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Grid-Scale Battery Storage for Variable Renewable Electricity in Sweden

A Study of Market Drivers and Barriers for Grid-Scale Battery Energy Storage Applications for the Integration of Wind Power in Sweden

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Abstract

This thesis explores how a market for grid-scale battery energy storage systems (BESS) can become reality in Sweden. Higher penetration levels of distributed, variable renewable energy (VRE) from wind power challenge the incumbent energy regime and require new solutions for the grid integration of renewables. As a consequence, a more flexible power system is needed in order to deal with the induced supply-side variability. Batteries, as one flexibility solution among several other options, have shown promising technological development and are a versatile electricity storage option. BESS can provide multiple benefits for different application areas on the grid at various scales. The emergence of grid-scale BESS in Sweden was analysed using the multi-level perspective (MLP) framework on socio-technical transitions. Despite the great potential and the rapid technological progress of BESS, it was found that regulatory factors, both in Sweden and the EU, currently constitute a major barrier for the deployment of large-scale electricity storage. Moreover, Sweden looks set to continue to increase the uptake of VRE from wind power, whilst a gradual phase out of nuclear power over the next decades is also likely. Whereas this would normally have negative implications for the power system, the ample hydropower capacity and sufficient interconnection to the neighbouring Nordic countries provide, at least for the near future, enough system flexibility and therefore reducing the need for the installation of BESS. However, the uneven geographic distribution of electricity consumption and generation across Sweden might give rise to flexibility solutions for enhancing local distribution networks in the future in order to eliminate potential regional bottlenecks.

Keywords: Sweden, battery energy storage, variable renewable energy, wind power, transition, multi-level perspective.

Executive Summary

This study set out to examine the uncertainties and opportunities in connection to grid-scale electricity storage through batteries in Sweden in order to accommodate increased volumes of VRE from wind power and provide additional power system flexibility. Higher penetration levels of distributed, variable renewable energy (VRE) from wind power challenge the incumbent energy regime and require new solutions. As a consequence of the grid integration of VRE from wind power, a more flexible power system is required in order to manage the induced supply-side variability. BESS, as a versatile electricity storage option, are one of several other solutions to enhance system flexibility by providing multiple benefits for different application areas at various scales. Batteries have shown promising technological improvements in recent years, mainly driven by the development in the automobile industry and the emergence of electronic vehicles (EVs), and are now becoming competitive with other flexibility solutions, such as more flexible generation assets, grid reinforcement and interconnection, or demand-side management.

In 2014, the Swedish electricity power mix consisted of approximately 42 % (or 64 TWh) generation stemming from hydropower and another 41 % (62 TWh) from nuclear power, while about 8 % (11.5 TWh) came from wind power. The latest projections from the Swedish Energy Agency (2015a) estimate a annual wind power production of 17 TWh by 2017. This development is mainly driven by the joint electricity certificate scheme between Sweden and Norway. Whilst the electricity system is characterised by ample interconnection to its neighbouring Nordic countries (at least for the near future), the weak economic outlook for nuclear makes a gradual phase-out over the coming decades seem likely. Hence, the uncertainties related the increased penetration level of VRE from wind power and the possible decommissioning of other disptachable power generation capacity might give rise to the utilisation of power system flexibility enhancing solutions, such as BESS.

Against this background, the guiding research question was formulated as follows: *How is the market for grid-scale BESS for integrating larger volumes of VRE from wind power becoming a reality in Sweden?* The two sub-questions *In which ways can BESS be integrated into the Swedish electricity grid?* and *What are the perceived drivers and barriers for the future investment and deployment of BESS in Sweden?* were stated to better operationalise the overarching question. The research was guided by several tasks and objectives to further delineate the study and provide information that contributes to answer the research questions. Therefore, an in-depth study on the electricity market development and configurations in Sweden with respect to its connection to the broader Nordic and European context was required.

The thesis is exploratory in nature. First, an extensive literature review on the various application areas and benefits of grid-scale BESS as one of several other solutions to enhance power system flexibility (e.g. more flexible generation assets, grid reinforcement and interconnection, or demand-side management) was conducted. This then supported the identification of a relevant and suitable conceptual framework and the formation of certain assumptions, which helped to refine the research problem and structure the study. Backed by this more theoretical base, it was possible to outline potential interview targets for collecting primary data. The multi-level perspective (MLP) framework on socio-technical transitions by Geels (2002a; Geels & Schot, 2007) and institutional theory was used for structuring and then analysing the observations. This approach helped to identify why certain patterns are prevalent and whether they can be seen as drivers or barriers for the future deployment of BESS in Sweden.

In general, it was found that that BESS are most suitable for quick-responding and short-term power services rather than bulk energy storage over longer time periods. Examples of grid

application areas are: frequency response, voltage control, inertia support and other ancillary services, ramp control and smoothing of VRE, T&D network congestion management and grid investment deferral. If several of these benefits can be combined (i.e. benefits-stacking), the value and profitability of BESS can be increased. Additionally, the aggregation of smaller-scale and distributed BESS (e.g. from industrial facilities or residential installations) could be used to provide local grid support services and help accommodate higher penetration levels VRE.

Turning to the specific market driver and barriers, it was found that there are currently major obstacles to the deployment and investment in BESS in Sweden. First and foremost, the regulatory framework for BESS, both in the EU and Sweden, is largely unclear with regards to ownership and right of dispatch (i.e. which actors may use it and where in the power system may it be used). This is mainly a result of the EU Directive 2009/72/EC (2009), which lays out the rules for the EU market liberalisation and particularly specifies unbundling requirements with the aim of prohibiting any network operator from participating in any form of electricity generation or supply. Therefore, TSOs and DSOs who are responsible for operating and developing the power grid may not operate or own electricity storage assets for making use of additional balancing services or as an alternative to eliminate bottlenecks in the grid. The situation for other electricity market actors is less restrictive. However, grid connection fees and energy taxes may apply when charging or discharging storage assets. The reason for this is that regulation does not clearly specify electricity storage assets as a singular asset category, and thus it can be seen as an energy consuming or generation unit, or even both, due to their very nature of charging, storing and discharging electricity. However, the EU is currently in the process of updating the Network Codes, and given the multiple benefits of grid-scale electricity storage, which have also been identified by various other studies, resolving this problem is advisable. In this sense, it is also somewhat understandable that Sweden is awaiting clear signals from the EU in order to update its regulatory framework with regards to electricity storage. However, with a clearer specification of storage assets, much uncertainty could be removed relatively easily, which would significantly improve the business case for providing grid services through storage assets.

Besides these regulatory barriers, the developments on the Swedish electricity landscape show more promising signs for the future uptake of BESS, although there is currently no imminent need for enhancing the overall power system flexibility. Generally, the Nordic power system is well interconnected and there is ample flexible generation capacity from hydropower, both in Sweden and Norway, thus reducing the need for electricity storage. Moreover, whilst a gradual phase out of nuclear power in Sweden seems likely (mainly due the weak economic outlook for the renewal of existing and ageing nuclear capacity), increasing penetration levels of VRE from wind power look set to continue in the near future. Despite the current flexibility of the power system, electricity demand (mostly in the South) and power generation (mostly in the North) are unevenly distributed across the country, therefore increasing the risk of power system bottlenecks. In addition, as most wind power generators are distributed in nature and connected to the local distribution grid (as opposed to centralised power generation units that connect to the transmission grid), there may be additional challenges on the local networks in the future. Hence, electricity storage for local grid support applications might be needed to enhance local power system flexibility and remedy certain issues. For this reason, it is even more important that the regulatory hurdles are cleared in order to maintain grid flexibility and network stability.

With the emergence of smart grid solutions, and to a certain extent also demand-side management, it was also found that the aggregation of smaller-scale BESS from residential or industrial prosumers (i.e. DERPs) could be used as a solution to provide additional and/or complementary local grid support services for enhancing power system flexibility. However, it is important to reinforce the fact that the regulatory requirements should be carefully evaluated in order to provide the right incentives for such solutions.

To sum up, BESS are certainly an emerging technology that could provide multiple valuable grid support services to enhance the overall power system flexibility, especially with the increasing shares of VRE. As of today, the market for BESS in Sweden is almost non-existent, despite the great potential in certain application areas. Whilst there are some drivers in the form of small niches for small-scale BESS applications and promising technological developments, regulatory hurdles and uncertainties coupled with still relatively high technology costs constitute the main barriers today. However, these obstacles do certainly not seem insurmountable and it remains to be seen how these will be managed in the future.

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Abbreviations

AC	Alternating current
ACER	Agency for the Cooperation of Energy Regulators (of the EU)
BESS	Battery energy storage system
BPR	Balancing responsible party
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CO_2	Carbon dioxide
COP21	21st Conference of the Parties (to the UNFCCC)
CPUC	California Public Utilities Commission
DERP	Distributed energy resource provider
DOE	U.S. Federal Department of Energy
DSI	Demand-side integration
DSO	Distribution system operator (sometimes also: distribution network operator, DNO)
EEGI	European Electricity Grid Initiative

ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EV	Electric vehicle
GHG	Greenhouse gas
HVDC	High-voltage direct current
IEA	International Energy Agency
IIIEE	International Institute for Industrial Environmental Economics
IPCC	Intergovernmental Pannel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre (of the European Commission)
LA	Lead-acid (battery)
LCOE	Levelised cost of electricity
Li-Ion	Lithium-Ion (battery)
MLP	Multi-level perspective
NaS	Sodium-Sulphur (battery)
NiCd	Nickel-Cadmium (battery)
PCI	Projects of Common Interest (to help create and integrated EU energy market)
PHS	Pumped hydro storage
ppm	Part per million
PV	Photovoltaic
RD&D	Research, development and demonstration
R&D	Research and development
REN21	Renewable Energy Policy Network for the 21st Century
RET	Renewable energy technology
SET-Plan	Strategic Energy Technology Plan (of the EU)
SETIS	Strategic Energy Technologies Information System (of the EU)
SMES	Superconduction magnetic energy storage
SNM	Strategic niche management
T&D	Transmission and distribution
TIS	Technological innovation system
TM	Transition Management
TSO	Transmission system operator
TYNDP	Ten Year Network Development Plan (from ENTSO-E)
VAR	Volt-ampere reactive (unit of reactive power in an AC electric power system)
VRB	Vanadium redox-flow battery
VRE	Variable renewable energy
UNFCCC	United Nation's Framework Convention on Climate Change
USA	United States of America

1 Introduction

> *"The revolution here is from hierarchical to lateral power. That's the power shift. So increasingly a younger generation that's grown up on the internet and now increasingly distributed energies, they're measuring politics in terms of a struggle between centralized, hierarchical, top-down and closed and proprietary, versus distributed, open, collaborative, transparent. This shift from hierarchical to lateral power, is going to change to way we live, the way we educate our children, and the way we govern the world."*
>
> Jeremy Rifkin.

1.1 Background and Problem Definition

Despite the fact that the science on anthropogenic climate change is evident (IPCC, 2013), as the "warming of the climate system is unequivocal" (p. 4) and the "human influence on the climate system is clear" (p. 15), global greenhouse gas (GHG) emissions, primarily from the persistent burning of fossil fuels, are still rising. Carbon dioxide (CO_2) concentrations have now reached a new milestone of above 400 parts per million (ppm) in the atmosphere, a level not seen in at least 800 000 years (Thompson, 2014). In the face of scientific evidence that indicates a growing crisis, international policymakers have still not been able to implement a global agreement to curb GHG emission and mitigate climate change related risks. Whether the year 2015 will mark a turning point in international climate change action with the upcoming global summit *COP21 of the UN Framework Convention on Climate Change (UNFCCC)* in Paris by the end of 2015 still remains to be seen. Yet momentum is building and in 2014, energy sector related CO_2 emissions have stalled for the first time in 40 years despite economic growth (IEA, 2015b), which could mark a first sign of decoupling CO_2 emissions from economic activity. Moreover, some countries and especially the European Union, as well as some of the larger and innovative corporations have realized the problem that inaction is simply too costly (Stern, 2007) and have thus started to take the lead to move forward on tackling climate change and transition their economies and energy systems.

As proven and cost-effective renewable energy technologies (RETs), such as solar and wind power, are now widely available and becoming cost-competitive with fossil fuel based energy technologies, the transition towards low-carbon economies within the next decades seems more and more certain (e.g. IEA, 2012, 2015a; IPCC, 2014; IRENA, 2014; Jäger-Waldau, Szabó, Scarlat, & Monforti-Ferrario, 2011; Martinez & Hughes, 2015; McCrone, Moslener, Usher, Grüning, & Sonntag-O'Brien, 2015; REN21, 2015). In many parts of the world and most European countries, wind energy is already today the cheapest form of new power generation, even without subsidies (Bloomberg New Energy Finance, 2015). Hence, it is expected that further cost reduction for wind and solar power of over 30 % until 2040 will lead to a doubling of the RET penetration level to 46 % of the electricity mix. In recent years, the deployment rates for RET in some parts of the world have seen significant increases due to rapid technology and installation cost reductions, as well as incentive mechanisms. As of 2014, China (153 GW), USA (105 GW), Germany (86 GW), Italy and Spain (both 32 GW) are the top five countries with the most installed renewable power capacity (excluding hydro) and other European countries like Denmark, Sweden or Portugal are among the world leaders of installed renewable energy capacity (excl. hydro) per capita (REN21, 2015). In some of those countries high levels of wind power penetration, with for instance almost 40 % for Denmark or 27 % for Portugal in 2014, are already a reality today and show that RETs are not only on the rise but also possible to handle in today's grids. However, the transition of entire economies and energy systems towards clean and affordable RETs presents not only policymakers but also other market actors and individual citizens with both significant challenges and opportunities.

On a global perspective, major recent publications (IEA, 2015a; IRENA, 2014; REN21, 2015), among others, all indicate that the decarbonisation of the electricity sector and increasing shares of RETs in the electrical system offers the biggest potential, both in terms of lowering GHG emissions and increasing the share of renewables. Turning focus to the Nordic region, the energy and electricity outlook scenarios described in the *Nordic Energy Technology Perspectives* (IEA, 2012) present scenarios that include a significant higher share of renewables, in particular wind power, in all Nordic countries ahead to 2050. While the overall power consumption in the Nordics has remained more or less constant over the past years, the decarbonisation scenarios until 2050 suggest a higher demand for electrification, which would also increase future electricity consumption (IEA, 2012). Likewise in Sweden, the Swedish Energy Agency (2012) and the Swedish grid operator Svenska Kraftnät (2013b) expect a larger share of renewables, mainly wind energy, to be deployed and integrated into the grid in the upcoming years. The Swedish Energy Agency (2014) predicts that while electricity demand will remain more or less constant, power production will increase during the next five years. After a peak around 2020, power production will decline due to planned phase-out of the oldest nuclear power reactors. The Swedish renewable energy target of 50 % (for total energy usage; or 63 % for the electricity sector) adopted by the Swedish Parliament (Regeringskansliet, 2010) under its commitment to the *EU Directive 2009/28/EC on the promotion of renewables* (2009), in combination with the Swedish electricity certificate system can be seen as the main driver for the expansion of renewable electricity production. The specific objective of the electricity certificate system is to increase the share of electricity produced from renewables by 25 TWh by 2020, and electricity from wind power is expected to be one of the biggest contributors (Swedish Energy Agency, 2012). May 31, 2015 marked a milestone one the Swedish electricity market, as wind power produced for the very first time (during an hour) more electricity than nuclear power (Svensk Vindenergi, 2015). In order to establish the required conditions for the further expansion of wind power production up to 30 TWh by 2020, from about 6.1 TWh in 2011, the Swedish Parliament has set a planning framework to cope with the rapid development. Sweden has seen double-digit growth rates well above 15 % in past few years for electricity produced from wind power and reported 11.5 TWh (ca. 8 %) of annual wind energy generation in 2014 (Svensk Energi, 2015b). The Swedish Energy Agency's (2015a) latest predictions show continued growth in wind power production up to about 15 TWh until the end of 2015 and around 17 TWh by 2017.

