholesale electricity market, and can also participate in the balancing and ancillary services, and capacity market. An example of limitations on simultaneous operation is in the ancillary services market, where rules ensure regulation service providers are committed for the period a regulation service is required in the up or down market. ESS operating in the energy or capacity markets could therefore be limited from the regulation market. Results from a US study concluded that rules permitting ESS to participate in asymmetric (bi-directional) bidding in the regulation up and down markets can provide up to a 400% increase in potential revenues [167]. Simultaneous participation in a combination of these markets would allow for increased return on investment and resulting viability for ESS implementations. Thus it is paramount electricity market structures are adapted or created to facilitate simultaneous ESS operation.

6.2.2. Updated ancillary services market requirements

The rules dictating resource of ancillary services, i.e. minimum size and energy delivery requirements can be avoided by creating or adapting the ancillary services markets to accept bids from ESS with rated power, but smaller energy capacity to provide regulation services for a shorter duration [167]. ESS facilities can be aggregated to meet power and energy capacity requirements, therefore the markets must be updated to facilitate aggregation. This is an option that would be more suitable for generators, suppliers or third party aggregators who can combine multiple ESS on the grid, which may or may not be owned by them.

6.2.3. Competition with established generation technologies

It is important a level playing field is provided by means of support mechanisms in place for ESS to be able to compete against established fossil fuel based technologies. A good example is in the UK where a capacity market is being developed. In this market, ESS will be vying with other established generation technologies in the capacity auctions based on forecasted capacity requirements [78]. While DR and ESS will be allowed to participate in the primary auction (which is based on a demand forecast 4 years in advance), their limited capacity, high investment cost and difficulty in forecasting operation years ahead makes them less competitive than other generation technologies. Consequently, interim time banded products with specific delivery parameters are being developed for a DR/ESS only capacity market in the secondary auction, which has a shorter forecast period of a year. In this case, it is recommended that a percentage of participants in the primary auction are allocated to DR and ESS solutions.

6.2.4. Compensation for responsiveness and accuracy of ESS

The market for ancillary services should be updated to provide adequate compensation for ESS and other technologies that can respond fast with high accuracy to provide short and long duration frequency response, and high ramp rates.

6.2.5. Wholesale electricity price cap

Due to the expected increase in intermittent RES in the years ahead, it is likely that price caps could be put in place by regulators in respective countries as a measure to curb excessive wholesale electricity market prices. It is paramount if necessary this price cap regulation should be carefully chosen to consider remuneration for flexible and back-up generators and demand such as ESS, which would be relying on periods of high volatility to recover investment costs.

7. Conclusions

ESS implementation should be considered for multiple functions, both regulated and competitive, to yield maximum benefits for investors. Indeed, these market and regulatory changes must allow ESS owners to profit from providing multi-stakeholder benefits in order for ESS technologies and operations to thrive. The overall success of ESS is also influenced by public acceptance of the technology and the qualities of the wider electricity system [53]. Although investment in ESS is currently capital intensive in comparison to alternative technologies, adequate regulation is considered a key influence that will drive down the costs and associated risks of investing in ESS. The lack of adequate regulations for the use of grid level storage impedes power system stakeholders and third party ESS owners from building a suitable and sustainable business model for the use of ESS. Regulatory changes and an upgrade of the electricity markets are required for ESS owners to develop an appropriate business case.

Once the operational characteristics and applications for using ESS on the grid are fully captured in the context of different electricity systems and markets, adequate regulations and market rules can be developed. It is important that the policies, regulatory requirements and electricity markets are stable to reduce uncertainty in investing in ESS as this will dictate the business models that can be implemented. In creating or updating policies, regulatory and market frameworks, the role ESS plays in the future power system, especially in facilitating the realisation of decarbonisation targets must be considered. While fiscal incentives and mandates may help promote the use of ESS, it may come at a price of increased capital costs for utilities due to the long payback time for ESS investments. This would become an issue for utilities that are regulated to drive down system costs. Therefore, this conflict needs to be addressed when developing regulations and policies for ESS.

It is apparent that radical changes need to be made to current regulatory and electricity market arrangements by the government and regulators to bolster ESS implementation. In making these changes, the government and regulators would need to thoroughly understand all the benefits that could be provided by using various ESS solutions across the power system. Ensuring the stability of regulatory and electricity market structures for ESS is also very important as it would provide a better economic climate for ESS and drive the advancement of the necessary technologies.

These changes should help to boost certainty of remuneration for ESS to operate both competitively and for regulated network support services, albeit in a sector with more established fossil fuel based technologies and conventional network reinforcement principles.

Under current regulatory and electricity market conditions, conventional solutions, such as fossil fuel based peaking plants for covering peak electricity demand, are seen as cheaper technologies when compared to ESS. However, this does not necessarily represent the true cost and value of ESS. This circumstance is expected to change as ESS technologies continue to advance, capital costs reduce, deployment experience increases and there is the opportunity to reconcile multiple value streams. The authors acknowledge that ESS is only one solution to manage the issues that will be encountered as power systems continue to evolve. There are other measures in place such as DR and interconnections that could be used as alternatives or together with ESS. Updated or new policies, regulatory and market frameworks would also need to consider these other options working in tandem alongside ESS to provide a secure, reliable and sustainable grid.

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