However, the integration of rapidly expanding RETs into the power system can pose challenges to the electrical grid for several reasons (Martinez & Hughes, 2015). First and foremost, renewables such as wind power and solar are variable renewable energy (VRE) sources: simply speaking, there is limited predictability as the wind does not always blow and the sun does not always shine, or shine brightly enough. [1] Balancing the variable and non-dispatchable supply with also fluctuating demand in the grid, for instance at times with excess energy production when there is more energy from VRE available than is actually needed (or the exact opposite with low VRE supply and peak demand), requires a well-coordinated interplay of various market actors and an adequate technological infrastructure with high

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[1] It is worth pointing out that renewable energy sources, such as wind and solar, are per definition *varying* or *fluctuating*, some people also tend to use *intermittent*, sources of supply depending on the availablity of the wind and sun. However, it is important to distinguish between these terms, as they are sometimes used interchangably which can be confusing. Renewables are not the only source of variablity in a power system and e.g. demand also fluctuates, but the electricity grid is essentially designed to balance supply and demand and handle such uncertainty. Large amounts of renewables distributed over a large geographical area on an aggregated level are much less varible then just one single unit in one location, and thus the aggregated supply of renewables in a system is more easily predictable despite its stochastic nature. On the other hand, conventional power plants, which sometimes fail or have to be switched off for some reason, are in that sense more *intermittent*, or *dispatchable*. For this reason and as additionally explained in various sources (IEA, n.d.; Knight, 2015; Morris, 2014; NREL, n.d.; Sørensen, 2015), most studies today use the term *variable renewable energy*, or short *VRE*. This thesis will therefore also only use the term *VRE*.

flexibility (IEA, 2014c; Martinez & Hughes, 2015; Milligan et al., 2009). Secondly, the spatially distributed nature of RETs, compared to the more centralized location of fossil fuel and nuclear power plants is another important aspect that needs to be dealt with when integrating increased amounts of RETs into the grid. Moreover, the sometimes geographically remote location in areas with favourable weather conditions (i.e. wind and sun) further adds to the complexity of integrating VRE into the grid (IEA, 2014c). Lower VRE penetration levels of about 5-10 % are normally not a significant technical barrier for grid integration. Some practical examples of countries like Germany, Denmark, Sweden, Spain Portugal, Ireland or the UK, which already reach or even exceed such penetration levels show that the grid integration has not been a major issue so far (IEA, 2014c). Some studies (IEA, 2014c; Martinez & Hughes, 2015; Milligan et al., 2009) show that grid integration for VRE penetration levels over 30 % are not only feasible but also come at modest costs increases to the power system in the future.

However and seen as a whole, these changes constitute a destabilisation of the existing energy regime and the emergence of a new energy landscape. This energy system transition challenges the *conventional* structure of the grid in a technical sense. It also threatens established business models and capacities of utility companies and other electricity market actors. Therefore, they are required to adopt fundamentally new and comprehensive ideas and solutions in order to cope with the transformation that is underway. Moreover, updated policies and regulations with the right incentives need to be adopted to account for the rapid changes on the energy landscape in order to enable a smooth transformation in a cost-efficient manner. The new energy landscape will most likely be more decentralised, interconnected, flexible and smart, much like the internet (Bronski et al., 2014, 2015; Parkinson & Gilding, 2014; Rifkin, 2011). A transition away from traditional nuclear and fossil fuel based energy systems towards completely renewable energy systems with the entire demand and supply based on renewable energy requires profound and well-synchronized changes in the following areas (Lund, 2010): demand response technologies related to energy savings and conservation (e.g. demand-side management), efficiency improvements in the supply system (e.g. combined-cycle gas turbines CCGT, combined heat and power CHP plants), and the integration of VRE sources.

With the background described above, the scope of this thesis therefore, deals with the integration of VRE sources, in this case wind energy, into the Swedish electricity system. However and besides these technological aspects of the transition towards renewable based energy systems, new applications, services and business models are also needed and require all market actors to respond to the changing energy landscape. Hence, this thesis will look into the uncertainties and opportunities regarding solutions, such as electricity storage, that enhance power system flexibility and help to accommodate increasing volumes of VRE. The expansion of wind power plays an important role in the Swedish Energy Agency's considerations towards a sustainable energy future. Therefore, the specific need to further investigate battery storage solutions as a means for providing system flexibility and therefore accommodating higher shares of variable wind energy was expressed by the Swedish Energy Agency.

Historically, most of the electricity was provided with centralised non-renewable energy sources, such as nuclear and fossil fuel based thermal power plants plus hydropower, which all where to a certain degree dispatchable and *only* had to deal with fluctuating demand (IEA, 2014b). Nowadays, managing the more variable electricity supply still heavily relies on dispatchable power plants to maintain grid flexibility. In Sweden, hydropower is essentially providing this flexibility service as a dispatchable electricity source due to the conventional system infrastructure in combination with the reliance on nuclear-based generation in the past. The IEA (2014c) suggests that first system-friendly deployment of VRE sources (i.e. timing, location, technical capabilities, design and curtailment) should be considered, then overall system and market operations can be improved and lastly new investment in further flexible resources should be made. Sweden is approaching higher penetration levels of wind power and reached almost 8 % of the total electricity production in 2014 (Svensk Energi, 2015b). This is expected to grow by approximately another 6 TWh until 2017 (Swedish Energy Agency, 2015a) and thus market design and system improvements together with investments in flexibility enhancing options are becoming inevitable at some point in the future. Research from Bloomberg New Energy Finance (McCrone, 2015) predicts that the global need for flexible capacity will be almost 15 times higher at approximately 858 GW in 2040. Besides using conventional power plants for more flexible production, there are basically three low-carbon options available to grid operators and other market actors to deal with the integration and balancing of supply from VRE to maintain grid flexibility (Bird, Milligan, & Lew, 2013; Cochran et al., 2014; Denholm, Ela, Kirby, & Milligan, 2010; IEA, 2014c; Lehmann et al., 2012; Sørensen, 2015; Trümper, Gerhard, Saatmann, & Weinmann, 2014):

- grid development and interconnections (e.g. trade and distribution arrangements),
- demand-side management (e.g. load-levelling via smart meters and/or time-dependent price differentiation),
- energy storage (at various scales and technologies).

Up until today, market actors often preferred the first two options because of familiarity, experience, cost-effectiveness, and existing grid infrastructure that is already in place (IEA, 2015a). However, energy storage technologies are becoming more and more cost-competitive on the market and are therefore expected to play a more important role in the future (Chen et al., 2009; EPRI, 2010; IEA, 2014a, 2014b; IRENA, 2015b; Kousksou, Bruel, Jamil, Rhafiki, & Zeraouli, 2014; Martinez & Hughes, 2015). In particular, the grid integration due to the increased uptake of VRE will become require additional solutions and applications for balancing, load-shifting and improvement of the power quality. Some argue (IEA, 2014a, 2014c; IRENA, 2015b; Martinot, 2015) that when penetration levels of VRE in stable and reliable power systems are above 30-40 %, energy storage appliances are becoming an integral part of the electricity grid. Other studies (Alexander, James, & Richardson, 2015; Budischak et al., 2013; Delucchi & Jacobson, 2011; Jacobson & Delucchi, 2011) have even demonstrated that power systems based on nearly 100 % renewables, in combination with the above mentioned flexibility options, including storage, are theoretically possible.

While some countries and regions in the world may not yet have the urgent need for energy storage solutions for various reasons, others have already taken measures to incentivise energy storage installations in order to accommodate increasing volumes of electricity from VRE sources. For instance in the USA, the *U.S. Federal Department of Energy (DOE)* has a multi-million US$ funding programme in place that helps to foster research, development and demonstration (RD&D) of energy storage solutions (Martinez & Hughes, 2015; U.S. Department of Energy, 2013). Moreover, the State of California has adopted a storage mandate in 2013 that requires the three biggest utilities to each install 1 325 MW of energy storage capacity by 2020 (CPUC, 2015; EPRI, 2013; IRENA, 2015b) in order to help integrate VRE and improve the power system flexibility. Other countries that started to promote energy storage solutions through regulations and incentive schemes include Germany, Italy, the UK Japan, or South Korea (IEA, 2014a; IRENA, 2015b; Martinez & Hughes, 2015; U.S. Department of Energy, 2013).

There exist a variety of different energy storage options, such as *pumped hydro storage (PHS)*, *compressed air energy storage (CAES)*, *flywheels*, as well as *electrochemical batteries* with *lithium-Ion (Li-Ion)*, *lead acid (LA)*, *sodium sulphur (NaS)*, or *redox-flow* technology. However, PHS is the most significant storage technology today and accounts for about 99 % of all installed electricity storage capacity, whereas for instance CAES only represents a very small fraction of 0.31 %, followed by NaS batteries with 0.22 % and Li-Ion battery with only 0.07 % (IEA, 2014b).

Since the 1970s, PHS has been installed, mainly in combination with nuclear power plants, similar to Sweden, where PHS could be used for price arbitrage to store excess electricity at off-peak times and then fed-in to the grid at demand peak hours to sell the electricity at high prices. This has proven to be an effective business model for utilities for years until the late 90s. But with the changes in market design and the uptake of renewables with very low marginal cost and oftentimes priority feed-in, wholesale electricity prices have come down. This basically eliminated the possibility of price arbitrage in many places and ultimately put such business models at risk (IEA, 2014b). However, the rapid deployment of renewables, with the need to handle supply-side variability, could trigger a new wave of storage deployment. Centralized PHS can still be a viable storage option under certain circumstances, but with location constraints, lower wholesale prices due to VRE, and the distributed nature of renewables, uncertainty remains (IEA, 2014b).

Other storage technologies with higher flexibility and at various scales seem to be better alternatives. When it comes to electrochemical batteries (or also *battery energy storage systems, BESS*), LA batteries are currently the leading technology in the industrial battery sector for grid support services, but their innovation potential is relatively low (IEA, 2014b). Li-Ion batteries show the most promising development, both in terms of capital cost decrease and performance improvements, mainly driven by the development and uptake of electronic vehicles (EVs) (Gerssen-Gondelach & Faaij, 2012; Liebreich, 2013; Normark & Faure, 2014; Nykvist & Nilsson, 2015; Weiss et al., 2012). Nonetheless, both the IEA (2014b) and IRENA (2015b) also point out that battery energy storage technologies show positive developments but further research and improvements are still needed in order upscale and make them a viable and competitive option for grid applications. The threshold of US$ 100/kWh is considered as a lower limit in order to compete on the market and technologies such as Li-Ion batteries are showing promising developments in this direction (IEA, 2014a; IRENA, 2015b; Liebreich, 2013). Li-Ion batteries have seen cost decreases of approximately 14 % annually since 2007, and currently Li-Ion battery costs are somewhere between US$ 300-600/kWh (Citigroup, 2015; IEA, 2015a; Liebreich, 2013; Nykvist & Nilsson, 2015). On the upper range, Citigroup (2015) analysts consider costs of around US$ 230/kWh, equivalent to current PHS grid costs, as the threshold target for BESS. Given the rapid cost decreases and steep learning curve, this translates into a global market potential of about 240 GW (excluding EV batteries) or more than US$ 400 billion by 2030. The IEA (2014a) Technology Roadmap on Energy Storage estimates a need for approx. 310 GW in additional storage globally that would be needed in order to accommodate global VRE shares of 27-44 % of total electricity production in 2050. Other market research (Navigant Research, 2014) predicts that utility-scale battery storage will grow by about 63 % annually over the next 10 years, which translates into global market revenue of about US$ 18 billion or 51 GWh of installed capacity, up from US$ 222 million or 412 MWh in 2014. Given this positive market outlook and against the background described above, this study attempts to explore potential market opportunities as well as drivers and barriers for BESS for the Swedish electricity market.

However, as such a transition in the energy industry goes beyond just technological changes, it requires a fundamental system-wide transformation that encompasses a network of different actors, institutions, as well as material artefacts and knowledge. In that sense it marks a regime shift from a fossil fuel based economy towards a more sustainable, low-carbon system along various dimensions, including technology, materials, organisation and institutions, politics, economics, as well as socio-cultural values and behaviour. According to literature (Markard, Raven, & Truffer, 2012) this sustainability transition, or more specifically a socio-technical transition of the energy landscape, does not just happen overnight but takes place over a considerable time-span (e.g. 50 years), involves multiple dimensions of the economic, social and technological landscape and ultimately shifts the established modes of production and consumption towards more sustainable ones. Hence, the emergence of battery energy storage on this new energy market landscape requires a social and technological innovation system that takes into account the multiple actors and dimensions. This research will therefore take a multi-dimensional approach to assess potential market drivers and barriers for BESS options on the Swedish electricity market.

Despite the fact that this thesis specifically explores market potentials within the Swedish context, it can be useful for market actors in other jurisdiction, especially those with similar market designs and perspectives, to draw some key learnings form this study. However, the country specific nature of this analysis does not attempt to discover universal and generalizable findings, but rather explore potential market drivers and barriers for BESS in the Swedish context. This might inspire others to undertake similar steps and further advance the required energy system transition in other settings, or further analyse some of the findings of this study in more detail. Therefore, this study should only be seen as a first attempt to look into uncertainties and opportunities connected to BESS in Sweden, which could subsequently form the basis of a larger study on the Nordic level (and beyond), or which could explore new business models or applications areas for BESS in Sweden (and other countries).

1.2 Purpose and Research Question

Against the background described above, the main aim of this thesis is to contribute knowledge through examining the uncertainties and opportunities in connection to grid-scale electricity storage of batteries in Sweden in order to accommodate increased volumes of VRE from wind power and provide additional power system flexibility.

Whilst there are many technological solutions to manage VRE, this thesis research focuses mainly on electrochemical battery storage technologies due to the promising development in recent years. The reason for this is that firstly, battery storage technologies are a very effective flexibility solution due to their technical characteristics that can be used in a variety of areas. Secondly and even though batteries are still quite expensive, they have seen significant technological improvements over the last years and are gradually of becoming a viable option instead of or in combination with other flexibility enhancing solutions, depending on their application area (Akhil et al., 2013; Chen et al., 2009; Dunn, Kamath, & Tarascon, 2011; EPRI, 2010; IEA, 2014c; IRENA, 2015b). Furthermore and due to the rapid development of these electrochemical storage technologies, it is not yet very well understood, at least in practice, what services battery storage options can provide in order to help integrate larger amounts of VRE and enhance grid flexibility. Especially from an institutional and business point of view, potential market opportunities as well as drivers and barriers of such battery storage solutions are still to be explored, especially with regards to the Nordic and Swedish electricity market. A better understanding of the different flexibility solutions, including their services and benefits as well as their market forces, in a specific market context can ultimately help to make smarter decisions in order to enhance grid stability and flexibility while saving costs. Moreover, some other countries have started to implement incentive schemes and support mechanisms for BESS and the Swedish Energy Agency perceived that there is a knowledge gap on the market potentials of such grid-scale battery storage technologies in Sweden. The Swedish electricity market actors, including utilities, transmission and distribution (T&D) companies, authorities, regulators, researchers, and other service providers all have unique know-how and expertise and play an essential role in shaping the future of the Swedish electricity system. Therefore, and in agreement with the Swedish Energy Agency, those market actors are being considered the main focus group for this study in order to investigate uncertainties and opportunities for the future deployment of BESS.

Within this context the guiding research question for this master thesis has been formulated as follows:

> *RQ: How is the market for grid-scale BESS for integrating larger volumes of VRE from wind power becoming a reality in Sweden?*

Based on this overarching question, two more specific research questions have been formulated with the purpose of better operationalizing the above question:

> *RQ 1.1: In which ways can BESS be integrated into the Swedish electricity grid?*
>
> *RQ 1.2: What are the perceived drivers and barriers for the future investment and deployment of BESS in Sweden?*

In order to help further delineate the study and provide information that contributes to answer the research question, the following objectives and tasks have been designed:

1. Carry out a literature review on transition theory, in particular with focus on sustainability transitions outlined by Markard, Raven and Truffer (2012), in order to delineate a suitable conceptual framework that helps to support the study in explaining transition processes and regime shifts of entire systems of production and consumption.
2. Identify and describe the current state of integrating and balancing VRE from larger volumes of wind energy into the Swedish electrical grid and outline the main flexibility options and storage applications, as well as their function(s) for the different market actors in Sweden.
3. Characterise and delimit the main functions and roles as well as benefits of electrochemical battery systems for the various electricity market actors within the context of grid integration and balancing of VRE from wind power.
4. Outline and describe in short the current state-of-the-art support mechanisms, incentive schemes and policies for grid-level BESS that are currently in place in other countries and regions around the world with the intention to better accommodate larger proportions of VRE and enhance power system flexibility.
5. Determine by the means of the adopted conceptual framework (i.e. multi-level perspective on socio-technical transitions) and with the data collected through interviews and literature how grid-scale BESS fit into the energy transition process on the Swedish electricity market against the need for grid integration and balancing increasing shares of VRE from wind power and contribute to grid flexibility.
6. Based on the findings from the previous task/objective and using the framework as a strategic tools to identify potential drivers and barriers among various levels and market actors in Sweden for large-scale BESS, potential market opportunities in Sweden for the future investment and deployment of BESS in combination with VRE can be outlined.

1.3 Scope and Limitations

What concerns the technological aspect, this thesis will solely focus on battery energy storage systems, more precisely electrochemical BESS on grid-level scale in combination with mid- to large-scale wind power installations.

Whilst there are various electrochemical battery technologies available and used today at various scales and for different applications, such as Lithium-Ion (Li-Ion), Lead-acid (LA), Sodium-Sulphur (NaS), Nickel-Cadmium (NiCd), or flow batteries (IEA, 2014b; Sabihuddin, Kiprakis, & Mueller, 2014), their characteristics and performance can vary significantly. Nevertheless, when compared to other electricity storage technologies, such as PHS, compressed air energy storage (CAES), flywheels, supercapacitors, or hydrogen, batteries share relatively similar characteristics in terms of application areas on the power grid (Denholm et al., 2010). Thus, for simplicity reasons, throughout this thesis the term *BESS* will be used simply referring to batteries in general, unless otherwise stated.

In order to make clear distinction here regarding e.g. *grid-scale* or *mid- to large-scale* installations for BESS and wind farms respectively, approximate range limits should be defined. However, when looking at BESS, there are various parameters, such as the charge and discharge capacity (Watts) or the energy storage capacity (Watt-hours), discharge time, or duration, round-trip efficiency, charging/discharging cycles or lifetime considerations that might be important and can greatly differ from installation to installation (EPRI, 2010). Hence, there is no definite range limit for *grid-scale* BESS, but for the sake of clarity a distinction can be made what actors install and use BESS and what purpose it serves. In this thesis, any BESS that is installed and used *in-front-of-the-meter*, as compared to residential *behind-the-meter* [2] battery installations, will be considered *grid-scale* as it serves mainly utilities, T&D companies and other electricity market service providers.

The same can be said for wind farms, as the rapid technological development of the wind turbines has led to ever larger and powerful installations (Wizelius, 2015). Therefore, any wind turbine and/or wind farms that are used for grid connection and are operated by any kind electricity market actor, except for private households and off-grid applications, can be considered *mid- to large-scale* installations.

According to the IEA (2014c), variable renewable energy sources include solar PV, onshore and offshore wind, wave and tidal energy, and arguably also run-of-river hydropower. Solar PV and wind power account for the largest shares of recently installed VRE energy installation, however for the context of Sweden solar PV installations only play a marginal role as of today and wind power is the fastest growing RET with a predicted capacity of 17 TWh by 2017. For this reason, throughout the thesis the term VRE will only be used in relation to wind power.

Regarding the geographical scope of the thesis study, only the Swedish electricity market will be considered. However and pertaining to some of the research objectives/tasks stated in the section above, it will be necessary not to limit the analysis solely on the Swedish electricity market but take into account the interconnection of the Swedish with the Nordic grid and electricity market (i.e. Nord Pool Spot market area). Additionally, for the task of briefly outlining support policies for BESS, it also makes sense to broaden the geographical scope. What is more, as Sweden is a Member State of the EU, legislation on the EU level is affecting Sweden to a considerable degree and needs to be taken into account too.

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[2] *Behind-the-meter* refers to any application that is literally located behind the electricity meter and not on the grid. All electricity end-users (households, businesses, etc.) are connected to the grid via an electricity meter that counts the electricity flow (i.e. consumption, and nowadays also electricity production e.g. from a rooftop solar PV installation). Therefore, all installations, be it solar panels or storage units, which are located *behind-the-meter* are not considered part of the grid as long as the electricity remains *behind-the-meter*. Consequently, *in-front-of-the-meter* means basically on the grid.

1.4 Ethical Considerations

The main purpose and scope of the study has been developed partially in collaboration with the Swedish Energy Agency. The main contact at the Swedish Energy Agency, *Johanna Lakso* (Wind Power Analyst at the Wind Power Unit as part of the Market Development Department), has expressed the need to investigate certain aspects regarding market potentials for grid-level battery energy storage in combination with wind energy in Sweden and policy support mechanisms for that purpose in other part of the world, such as the USA. However, the remaining parts of this thesis, namely problem definition, research question, further scoping, research method and methodology, as well as the analysis have been developed and conducted by the author. With regards to the data collection, the data from interviews and literature have been gathered and analysed independently by the author. As stated above, the Swedish Energy Agency has provided some valuable contacts, but the majority of the interviewees have been selected independently by the author or via recommendations by other interviewees and according to the priorities presented in the method section (see *Section 3.3*).

1.5 Target Audience

The intended target audience for this thesis is first and foremost Swedish and Nordic electricity market actors, policymakers and other stakeholder involved in investing and deploying renewables and energy storage options. Utilities, and grid operators (both transmission and distribution companies) that deal with the installation, generation, connection and integration of wind energy into the electrical grid might have an interest in the current and potential future market developments. Policymakers and regulators might be interested in options to enhance grid flexibility and what market design conditions are currently supporting or withholding the deployment of BESS. Other researchers and academics might be inspired by the finding of the study to further investigate and research the field of BESS. The Wind Power Unit at the Swedish Energy Agency, with which the topic has been developed to provide inputs to their current work wind energy integration, serves of course as another main target audience. Hence, the readers of this study are expected to have some general technical understanding in the field of the energy and electricity.

1.6 Thesis Disposition

Following this introductory chapter, the second chapter gives a review of the current role of electricity storage in the power market. VRE integration challenges are summarised and the most important functions, applications and benefits of BESS in the power system are introduced. Then, support policies for BESS in other markets around the world are presented.

Chapter three elaborates on the methods and methodology used for this thesis. It starts with a brief literature review sustainability transitions, in order to identify a useful conceptual framework to structure the findings and analysis. Moreover, the applied research methods and chosen methodology are outlined.

The fourth chapter presents the findings using the selected conceptual framework.

In chapter five, the results of the previous chapter will be analysed. Furthermore, it will be discussed how methodological choices have influenced the results.

And finally, chapter six contains the conclusions of the study and makes some recommendation for future research.

2 Grid Integration of VRE and Battery Energy Storage

This chapter provides a literature review on the grid integration of VRE with special focus on the Swedish and Nordic electricity market structure. Furthermore, the main roles, functions, application services and potential benefits of battery energy storage system (BESS) for market actors are presented, both generally and in relation to Sweden. Finally, the last section provides a brief overview of policy support mechanisms and incentive schemes in other countries and regions around the world.

2.1 Power System Integration of VRE

From a technical perspective, the electrical power system is rather complex (Wizelius, 2015). The operation of power systems is a process that requires a constant balance of supply and demand in a narrow frequency band around 50 Hz in a cost-effective and efficient manner. Historically, power systems have been based on centralized electricity production units with the grid operators' main task to match the electricity demand (load) with the supply (generation) by forecasting the varying load and providing enough supply (Denholm et al., 2010). While some of the installed generation capacity supplies the baseload[3] power for large constant demand, the total generation capacity of a system is built to accommodate maximum loads. For this reason, some of the installed generation capacity is often unused and only switched on, or ramped up, for higher intermediate or peak loads to balance and regulate the power system. The output of flexible generation units, such as hydropower or CCGT and CHP plants, can relatively easily and quickly be changed, and therefore such installations are more suitable for *load-following* to accommodate variation in higher daily, weekly or seasonal demand. Moreover, some of these flexible units serve as responsive reserves for unforeseen variations (e.g. ancillary services for frequency regulation, load-forecasting errors, or other contingencies) and are often online running only as *spinning reserves* (i.e. they are running at reduced capacity and can be ramped up when needed). Nevertheless, such reserves, especially spinning reserves, increase the cost and reduce the efficiency of a power system, as it is usually less economic to run an installation at reduced capacity. On the other hand, less flexible generation units with high capital costs, such as nuclear power stations, are better suited for providing more constant power output and run close to maximum capacity supply (Denholm et al., 2010). Ultimately, power generation sources can be ranked according to their short-run, marginal costs in a so-called *merit-order* (excluding second order for reserves), which determines which installations will run first and ensures an efficient and cost-effective system operation. Hence, units with the lowest marginal short-run cost (e.g. hydropower) run whenever they are available to meet the expected demand, and generators with higher short-run costs, e.g. small thermal generation plants (e.g. CCGT or thermal coal), are only used for peak loads (Grubb, 1991).

However, with the increased uptake of variable renewable energy (VRE) in particular from wind and solar, the task of keeping the grid at constant balance becomes more challenging as not only load fluctuates but also some generation output varies. What is more, VRE sources are by their nature more decentralized and distributed and cannot as easily be ramped up or dispatched as the more centralized thermal generation units. The IEA (2014c) notes that the deployment of VRE leads to system impacts, which result from complex interactions of

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[3] The term *baseload* implies that such large generation units basically run around the clock at more or less constant capacity (usually close to full capacity) and thus steadily statisfy the minimum demand. However, and as the name suggests, such *baseload* generation units are rather inflexible and can only slowly be ramped or dispatched. In the emerging new electricity systems with increasing VRE sources, these characterisitcs are less and less needed, as more flexible generation units in combination with other flexibility solutions are more useful (Mariotte, 2015). Therefore, the term *baseload* seems rather archaic nowadays and will be avoided throughout the rest of this thesis.

various system components and are thus very system-specific. For instance, system properties, such as the spatial distribution of a system as well as how well supply from VRE sources and demand match, can have a distinct effect on the grid integration of VRE. On the other hand, some key characteristics of VRE generators (i.e. wind and solar) have a significant effect on power system's operations and investments, and seem to be more or less ubiquitously relevant (IEA, 2014c):

- *low short-run cost*, i.e. VRE run at very little cost once installed;
- *variability*, i.e. the available power output from VRE depends on weather patterns (wind or sun) and fluctuates over time and space;
- *uncertainty*, i.e. accurate forecasting of the power generation from VRE is usually only possible in the short term;
- *location-constrained*, i.e. geographic availability of VRE sources is not evenly distributed across areas and can only transported via the power grid (unlike fuels that can be shipped to different locations);
- *modular and distributed*, i.e. individual VRE generator units are much smaller than conventional thermal or hydropower plants and usually more decentralised;
- *non-synchronous*[4], i.e. generators of conventional power plants rotate synchronously at the same speed linked to the grid frequency and create system *inertia* (i.e. *spinning mass*), but VRE installations connect non-synchronously to the grid with power-electronics and provide limited (wind) or no (solar) spinning mass.

This gives rise to questions on how resources in the system can be optimized, how VRE sources can efficiently be integrated into the power system and how loads can be handled more flexibly, in order to maintain the balance and frequency in the grid. However, the knowledge and understanding of such questions and the above mentioned characteristics for VRE integration continues to evolve and will be briefly explained in more detail below.

Low Short-Run Cost of VRE

Costs for renewable power generation have seen dramatic declines over the last few years, especially VRE sources such as solar PV and wind power. In some cases, the *levelised cost of electricity (LCOE)*[5] for solar PV is already lower than fossil fuel based electricity generation without any financial support, and onshore wind is in many geographic areas even the most cost-competitive source of electricity available (IRENA, 2015a). Moreover and coupled with support mechanisms, future cost reductions can be expected that will further drive the deployment of renewables, which in turn drives down costs again; like a positive cycle. A transformation process in the power generation sector is already underway and the effects of low costs from VRE can already be witnessed on the power market. Once VRE are installed, they provide electricity at very low costs, practically for free (IEA, 2014c). As one can expect, this has far reaching impacts on other generation sources on the power market. Simply put,

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[4] Generators of all large power production units (e.g. nuclear or thermal power plants) rotate at the same *synchronous* speed and their electro-mechanical connection to the grid and this essentially determines the grid frequnecy of 50 Hz. This synchronous movement of large machinery creates a spinning mass and when there is deviation from the target grid frequency, it is experienced by all units simultaniously. A deviation from the target frequency tries to slow down or speed up these large generation units but due to their inherent inertia it would require a lot of energy to actually do so. Thus, the rotating spinning mass of the inert generators helps to stabilise the grid frequency (IEA, 2014c).

[5] *LCOE* is a metric to compare different electricity generation technologies while taking into account the multiple cost components for a given technology, such as manufacturing, installation, operation and maintenance cost, resource quality, performance, efficiency, fuel costs (if any), lifetime, cost of capital etc. IRENA (2015a) defines LCOE as „the ratio of lifetime costs to lifetime electricity generation, both which are discounted back to a common year using a discount rate that reflects the average cost of capital“ (p. 12). Also, it is important to note that *levelised cost of electricty* and *levelised cost of energy* are essentially the same (at least for the use in this study), as electricity is just a particular form of energy.

with the integration of larger volumes of VRE and given constant demand and no power plant retirement, the incumbent power generators are gradually displaced and their market share is reduced (i.e. merit-order effect, as illustrated in *Figure 2-1* below).

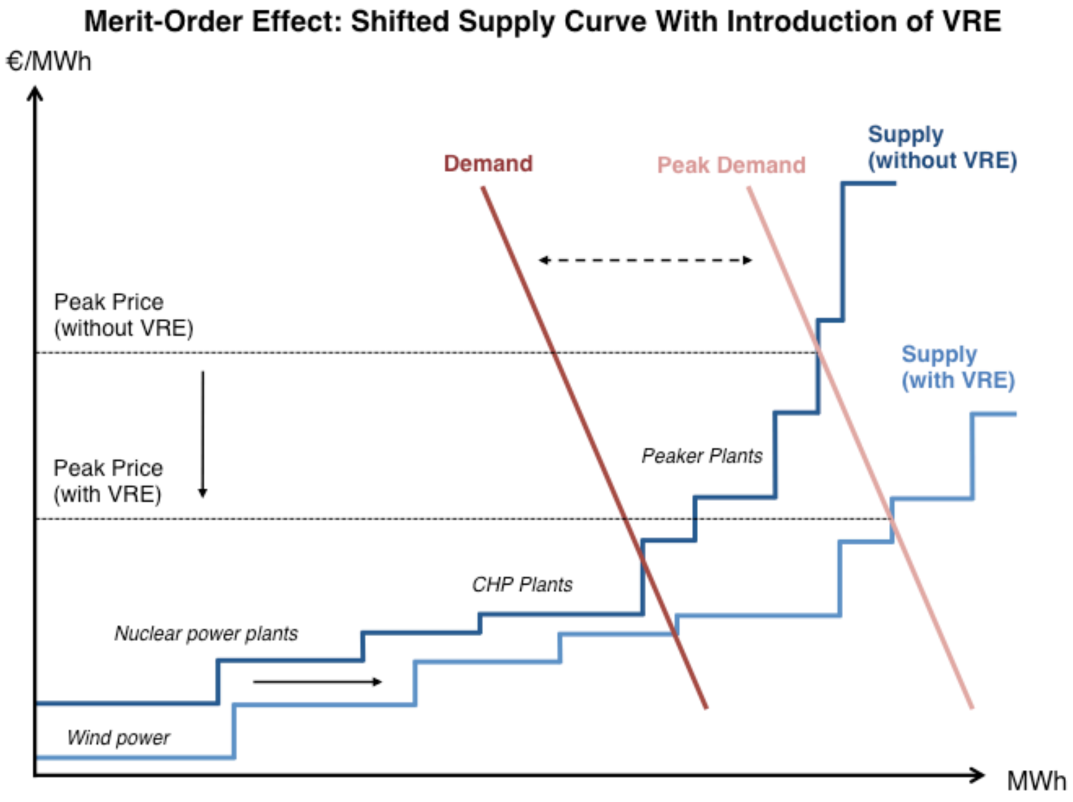

Figure 2-1. Simplified illustration of the merit-order effect (leftward shift of supply curve) resulting from the integration of low-cost VRE from wind power.

Source: own illustration based on similar figures (EWEA, 2010, p. 11; IEA, 2014c, p. 30).

Due to essentially zero marginal generation costs of VRE units, they rank highest in the merit-order on the electricity market and are used whenever available (Grubb, 1991). This holds still true in practice on the electricity market but the picture is a bit more complicated due to support policies of VRE sources. Usually, power generators sell their electricity on the market slightly higher than their marginal cost in order to make a profit. However, VRE generators with performance based support mechanisms (e.g. feed-in tariffs or green electricity certificate schemes) that offer their electricity directly on the market are able to bid below their true short-run cost, sometimes even at negative prices, since they still receive revenue (as long as support remains). In addition, VRE generation units often have priority dispatch, which means that they are allowed to feed-in their electricity at any time (IEA, 2014c). The result is that VRE generators displace the most expensive generators at the lower end of the merit-order and therefore reduce the electricity price (Clifford & Clancy, 2011; Sáenz de Miera, del Río González, & Vizcaíno, 2008; Sensfuß, Ragwitz, & Genoese, 2008). As a result of the merit-order effect, some generation units get pushed out of the market or have to run at reduced capacity. The overall effect of this is that there will be increased short-term variability and uncertainty of net load (i.e. total load minus VRE supply) on the power system (IEA, 2014c). Consequently and as VRE generators come on top of the merit-order, less other plants for providing minimum constant demand and more flexible generation in the form of mid-merit (for intermediate net load balancing) or peaking units (for peak loads) will be needed. A central effect of this transition process on the electricity market with larger shares of low-cost VRE is that GHG emissions from fossil fuel based power plants will be reduced and gradually replaced with renewable, emission-free[6] electricity (Holttinen, 2004).

Variability of VRE

A common belief is that VRE sources are intermittent and unreliable, as their production is difficult to forecast, fluctuates largely over times depending on weather conditions, and some sort of backup or firming is needed in order to smooth or shift their output (Milligan et al., 2009). However, such claims can be misleading and do not reveal the full picture of their roles, including costs and benefits, in the power system. In fact, several studies (Albadi & El-Saadany, 2010; Bird et al., 2013; Denholm et al., 2010; EPRI, 2011; Holttinen, 2005; Milligan et al., 2009; Milligan & Kirby, 2010; Wan, 2012) in different regions or countries with a substantial volume of VRE have shown, that the short-term variability of wind power decreases as more wind power units are deployed and integrated over a relatively large spatial area (over 100 km). The reason for this is quite simple and based on principle of statistical independence, as it can be seen in *Figure 2-2*.

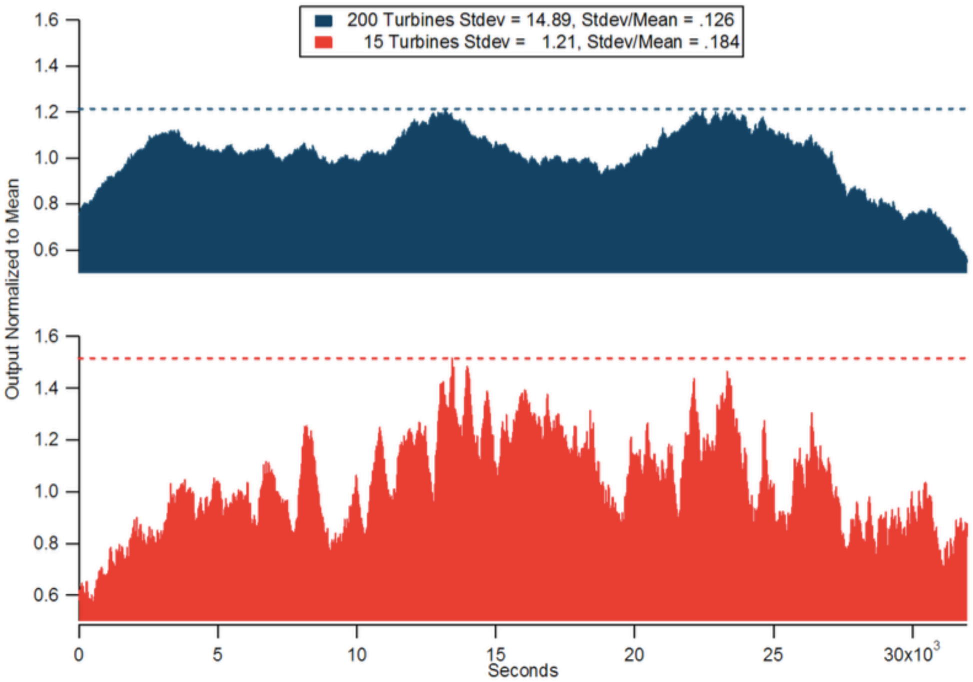

Figure 2-2. The difference of variability on the normalised output between 15 and 200 wind turbines.

Source: adopted from Milligan et al. (2009, p. 90).

For instance, only a few wind turbines, which are located in the same area, have the same wind conditions and thus vary more or less uniformly, plus the variability of their individual power output has a greater effect on the variability of the aggregated output. On the other hand, several hundred turbines spread over a large geographic do most likely not face the exact same

---

[6] The electricity supplied by VRE sources, such as wind and solar power, is essentially free of CO_2 or any other GHG emissions. However, when taking into account the full life-cycle, including materials, manufacturing and installation processes etc., CO_2 emission for e.g. wind power account for approx. 10 gCO_2/kWh of produced electricity. It should be noted though, that this number can vary significantly depending on various assumptions and situations (Lenzen & Munksgaard, 2002).

conditions across different sites and because of their larger number, the individual wind turbine variability has almost no effect on the variability of the aggregated power output. Thus wind power benefits greatly from aggregation and higher penetration levels over larger geographic areas, as the short-term power output of more wind turbines is much smoother and generally stochastic. On an aggregated system level, VRE output is very unlikely to experience very immediate up- or downward changes, and for this reason VRE sources are not intermittent but rather variable. Hence, when looking at the variability of VRE generators, the time period is what matters (IEA, 2014c). The variability of wind power output for short time periods (i.e. seconds and minutes) is smaller than over longer time periods (i.e. hours, days, or even weeks). When considering long-term wind power variability, Wan (2012) even argues that the inter-annual and seasonal changes of wind power output depend mainly on climate and regional weather patterns and therefore show similarities to hydropower. However, the variability of VRE generators can never be fully eliminated and yet this is another reason why more flexibility for balancing the grid is needed.

Uncertainty of VRE

Additionally, grid operators and generators have experience with unexpected changes in supply and demand by constantly adjusting the output of power plants and are thus somewhat used to dealing with uncertainties and variability. As system operators follow the changes in demand with controllable generation, the addition of VRE source does not significantly change the situation, as it would in fact be rather costly to follow the generation of a single source or load. The new reference point with VRE sources for grid operators is then the *net load*, i.e. the total demand minus generation from VRE sources (Cochran et al., 2014). In other words and simply put, the integration of VRE supply into the power system can functionally be seen as a *reduction* in demand from a grid operator's point of view (see *Figure 2-3* below).

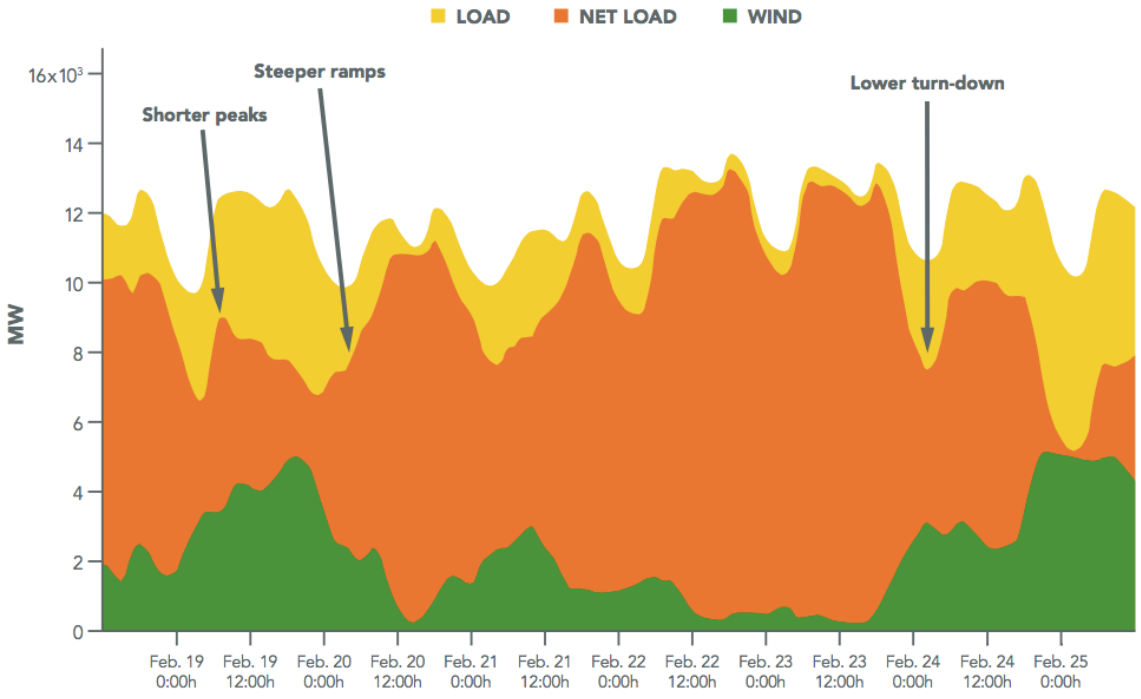

Figure 2-3. The integration of VRE from wind energy reduces the net load on the power grid.

Source: adopted from Cochran et al. (2014, p. 2).

Hence backup power plants, or storage units just for the sake of VRE generation is not required and would be quite costly (Milligan et al., 2009). Nonetheless, sufficient flexible generation resources and ancillary services for power quality and frequency support will be needed for high VRE penetration levels. Moreover, forecasting the VRE output also helps to reduce uncertainty, even though it is not possible to fully predict weather patters in the future that affect VRE generation. In recent years, the forecast for VRE output has increased substantially due to improved forecast models and more experience and knowledge with VRE integration. In general it can be said that the closer to real-time and the shorter forecast time intervals are, the more accurate the forecast becomes, which in turn reduces uncertainty and also operation costs. This implies that planning decisions for power system operations and the integration of VRE moves closer to real-time. But again, as the demand-side is also fluctuating and requires forecasting, it is likewise a source of uncertainty for power system operators. Therefore, the reserve and flexibility requirements of power systems depend on the aggregate uncertainty level (IEA, 2014c).

Location Constraints of VRE

The uneven distribution and decentralised nature of VRE sources can also have an effect on transmission lines and interconnectors. While incumbent power generation plants are also somewhat distributed across the grid, they are often placed near areas with high demand (with the exception of hydropower which is location-constrained). In contrast, VRE generators are installed where the weather conditions are most suitable. Similar to hydropower plants, such locations (i.e. offshore wind) may not necessarily be close to areas with high loads and thus the electricity has to be transported via transmission lines and interconnectors. This gives rise to questions whether the grid infrastructure should be built or expanded first in order to encourage the deployment of VRE installations in remote areas or vice versa; whether less favourable VRE source closer to demand areas might be more cost-effective; or whether the benefits of VRE generators justify the investment costs in grid infrastructure (IEA, 2014c). Curtailment of wind power generation in locations with weak grid connection might be one option to decrease the need for transmission line expansion (Agora Energiewende, 2013). Electricity storage applications close to wind power installation could be another possibility, which would then also reduce the need for power curtailment (Denholm, 2012).

Modularity and Distributed Nature of VRE

Furthermore, as VRE generation units are much smaller (e.g. a few hundred kW up to around 7 MW for wind turbines) and more dispersed, they are often connected to the distribution grid rather than to the transmission grid. As VRE penetration levels increase, this can direct implications on the local transmission grid and will need adjustments in grid infrastructure and operation. The power flow between transmission and distribution grid becomes bi-directional and smart grid solution for the sub-grid will be needed in order to maintain voltage and grid stability (IEA, 2014c). Once again, more flexibility will also be needed on local distribution grids in order to keep them stable and avoid curtailment of VRE output. BESS at various scales could therefore provide such flexible services in a smart grid (Agora Energiewende, 2013; Denholm, 2012). However, some researchers (Denholm et al., 2010; Milligan et al., 2009; Sørensen, 2015) also point out that power systems with larger volumes of VRE installation, which are of smaller scale and more distributed, are more stable and resilient than systems based on centralised generation units. That is because the output of VRE can be relatively well forecasted and the unpredicted failure of an individual unit in distributed system with smaller units does not interrupt the system as severely as in a more centralised system with large power plants.

Non-synchronous Nature of VRE

What is more, is that incumbent power generation plants run in a synchronous manner with the same spinning speed that ultimately defines the grid frequency of the power system. Their electro-mechanical link to the grid creates a sort of *spinning mass* that is called *inertia*, and helps to maintain the grid frequency at constant levels. VRE generators on the other hand are non-synchronous and use power electronics to connect to the grid. Thus, they lack the electro-mechanical connection to the grid that provides system inertia. With high volumes of VRE generators more and more synchronous power generator units are displaced and at some point alternative ways to provide this inertia need to be found. For instance, the rotating blades of wind turbines also contain spinning mass that can be used to provide *synthetic inertia.* Fast-responding battery storage applications, especially for solar PV but also for wind power, can also be used to provide synthetic inertia and help to maintain the grid frequency at constant levels (IEA, 2014c).

It is important to stress again, that the nature of such integration challenges (e.g. operational practices, grid infrastructure, the generation fleet, as well as regulatory and administrative issues) are system-specific and differ from power system to power system, depending on various factors and circumstances. Precisely because of those challenges there is a need for services and applications that can provide more flexibility on the grid to accommodate larger volumes of renewables (Bird et al., 2013). Such flexibility measures will certainly entail additional costs and can become a barrier for further expansion of VRE generators at higher penetration levels (Albadi & El-Saadany, 2010). To what extent such costs can be associated solely with the integration of VRE sources remains largely unclear despite many attempts to do so (Milligan et al., 2011). It can be argued that flexibility solution are and will be adopted irrespective of increased shares from VRE because they help to reduce overall power system costs (Bird et al., 2013).

Additionally, it is crucial that regulatory barriers for flexibility solutions are removed in order to ensure efficient and cost-effective allocation of resources. For instance, IRENA (2015a) affirms that "there are no technical barriers to the increased integration of variable renewable resources, such as solar and wind energy. At low levels of penetration, the grid integration costs will be negative or modest, but can rise as penetration increases. Even so, when the local and global environmental costs of fossil fuels are taken into account, grid integration costs look considerably less daunting, even with variable renewable sources providing 40 % of the power supply. In other words, with a level playing field and all externalities considered, renewables remain fundamentally competitive" (p. 14).

2.1.1 The Need for More Flexibility in the Power System

In order to provide enough flexibility on the grid with increased penetration levels of VRE, there are numerous solutions at hand to ensure effective and efficient system operation. In general, the existing grid infrastructure and generation fleet, the VRE penetration level, market operations and pricing mechanisms, as well as operating procedures determine the power system flexibility (EPRI, 2011). On the one hand and as outlined in the previous subsection, there are several other options for the optimised grid integration of VRE (e.g. inertia support, frequency regulation, or other ancillary services) (Bird et al., 2013). On the other hand, as the grid integration of VRE has usually system-wide implications, the literature (Bird et al., 2013; Cochran et al., 2014; Denholm et al., 2010; IEA, 2014c; Lehmann et al., 2012; Sørensen, 2015; Trümper et al., 2014) generally identifies four flexibility options for the power system that can help to accommodate larger volumes of VRE:

- *grid infrastructure* (i.e. grid development, interconnections, trade arrangements);
- *dispatchable and flexible generation* (e.g. CHP, CCGT, or hydropower);
- *energy storage* (i.e. at various scales and technologies for different applications);
- *demand-side management* (e.g. via smart pricing and smart grid solutions).

While these four solutions are more or less technology and infrastructure related, operational and institutional flexibility enablers are at least equally important because they have a direct influence on technological choices and infrastructure investments. Operational and institutional options can include optimised system operations (e.g. resource planning, forecasting, and scheduling) and improved market design (e.g. coordination between balancing areas, or pricing mechanisms) that can help to better manage uncertainty and variability on the gird with higher levels of VRE (Bird et al., 2013; Cochran et al., 2014; EPRI, 2011; Trümper et al., 2014). *Figure 2-4* below summarises state-of-the-art flexibility options along various areas while comparing relative costs of each option.

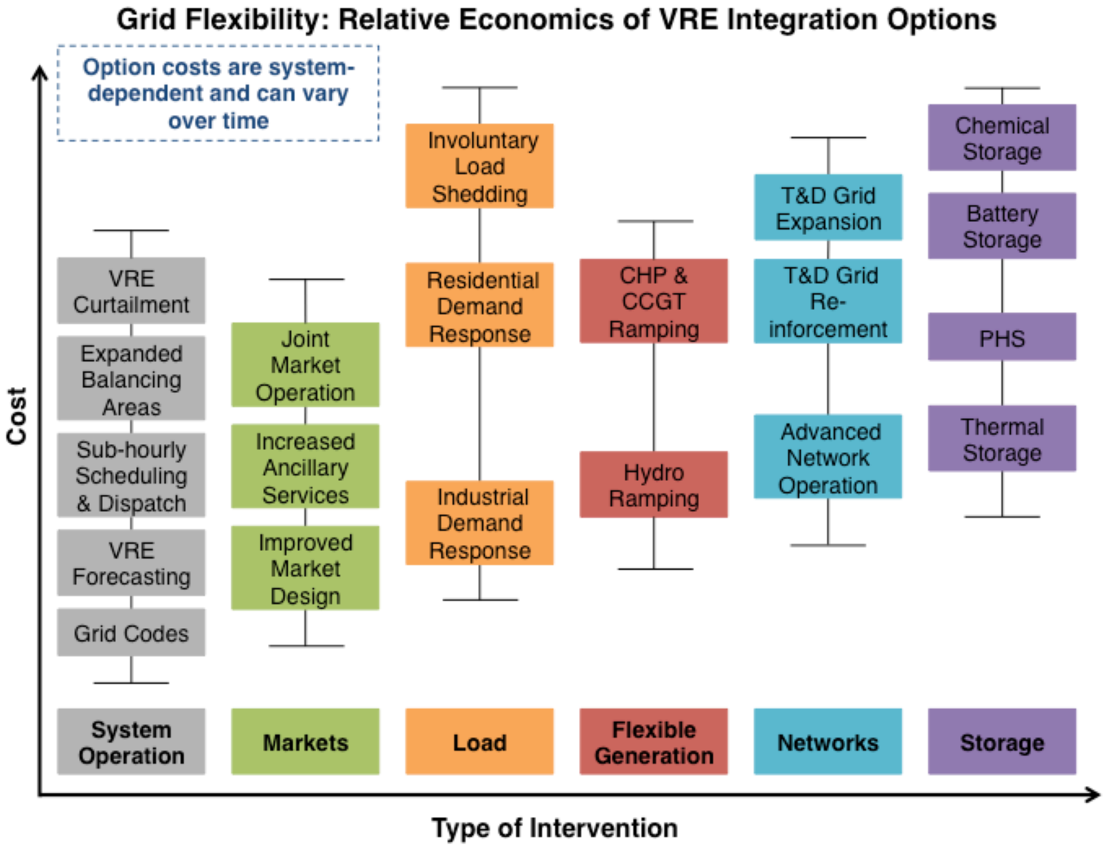

Figure 2-4. Relative economics of the currently available VRE integration and grid flexibility options.

Source: own illustration based on Cochran et al. (2014, p. 11).

As it can be seen, operational and institutional solutions (i.e. *system operation* and *markets*) are relatively cheap compared to infrastructure related and technological options (i.e. *load*, *flexible generation*, *networks*, and *storage*), but can vary depending on system-specific characteristics and circumstances. However, it is important not to focus only on the costs, but also take into account the potential benefits (e.g. reduced GHG emissions, increased energy independency, job creation and economic activity) of such flexibility solutions (IEA, 2014c). Amongst other things, the overall system and market design (including regulations and policies), the power plant fleet, the deployment level of VRE, or geographical characteristics determine the actions that should be envisaged in a coordinated way to ensure system flexibility (Cochran et al., 2014; IEA, 2014c). Additionally, societal factors such as general public perceptions and acceptance of new technologies or transmission lines also play a role when it comes to flexibility solution and the integration of VRE (Cochran, Bird, Heeter, & Arent, 2012; IEA, 2014c). Therefore, it is of utmost importance that the different market actors and stakeholders (including policymakers, regulators, grid operators, utilities, and other service companies) coordinate and integrate their actions and investments in order to ensure an efficient and cost-effective allocation of resources that provides enough flexibility (Bird et al., 2013; Cochran et al., 2012). If the necessary actions are not well coordinated and executed, the power system can face serious challenges and it might become rather expensive to fix it. Creutzig et al. (2014) stress that "a coordination of these in different categories is crucial as energy investments are strongly path-dependent, i.e. sub-optimal investment decisions taken today are perpetuated over a long period of time" (p. 1025). *Table 2-1* below gives a brief overview of the different technology related flexibility options and their relative contribution to VRE integration (in the context of VRE characteristics presented in the previous *Section 2.1* above).

Table 2-1. The suitability for contribution of different flexibility options to VRE integration.

Flexibility option	*Uncertainty*	*Variability*			*Location constraints*	*Modularity*	*Non-synchronous*
		Ramps	*Abundance*	*Scarcity*			
Distribution grid	o	X	X	o	- -	X X	-
Transmission grid	X	X X	X	X	X X	- -	X
Interconnection	X	X X	X X	X	o	- -	X X
Dispatchable generation	X X	X X	X X - -	X X	-	o	X
Distributed storage	X	X	X	X	-	X X	o
Grid-level storage	X	X X	X X	X X	-	- -	X
Demand-side integration small-scale (distributed)	X	X X	X X	o	-	X	X
Demand-side integration large-scale	X	X	X X	o	-	- -	X

<u>Note:</u> X X : very suitable; X : suitable; o : neutral; - : less suitable; - - : unsuitable.

Source: (IEA, 2014c, p. 166)

Whether the transformation of power systems away from the incumbent and centralised structure towards a more distributed and flexible layout based on renewables will be successful depends on various the system-specific settings and factors that have to be taken into account and should carefully be analysed before actions are taken. There will certainly not be a "one size fits all" solution, but rather a combination of multiple options, depending on the specific system characteristics and future technology and cost developments. Or as the IEA (2014c) puts it: "Large-scale integration of VRE is a dynamically evolving field. The innovations that will be most relevant for VRE integration a few decades from now may well be largely obscure today. Accordingly, it is difficult to predict what the make-up of the optimal portfolio of flexibility options will be several decades from now. For example, the evolution of costs is uncertain for many storage technologies and the true potential of DSI [i.e. demand-side integration] is still to be determined under real-life conditions." (p. 166). As it would go beyond the scope of this study to examine all potential flexibility options to accommodate higher shares of VRE generation, the focus here will be on storage options only, in particular electrochemical battery storage. However, before focusing on the role and benefits of BESS, the following section examines the need for grid flexibility in the Swedish electricity system.

2.1.2 The Swedish Power System and Grid Flexibility

The electricity market system consists of several actors (as shown in *Figure 2-5* below). The electricity producers (utilities) are operating the required power capacity and generate the electricity. The five biggest utilities (producing more than 70 % of Sweden's electricity) in Sweden are: *Vattenfall AB*, *E.ON Sverige AB*, *Fortum Power and Heat AB*, *Statkraft Sverige AB*, and *Skellefteå Kraft AB* (Svensk Energi, 2015a). The grid is divided into three levels: a national transmission grid (operated by the TSO *Svenska Kraftnät*), the regional distribution networks (operated by mostly three large DSO companies, *E.ON Power Grids*, *Fortum Distribution*, and *Vattenfall Power Distribution*), and local distribution networks (operated by approx. 170 companies, of which many are municipality owned) that physically deliver the electricity to the consumers and households (Wangel, 2015). Additionally, electricity producers sell their electricity on the power market (in the Nordics it is the *NordPool Power Exchange*) to electricity retailers, which in turn sell the electricity to their customers (e.g. households and industries). Following EU Directive 2009/72/EC (2009), the TSO and DSOs are regulated markets, usually in the form of natural monopolies, whereas the power generation, trade and retail/supplier business are deregulated, free markets (JRC, 2013). In the past, grid development in Sweden was mainly driven by the power production and the need to balance the spatial mismatch between generation and consumption, caused by the deployment of hydropower stations in the Northern part of the country after 1940 and installation of nuclear power plants between the 1970s and 1980s. In recent decades, increased market integration and cooperation as well as ensuring security of supply can be seen as the main drivers. However, the integration of VRE from wind power is still somewhat missing from a grid development perspective due to the large uncertainties associated with the integration of VRE and the more distributed and fragmented structure of such renewable sources (Wangel, 2015).

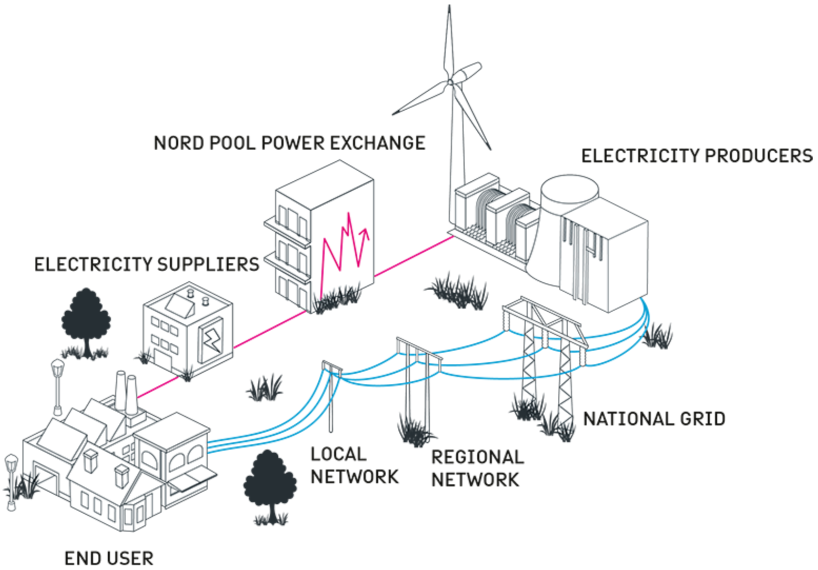

Figure 2-5. Schematic illustration of the Swedish electricity system and the various market actors.

Source: adopted from Svenska Kraftnät (n.d.)

The Swedish Power Mix

The Swedish electricity market is historically built around the production of electricity from nuclear power reactors and hydropower stations, including some smaller pumped hydro storage (PHS) power stations. The three nuclear power plants with currently ten reactors in operation provided around 62 TWh (or 41 %) of the total power production in 2014 (Svensk Energi, 2015a). The hydropower stations, which are mainly located in the Northern parts of

Sweden, provided about 64 TWh (or 42 %) of the total electricity production in 2014 (see also below in *Figure 2-6*). However, electricity sourced from hydropower is more flexible than nuclear power as it is more easily dispatchable and can act as a large storage reservoir for both daily and seasonal variations. The incumbent Swedish utility companies have relied for decades on nuclear and hydropower providing the bulk the electricity needs, whereof hydropower is also used to supply peak demand power and serves as a reserve for daily and seasonal variations. Due to large transmission lines from the North to the South of the country, as well as interconnectors to its Nordic neighbouring countries, the Swedish grid is relatively strong and reliable. However, with the uptake of large amounts of VRE, especially from wind power, in the last years, the structure of the Swedish electricity market is about to change significantly in the upcoming years. On top of that, some of the ageing nuclear power stations are planned for decommissioning over the next decades and the stricter requirements for the construction of larger-scale hydropower plants imply a de facto ban on such new hydropower stations (Swedish Energy Agency, 2012). Thus, in order maintain the required generation capacity, significant investments in renewables have to be made and wind power is expected to be a major source.

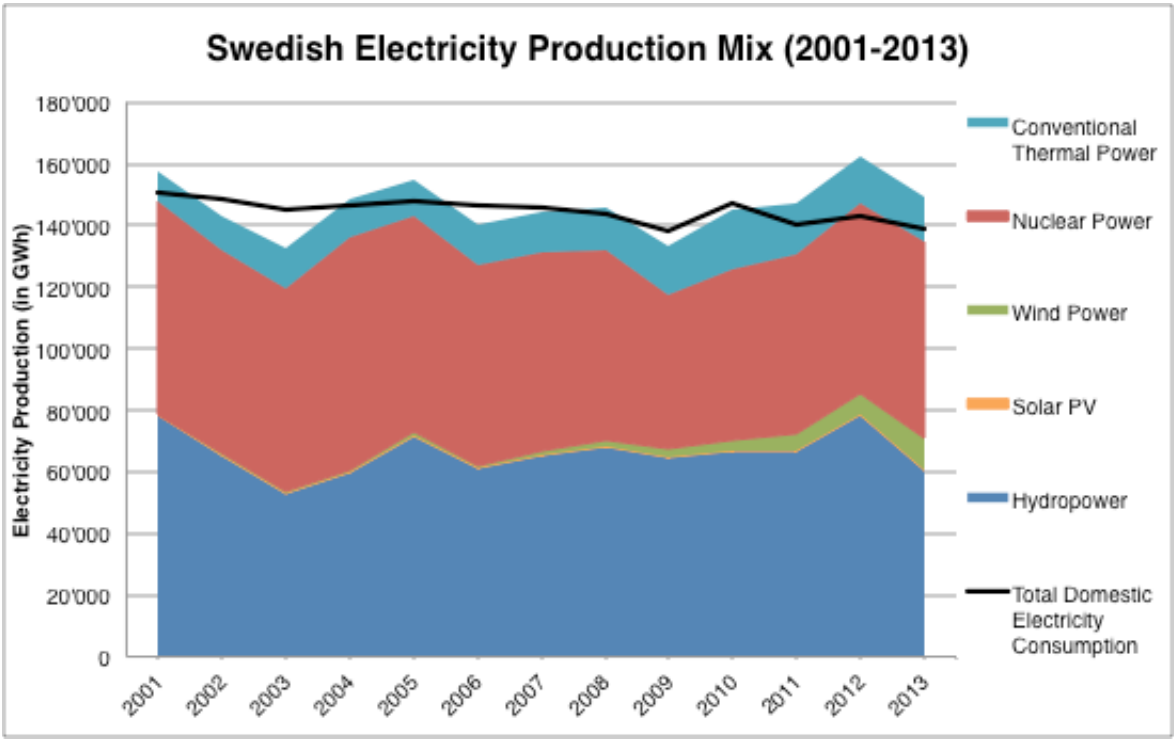

Figure 2-6. The Swedish electricity production mix and total domestic consumption between 2001-2013 (excluding electricity import and export).

Source: own illustration based on official data from Statistics Sweden (SCB, 2014).

The Swedish electricity certificate scheme, which was introduced in 2003 in Sweden, increased the renewable electricity production (mainly biomass CHP and wind power) by 13.2 TWh until the end of 2011. In 2012, a new electricity certificate scheme was introduces together with Norway with the goal to expand the electricity production of renewables by another 13.2 TWh totalling up 26.4 TWh by 2020 (Swedish Energy Agency, 2012). Wind power, which in 2014 already generated 11.5 TWh or almost 8 % of total electricity production in Sweden (Svensk Energi, 2015a), accounted for more than 30 % of all production under the certificate scheme in 2011 (Swedish Energy Agency, 2012). Wind power is expected to further increase its share and make significant contributions to the electricity scheme in Sweden and Norway until 2020 due to the rapid technology development and further cost reductions. The latest predictions by the Swedish Energy Agency (2015a) estimated a annual wind power production of 17 TWh by 2017. An earlier outlook scenario with sensitivity analyses taking into account further technology cost reductions for wind power (Swedish Energy Agency, 2014) predicted around 19 TWh annual wind power production by 2020. These numbers seem reasonable given the current developments. An graphical illustration of the Swedish electricity generation mix for years 2001 until 2013, including the annual domestic consumption but without import and export statistics, can be seen *Figure 2-6* above.

Future Scenarios for the Deployment of Wind Power in Sweden

A very recent study (Olauson, Bergström, & Bergkvist, 2015) conducted under the *Vindforsk IV* framework (research project between the Swedish Energy Agency and Energiforsk AB during the period 2013-2017) modelled the fluctuation of future wind power production in Sweden based on time series (with high temporal resolution) from meteorological wind data and information from individual wind turbines under different scenarios of wind power deployment. A total of over twenty different scenarios with annual energy production of 20, 30, 50 and 70 TWh from wind power in Sweden were developed based on realistic assumptions with actors in the wind power community. The model, which was validated against actual wind power data from the TSO Svenska Kraftnät, revealed that deploying more VRE of wind power in Sweden has an expected effect of reducing variability of wind power output. The *capacity factor* [7] of wind power installations and the share of offshore wind parks have the most significant effect on the wind power variability in Sweden, and with an optimised localisation of wind farms the variability can significantly be reduced. In other words, with the right planning of wind power deployment across the Swedish grid, the expected impact on the power system from the integration of higher penetration levels of wind power can actually be reduced. Earlier studies by Holttinen (2004, 2005) on the effect of larger-scale wind power production on the Nordic power system reveal similar results and conclude that the good interconnection between the Nordic countries is highly beneficial for higher integration levels of wind power due to the wider geographical dispersion. These studies for the Swedish and Nordic region are largely in accordance to other literature (Albadi & El-Saadany, 2010; Bird et al., 2013; Denholm et al., 2010; EPRI, 2011; Milligan & Kirby, 2010; Wan, 2012) and what has been discussed earlier.

Flexibility in the Swedish Electricity System

As it has been discussed before, requirements for more flexibility in the grid to accommodate wind power depend on various factors such as wind power penetration level, the overall wind power output variability, the location of wind power installations, the capacity and strength of the transmission network, balancing resources, the forecasting accuracy, as well as operational system capabilities. In general it can be said that with an increase in wind power penetration, the cost for operating and balancing a power system also increase (EPRI, 2011). In order to assess the power system flexibility for Sweden, while keeping in mind its interconnectedness with other Nordic countries, it seems most suitable to check against the signs of inflexibility, as it is sometimes easier to identify those rather then flexibility. Such signs of insufficient system flexibility can include (Cochran et al., 2014):

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[7] The *capacity factor* of a power plant is the ratio (expressed in percentage) between the actual annual power output and the potential nominal power (i.e. if the plant would run at full speed all the time) during a year. Alternatively, it can also be experessed as *full load hours* (Wizelius, 2015). For wind power installations in Sweden, the capacity factor was found to be around 24 % on average between 2007-2012 (Olauson, Bergström, & Bergkvist, 2015), but can vary depending on various factors such as weather conditions, locations and installations size.

- *difficulties to balance demand and supply* (resulting in frequency deviations) and/or balancing violations in certain grid areas;
- *significant VRE curtailment* (due to excess supply or transmission constraints);
- *negative market prices and/or high price volatility* (e.g. due to inflexible generation plant fleet, surplus VRE generation, or transmission constraints).

As of today, Sweden has a relatively strong and reliable grid due to its good system infrastructure and ample generation capacity with mainly nuclear and hydropower, plus some wind power. In a report on the integration of wind power, the Swedish TSO Svenska Kraftnät (2013a) states that the risk of power shortages in the grid are lower than 0.1 %, unless some of the nuclear power reactors are closed down. The same report also concludes that the risks for power shortages in the Southern parts are greater and in the case of closures of some nuclear reactors can even exceed the Nordic grid (NORDEL) risk limit of 0.1 %. The reason for this is the greater loads in the Southern areas of Sweden and the higher dependency on nuclear power. Since 2011, the Swedish grid is divided in four *bidding areas* (*SE1 – SE4*, from North to South, see also *Appendix I* for a map illustrating the bidding areas), and most of the hydropower is produced in the areas SE1 and SE2. A smaller amount of hydropower and the nuclear power plants are located in the more Southern area SE3 where also most of the loads occur as the majority of the population and economic activity is located. Wind power production is relatively evenly distributed across the four areas, with slightly higher production in the areas SE2 and SE3 and lowest output in the most Northern area SE1. However, it is also pointed out that with more flexibility in bidding areas SE3 and SE4 a slightly lower amount of nuclear in combination with larger volumes of VRE from wind it would still be possible to keep the risk of power shortages under 0.1 %. Solutions to enhance grid flexibility include more flexible and dispatchable generation units (e.g. CHP or CCGT), demand response management (e.g. smart grid solutions), and stronger distribution grids (e.g. power system investments), but storage options in particular are not mentioned (Svenska Kraftnät, 2013a). Therefore, the Southern areas in Sweden seem to have higher demand for flexibility, which could potentially be seen a need for BESS. Overall, the Swedish grid seems quite stable and from this perspective, the need for more flexibility in the near future is expected to be rather low. However, Wangel (2015), who analysed the drivers and barriers for the development of the Swedish transmission grid, also found that the additional integration of VRE from wind power is a potential driver for transmission and distribution grid expansion due to the connection obligation from 1997 to connect all new power production units. From this perspective, the Swedish TSO and DSOs are basically obliged to expand the grid and therefore reduce bottlenecks. Moreover, the purpose to divide the Swedish electricity market into four bidding areas was partially to make the bottlenecks on the grid more visible via price signals and better emphasise the need for investments in power production in areas with higher loads (Wangel, 2015). For instance, in order to decrease the expansion of long-distance transmission lines, more wind power in the South instead of the North would be beneficial.

Wind power curtailment in Sweden is expected to occur only to a limited extent where there is not sufficient grid connection or capacity in order to avoid voltage problems. Svenska Kraftnät or the DSOs can order curtailment in such rare circumstances and it has indeed only occurred a few instances, e.g. a wind power installation around Jönköping (Lew et al., 2013). Thus, curtailment of VRE output from wind power in Sweden has so far not been a major issue and is most likely related to the fact that there is a connection obligation in place. It also speaks for the fact that Sweden today has a relatively stable grid with sufficient flexibility. Adequate grid capacity is one mitigation option for VRE curtailment, but energy storage options, as well as institutional or operations changes could also be considered if this would become a problem in the future (Lew et al., 2013; Milligan et al., 2009).

An earlier study by Holttinen (2004) found that electricity prices in the Nordic market will be affected by increased volumes of VRE from wind, resulting in lower spot market prices and higher regulating power prices. The *Nordic Market Report 2014* from Nordic Energy Regulators (NordREG, 2014) states: "Wind energy has a negative effect on prices as there is no fuel cost connected to production. Wind energy may in some cases cause negative prices in hours with low demand. On the other hand, when wind production fall short of expected values, it may be a contributing factor to high prices, both in the Day-Ahead and Intra-day markets." (p. 29). Additionally, in the same report it was found that the price structure for the Nordic market shows considerably less price volatility than for the Germany market and that large volumes of wind power contributes to more variable prices in Germany. However, negative prices on the Nord Pool Spot occurred relatively seldom compared to Germany. Therefore, the market price signals indicate also a rather flexible Nordic grid, but it is difficult to determine the isolated effect for Sweden, as such data is only available on an aggregated level.

In summary, it can be said that the Swedish (and Nordic) power system today is relatively stable and does not reveal any major signs of inflexibility. From this point of view, the need for more system flexibility, at least for the near future, does not seem to be very urgent. However, the expected development on the power system with a transition away from nuclear power and towards increased volumes of VRE from wind within the next 5–10 years could somewhat change that picture, especially in some parts of the grid. Therefore it is important to coordinate and plan actions ahead and create long-term incentives for increased flexibility in order to anticipate challenges that could emerge on several levels in the power system. The *Swedish Coordination Council for Smart Grids* (Samordningsrådet för smarta elnät, 2014), which was appointed by the government, evaluated the potential and opportunities for smart grids in Sweden and recommended (among various other things) that incentives contributing to increased grid flexibility, both on the demand and supply side, should be enhanced so that market actors can optimally utilise their resources. In addition, emerging opportunities associated with energy storage applications were identified by the Swedish Coordination Council for Smart Grids (2014) to be one of the various options.

2.2 Roles and Functions of Energy Storage in the Power System

According to the IEA (2014a) "Energy storage technologies absorb energy and store it for a period of time before releasing it to supply energy or power services. Through this process, storage technologies can bridge temporal and (when coupled with other energy infrastructure components) geographical gaps between energy supply and demand." (p. 6). From this definition it can be seen that energy storage technologies have various application areas and can be categorised along several parameters. The most important benefit of energy storage is that it allows for decoupling of power generation and consumption and therefore providing more flexibility and to some extent reducing the need for providing additional disptachable power generation units and transmission lines (Sabihuddin et al., 2014). Moreover, it helps to mitigate some of challenges associated with integrating VRE into the electricity grid.

Different Energy Storage Technologies

Commonly, energy storage technologies are distinguished between their physical properties and how the energy is converted and stored (see *Table 2-2*). However, for the purpose of this thesis, it is important to further differentiate the five categories between the underlying storage concepts of *power-to-power*, *power-to-heat*, and *power-to-fuel*. Whilst the latter two convert electricity to heat or a fuel (e.g. gas or hydrogen) and interlink the electricity system with the fuel and/or heat system, the reconversion back to electricity is technically possible but highly inefficient (relatively low round-trip efficiency) and therefore costly. On the other hand, *power-to-power* storage technologies typically store electricity by converting it to another form of energy (mechanical, kinetic, potential, electrical, electrochemical, chemical, thermal) and then at a later stage inducing it to reconvert back into electricity (IEA, 2014b), which yield a higher round-trip efficiency.

Table 2-2. Overview of the different energy storage methods, technologies, and concepts.

Storage method	*Storage technology*	*Storage concept*
Mechanical (or also kinetic or potential)	• Pumped hydro storage (PHS) • Compressed air energy storage (CAES) • Flywheel energy storage (FES)	power-to-power
Electrical	• Capacitors & supercapacitors • Superconduction magnetic energy storage (SMES)	
Electrochemical	• Lithium-Ion (Li-Ion) • Sodium-Sulphur (NaS) • Lead-acid (LA) • Nickel-Cadmium (NiCd) • Flow batteries (e.g. Vanadium redox-flow battery VRB)	
Chemical	• Hydrogen • Synthetic natural gas (SNG) • Other chemical (e.g. biofuels)	power-to-fuel
Heat/thermal	• Water • Molten-salt energy storage (MSES) • Phase change material storage (PCM)	power-to-heat

Source: (IEA, 2014b; Normark & Faure, 2014, p. 3).

As the scope of this study only deals with VRE and its integration into the power grid, *power-to-fuel* and *power-to-heat* storage concepts will not be further dealt with. What concerns storage technologies that fall under the category *power-to-power*, or sometimes also referred to as electricity storage, it is interesting to point out that of the currently installed electricity storage capacity in the world, PHS represents almost 99 %. The remaining 1 % is a mix electrochemical batteries, CAES, flywheels, and flow batteries. The reason for the high large share of PHS is that such bulk storage was built in parallel with the deployment of nuclear power after the 1970s in order to handle intermediate and peak loads. PHS was has been a useful application alongside nuclear power generation for arbitrage services between expensive peak load hours and less-costly low demand times (IEA, 2014b). Whether conventional hydropower reservoirs (and also *run-of-the-river*, without pumping mode) can be considered as energy storage is debatable, but since the energy is not stored by converting electricity into mechanical/potential energy and then reconverted back it is often rather seen as a dispatchable power generation unit.[8] Such conventional and *run-of-the-river* hydropower installations are the most common type of hydropower generation in the Nordic and Swedish context.

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[8] There is a clear destinction between *run-of-the-river* hydropower stations and *pumped hydro storage (PHS)*. While the latter uses low-demand/low-price hours to pump water up in a reservoir and then release it again via a turbine that generates electricity when most needed (intermediate and peak hours, for price arbitrage), the former usually utilises large dams to control the (one way) water flow and produces electricity through controlable/dispatchable turbines when needed. Both types use a large reservoir to *store* the water (i.e. potential mechanical energy), but PHS pump the water up the hill, which is then reconverted back to electricity, while *run-of-the-river* hydropower only uses a dam to hold back the water.

Power System Applications of Electricity Storage

However, with the IEA (2014b) points out that "storage applications and their development are influenced by the evolution of the whole energy system. In the same way that price arbitrage triggered PHS deployment, other additional storage applications may trigger a new deployment wave of energy storage technologies as well as additional PHS and CAES" (p. 244). With increased deployment and integration of distributed VRE, the growth of electrification and use of electric demand technologies, the rollout of smart grids, as well as an advance of self-consumption through self-generation, especially in remote and off-grid areas caused renewed interest in energy storage applications and could trigger a new wave of storage deployment. Moreover, the advances in storage technologies, the increased uncertainty and volatility of fossil fuel prices, the development of deregulated energy markets and challenges associated with building new transmission lines further accentuate the interest in energy storage (Denholm et al., 2010; EPRI, 2010; IEA, 2014b).

In order to compare the different storage technologies, a variety of important parameters are commonly used, such as specific energy, energy density, specific power, power density, round-trip efficiency, lifespan, cycle life, self-discharge rate, scale, energy capital cost, power capital cost, application, technical maturity, and the environmental impact (Sabihuddin et al., 2014). Hence, depending on the application(s) and the service(s) a storage technology is supposed to provide, some of these parameters might be more relevant than others. An example of several energy technologies for power system applications comparing their size and discharge time is given in *Figure 2-7* below.

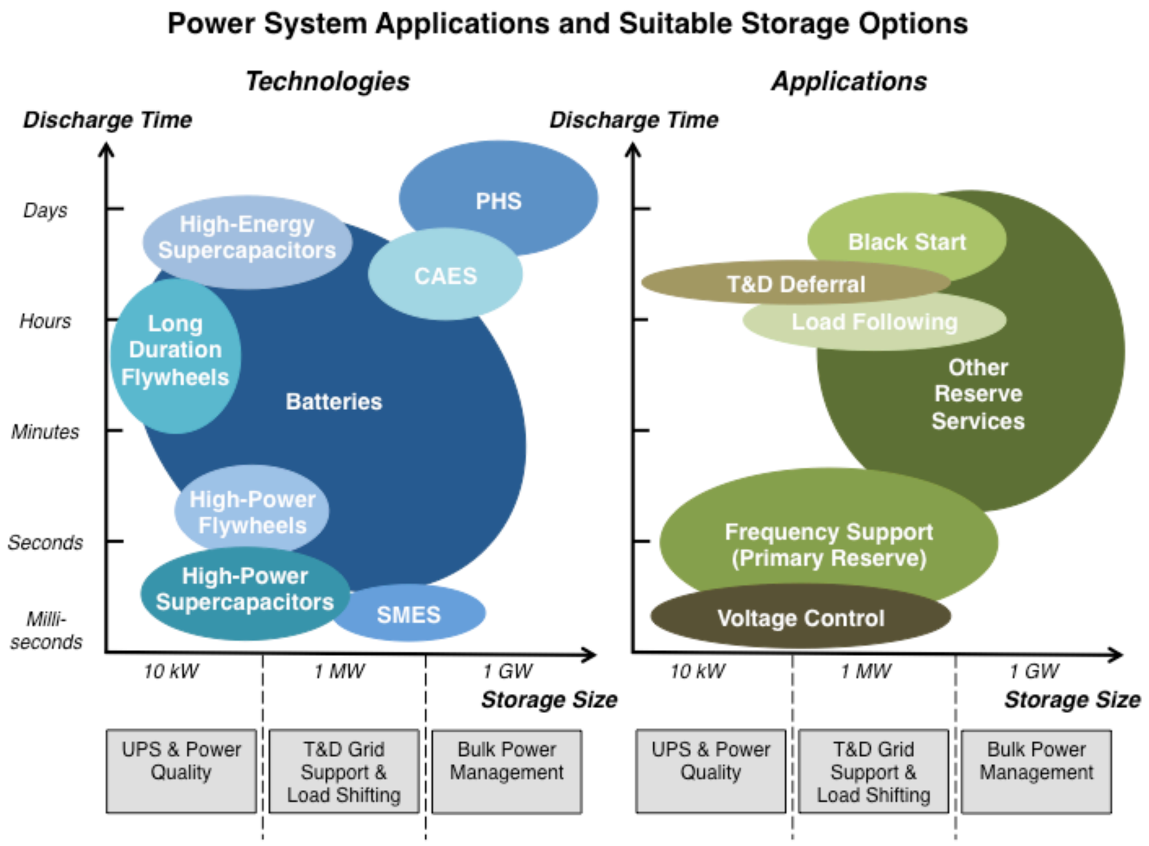

Figure 2-7. Examples of suitable storage technologies for power system applications.

Source: own illustration based on IEA (2014c, p. 142)

Although, many storage technologies can deliver different services, the technology costs and their perceived benefits for a particular application or service are a critical metric to whether they are or will be deployed. This cost is usually measured in *LCOE* (see again *Section 2.1* for explanation) as it makes different storage technologies somewhat comparable to one another, similar as to compare different technologies for electricity generation. *Table 2-3* provides an overview of some of the most important performance and cost parameters of the most common energy storage technologies today.

Table 2-3. Typical performance parameters and investment costs of different electricity storage technologies.

Storage technology	*Maturity stage*	*Power output (MW)*	*Response time*	*Efficiency (%)*	*Lifespan (years)*	*Cycle life*	*Power cost ($/kW)*	*Energy cost ($/kWh)*
PHS	Mature	100-5 000	sec-min	70-85	30-50	20 000-50 000	500-4 600	30-200
CAES	Deployed	100-300	min	50-75	30-40	10 000-25 000	500-1 500	10-150
Flywheels	Deployed	0.001-20	< sec-min	85-95	20-30	> 50 000	130-500	1 000-4 500
Super-capacitors	Demo.	< 1	< sec	85-98	20-30	> 10 000	130-515	380-5 200
SMES	Demo.	< 10	< sec	90-95	20	> 30 000	130-515	900-9 000
Li-Ion battery	Deployed	0.001-5	sec	80-90	10-15	5 000-10 000	900-3 500	500-2 300
NaS battery	Deployed	1-200	sec	75-85	10-15	2 000-5 000	300-2 500	275-550
LA battery	Deployed	0.001-200	sec	65-85	5-15	2 500-10 000	250-840	60-300
VRB	Deployed	0.001-5	sec	65-85	5-20	> 10 000	1 000-4 000	350-800

Note: All numbers are approximate ranges that can vary over time. Power and energy costs are investment costs only and do not include operating and maintenance costs.

Source: (IEA, 2014b, pp. 253–254)

Even though this thesis focuses on the grid integration of VRE and therefore, as it has been discussed in the previous subsection, more grid flexibility is needed, it would be beyond the scope of this study to include all various electricity storage technologies. Instead, the focus will be solely on electrochemical battery storage technologies. There are several reasons for this choice. First of all, batteries (e.g. Li-Ion or NaS) show great physical properties in terms of specific energy- and power-density, long-term stability, safety and efficiency (Dunn et al., 2011; Yekini Suberu, Wazir Mustafa, & Bashir, 2014). Secondly, technology related costs for battery storage technologies have seen significant improvements with over the last few years (as introduced in *Chapter 1*). Some battery energy storage technologies are close to become cost-competitive with other assets providing power system flexibility, such as PHS, CHP and CCGT, demand response management or investments grid expansion or reinforcement. The literature (e.g. Citigroup, 2015; IEA, 2014a, 2014b; IRENA, 2015b; Liebreich, 2013; Nykvist & Nilsson, 2015) expects that a cost range between US$ 100-230/kWh for Li-Ion batteries would be needed to compete with other solutions, but currently technology costs for Li-Ion batteries are in the best case somewhere around US$ 300-600/kWh, depending on the application and market. Simply speaking, the greatest barrier for mass deployment of battery storage installations as of today is cost and thus they are still lagging behind compared to other flexibility alternatives, such as transmission, interconnection, and demand-side management potentials (Sørensen, 2015; Tuohy & O'Malley, 2012; U.S. Department of Energy, 2013). However, the outlook for grid-scale electricity storage looks promising (see *Chapter 1*) and some of those battery technology applications have been deployed recently in several places for providing different power system services and at various scales, mostly for niche applications (Akhil et al., 2013; Dunn et al., 2011; Tuohy & O'Malley, 2012). As it can be seen in *Figure 2-7* above, battery storage technologies are quite versatile and therefore suitable to cover a wide range of power system applications. Moreover and due to their modularity and mobility, battery storage devices provide great flexibility in many ways.

2.3 Applications and Benefits of Battery Energy Storage Systems

Notwithstanding the current limitations of certain electricity storage technologies, in particular with regards to cost, storage systems can generally satisfy a variety of applications and services across the electricity system value chain. The most relevant applications and services identified in the literature are summarised in *Table 2-4*.

Table 2-4. Power system energy storage applications and services across various levels of the power system.

Generation & bulk energy services	
Electric energy time-shift (arbitrage)	Charging and storing electricity at low-demand/low-price times and then discharging at peak-demand/high-price times. Also for storing excess energy production to avoid curtailment (e.g. peak output shaving and firming of VRE supply).
Electric supply capacity	Deferring/replacing investments in additional peak load capacity. Seasonal/weekly storage to balance weather related fluctuations.
System operation & ancillary services	
Regulation & frequency response	Automated balancing of quick variations in supply and demand (dispatch timeframe: seconds to minutes). Inertia support for larger shares of non-synchronous VRE generators.
Load following (spinning, non-spinning, and supplemental reserves)	Manual balancing of power system fluctuations (dispatch timeframe: minutes to hours), e.g. to handle intermediate and peak loads. Ramping support for VRE generators.
Reserve capacity	Contingency reserves to handle rapid changes in supply, e.g. due to failure of a generation unit.
Voltage support	Reactive power control to mitigate voltage fluctuations (e.g. with higher volumes of non-synchronous generation units).
Black start provision	Support for power system restart after complete system failure (i.e. many conventional power generation units need electricity for restart).
Transmission infrastructure services	
Transmission upgrade deferral	Storage to defer or replace investments in transmission line upgrades.
Transmission congestion relief	Temporary bottlenecks and over-stressed transmission grid parts can be eliminated with modular and mobile storage units.
Distribution infrastructure services	
Distribution upgrade deferral	Storage to defer or replace investments in distribution line upgrades.
Distribution congestion relief	Temporary bottlenecks and over-stressed distribution grid parts can be eliminated with modular and mobile storage units.
Voltage support	Reactive power control to mitigate voltage fluctuations (e.g. with more VRE generation units connected to the distribution grid).

End-user/customer energy management services	
Power quality	Storage units for micro-grid and smart grid systems to improve grid reliability and performance (e.g. voltage and frequency support). Aggregated storage units to assist utilities/DSO with ancillary services.
Power reliability & back-up generation	Backup power for uninterruptable power supply (UPS) systems or off-grid installations by replacing expensive diesel generators.
Retail electric energy time-shift (arbitrage)	Electricity use from storage units during peak-demand/high-price times and recharge during low-demand/low-price times.
Demand charge management (cost savings)	Reduce dependency from the grid through self-consumption (e.g. combination of behind-the-meter solar PV and storage) and avoid high retail electricity prices and reduce load.

Sources: (Akhil et al., 2013; Chen et al., 2009; EPRI, 2010; IEA, 2014a, 2014b; IRENA, 2015b; U.S. Department of Energy, 2013).

Some the above applications (in *Table 2-4*) are more used to deliver general services to the power system in order to enhance overall flexibility, while others (e.g. electricity time-shifting, transmission curtailment, frequency response, voltage and power quality support) are more directly related to the grid integration of VRE (Chen et al., 2009; IRENA, 2015b). Tuohy and O'Malley (2012) identified six potential application areas for storage (also included in *Table 2-4* above), which are directly related to support the integration of wind power:

- *long-term seasonal storage*, i.e. to balance and shift seasonal variations both in wind power output and demand in certain regions (e.g. through PHS, CAES, or power-to-fuel);
- *daily time-shift of wind output*, i.e. to balance daily fluctuations of wind power output and peak demand times (e.g. between day and night);
- *management of uncertainty*, i.e. as a hedge against forecasting errors in wind power output for short timeframes;
- *transmission curtailment reduction*, i.e. to avoid wind power curtailment and/or defer/replace investments in grid infrastructure upgrades;
- *reduction of (short-term) fluctuations & power quality support*, i.e. quick-responsive storage units for voltage support and reactive power;
- *grid frequency support*, i.e. quick-responsive storage units for inertia support and short-time wind power output variations.

It is important to point out that while storage can help to overcome some of these challenges associate with higher VRE penetration listed earlier, in some instances grid-scale storage applications have limited potential and can only help to mitigate certain aspects such as location constraints or the distributed and modular nature of VRE generation units (IEA, 2014c). The reason for this is that it would require too large or too many storage installations for very specific VRE generation units, which would be inefficient and too costly compared to other flexibility options. Generally, storage applications in connection to wind power integration would have to meet the following characteristics (EPRI, 2010; IEA, 2014b):

- *size:* 100-400 MW for time-shift and centralised ancillary services (1-10 MW for more distributed ramp and voltage control);
- *discharge duration:* 1-60 minutes for ancillary services (a few hours for time-shifting).
- *full charge-discharge cycles:* 0.5-2/day or 300-500/year (for ancillary services even more approx. 5 000-10 000 per year);
- *desired lifetime:* 20 years;
- *response time:* seconds to minutes for ancillary services, minutes to hours for time-shifting.

As it has been pointed out earlier (e.g. see *Figure 2-7* above), battery storage units can cover a wide range of applications and services, most of the ones which are listed in *Table 2-4*, but the feasibility for batteries is highly dependent on the specific purpose, technical requirements, scale and costs. The IEA (2014b) highlights that "by its very nature, storage does not operate in isolation; its true value is as an integrative technology that interacts with the electricity system to define deployment opportunities" (p. 245). Therefore, it is quite difficult to exactly predetermine which storage applications and services batteries can and will serve, as they compete with other storage technologies on the market and the most suitable solution may differ from situation to situation. For this reason the *U.S. DOE* (Akhil et al., 2013) issued a handbook for electricity storage that contains step-by-step methods and tools to assess the feasibility and business case of storage applications in the power system. Whether electricity storage is a feasible option for a certain issue in the grid hinges upon several factors and indicators, such as the function and services, location, ownership, size, alternatives, costs and benefits, grid impacts etc. and has to be analysed properly. However, due to the high costs associated with energy storage, especially BESS, multiple complementary applications and services across the energy system value chain should be *bundled* in order to increase the benefits. This aggregation of several benefits is also called *benefits-stacking* (EPRI, 2010; IEA, 2014a; U.S. Department of Energy, 2013). *Figure 2-8* illustrates how the overlapping benefits of multiple applications and services can be combined in order to monetise synergies of energy storage installations across the power system value chain. This could require the cooperation of several market actors or would open up the opportunity for new third-party actors that provide several services and sell them to established market actors.

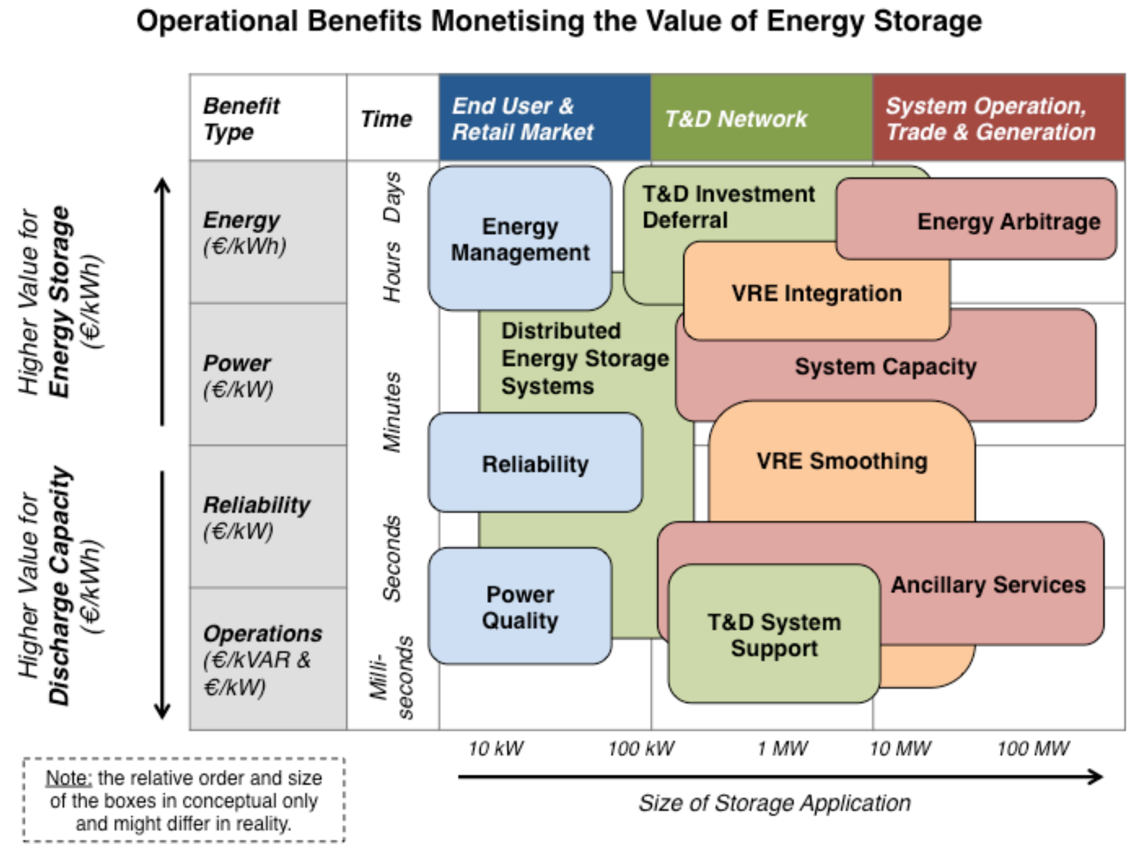

Figure 2-8. Operational benefits across the power system monetising the value of energy storage through "benefits-stacking".

Source: own illustration based on EPRI (2010, p. xii).

Going back to *Figure 2-7* in the previous section, which show the potential application areas for BESS, it becomes more obvious that such BESS can combine several power system services and make use of *benefits-stacking*. For instance, a BESS can be deployed in order to help integrate the VRE generation (i.e. ramping and smoothing) plus provide additional ancillary services (i.e. inertia and voltage assistance) and support the transmission or distribution system (i.e. temporarily mitigate bottlenecks). However, it should be noted that both *Figure 2-7* and *Figure 2-8* above are rather conceptual and therefore very general comparisons and might not cover the full range (in terms of size or discharge time) of the applications and services. The literature (Divya & Østergaard, 2009; EPRI, 2010; IEA, 2014b; Joseph & Shahidehpour, 2006; Normark & Faure, 2014) mostly agrees that currently BESS are most suitable to provide more short-terms services between seconds and several minutes of discharge duration (e.g. system operations and ancillary services, power quality, peak shaving and renewable firming, transmission and distribution infrastructure services) mainly due to high technology costs that somewhat constrain the scale of BESS. Additionally, the rapid response time of BESS makes them ideally suited for short-term applications, such as for frequency reserve capacity, ramp and voltage support, as well as the deferral of gird expansion or reinforcement in some cases (EPRI, 2010; JRC, 2013). *Appendix II* provides a table with estimated quantitative benefits of selected energy storage applications and services, which could help to better compare costs and benefits of certain storage applications and identify the most economically suitable services.

2.4 Support Mechanisms and Incentive Schemes for BESS

As it was already mentioned before, there is increasing interest in electricity storage in many areas, mainly driven by the increased deployment of VRE installations around the world and the need for more power system flexibility. As already mentioned earlier, the need power system can differ quit significantly across countries that have all different characteristics in terms of electricity generation mixes, infrastructure and demand patterns. Therefore, network stability and reliability, as well as need for more or less grid flexibility, are highly system specific. Thus, the need for electricity storage application may vary considerably. For instance and as it has been shown above, the Nordic system is relatively stable and flexible. On the contrary, the power system in the USA faced some critical grid issues in the early 2000s with a number of major blackouts that affected large areas of the country (Biello, 2013; Minkel, 2008). Since then, the regulatory authorities have taken up measures to enhance grid stability and flexibility through investments in flexibility measures (e.g. transmission network reinforcement, smarter grids, demand side flexibility). However, with the uptake of more VRE from wind and solar PV in the USA, new challenges concerning the grid stability and/or balancing varying supply and demand arise. Electricity storage applications might provide a remedy, especially for the integration of larger volumes of VRE.

As most of the storage technologies, including BESS, are currently only used in niche applications due to high costs, support mechanisms and incentive scheme may be needed to enable and foster the deployment of electricity storage systems. For instance the IEA (2014b) points out that “the value of a given application will largely depend on the regulatory framework, the policy support and specific conditions of the power system” (p. 250) and underlines the need for a favourable market environment. The literature (Bürer & Wüstenhagen, 2009; Grubb, 2004) on policy support for technological innovation recommends various options of support mechanisms and incentive schemes, depending on the technological development stage and the specific context, as it can be seen in *Figure 2-9* below. The big challenge is usually to bring new technological innovations from research laboratories to the commercial market. Especially the middle stage between demonstration projects and niche market applications (also referred to as the *technology valley of death*), where the innovation is facing the tough challenges of the market environment and is starting to compete with established products and services, can be decisive for the commercialisation of the novelty. In early development stages policy interventions in the form of *technology push* mechanisms, such as R&D support, tax breaks, or governmental demonstration grants and funds, can be beneficial. In later phases closer to market introduction and breakthrough, *market pull* policies in the form of public procurement, feed-in tariffs, tax credits, mandates, performance and portfolio standards, or simply creating a level playing field can be very helpful. Furthermore, it is also stressed in the literature (Bürer & Wüstenhagen, 2009; Grubb, 2004; Held, Haas, & Ragwitz, 2006) that such support policy instruments should be clear and of long-term focus in order to be efficient and effective and create a stable environment for investors and market actors. However, whether governmental support and incentive mechanisms are introduced is usually dependent on a particular need perceived from the regulatory side for new technologies and services (Bürer & Wüstenhagen, 2009). The grid stability and flexibility challenges in the USA and some other countries can be seen as an example here, as it will be shown below.

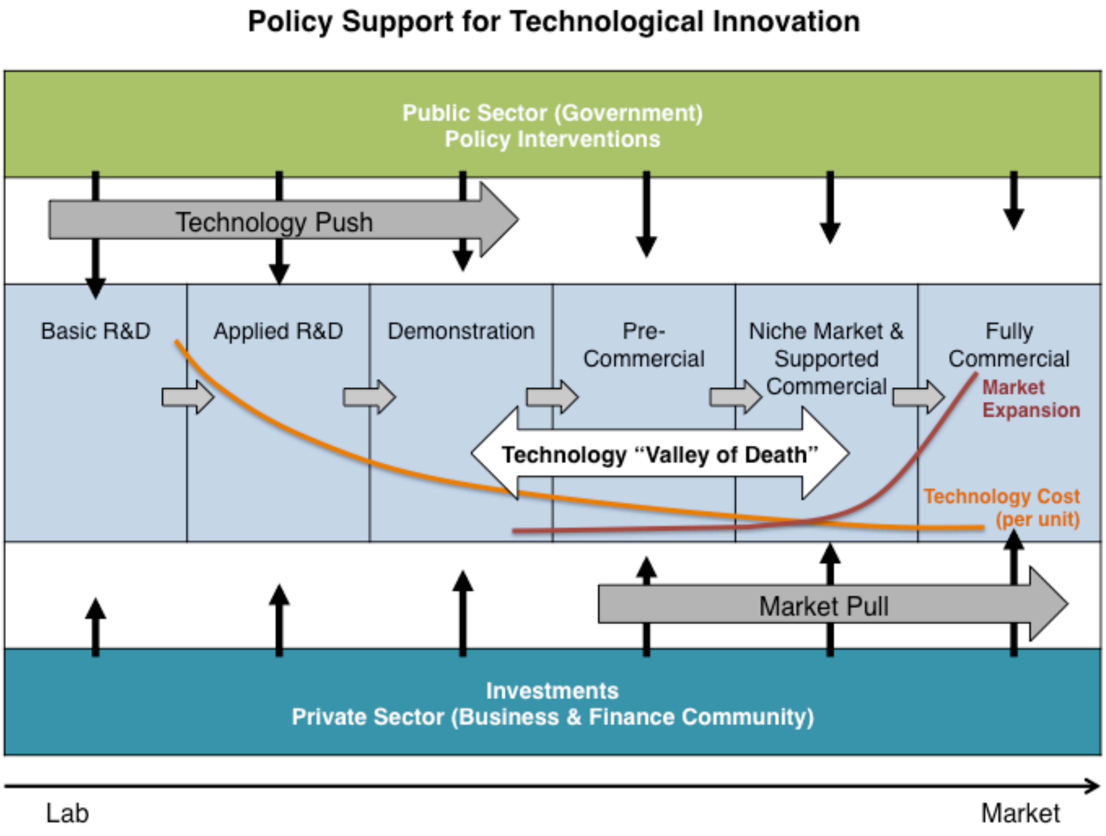

Figure 2-9. Policy support for technological innovations to overcome the "valley of death".

Source: own illustration based on (Bürer & Wüstenhagen, 2009; Grubb, 2004).

In recent years, several countries around the world have implemented policies that aim to promote storage applications at different part across the energy system value-chain. In most cases, the reason for the introduction of such technology support mechanisms is the grid integration challenge of variable wind and solar power as a consequence of increased VRE penetration level. In some cases (e.g. USA or Italy) and as already been elaborated above, these VRE integration challenges are also coupled with a relatively weak grid infrastructure that lacks resilience. *Table 2-5* below provides a brief summary of some countries that have certain policy instruments in place to promote or incentivise energy storage applications. As it can be seen, there are several countries actively supporting and encouraging energy storage for various reasons and purposes. However, it is important to note that it would go beyond the scope of this thesis to provide a complete list here. Instead, it should be seen as an indicative overview of some *state-of-the-art* policy mechanisms. Moreover, as it turns out, it is rather difficult to find useful information on such support mechanisms and incentive schemes (with the exception of the ones listed), mainly because the information is only available in other languages or written down in complicated regulation texts.

Table 2-5. International landscape of electricity storage support policies.

Country	*Type of support*	*Actions, projects and funding*	*Technology & applications*
USA	Direct mandate, market evolution, price distortion reduction, international collaboration	Energy Storage Programe by the *U.S. DOE* to provide funding of approx. US$ 200 million between 2011-2015 for RD&D of new and advanced energy storage technologies. California State mandate (October 2013) requires the biggest utilities to procure 1 325 MW of storage until 2020.	Research is focused mainly on electricity storage technologies, such as chemicals and batteries, flywheels, SMES, CAES. Technology neutral (except PHS).
Germany	Support of RD&D documentation, public information, direct subsidy for distributed battery storage	Energy storage initiative by the government providing approx. € 200 million for RD&D in grid storage projects. Subsidies (low-interest load plus grant) for 30 % of battery storage system cost associated with household solar PV installations.	Hydrogen, CAES, batteries, and *power-to-gas*; mostly for frequency regulation. Li-Ion batteries (together with distributed solar PV systems).
Italy	Support of demonstration projects, market evolution	51 MW of storage commissioned and an additional 24 MW funded, in total 75 MW of batteries for the use on the T&D network by 2015 (mainly due to grid reliability issues from high shares of VRE capacity relative grid size).	35 MW NaS batteries for long-duration discharge; additional capacity is focused on reliability issues and frequency regulation.
Japan	Support of demonstration projects, performance documentation	Approx. US$ 263 million for subsidies for 30 MW of Li-Ion batteries approved by the Government; additional subsidies for end-users to install batteries with solar PV installations (2/3 of the purchase price, representing approx. US$ 98 million)	Primarily Li-Ion batteries; and increased regulatory approved storage devices from 31 to 55 MW.
China	Demonstration project, performance testing	Under the current *Five Year Plan* of the government, 25 GW of storage for wind power is forecasted, financial support of demonstration projects.	E.g. Li-Ion battery system demonstration project in Zhangbei, Hebei for providing grid flexibility.
South Korea	Support of demonstration project, performance documentation	Revision of electricity rates to encourage storage, target of 154 MW storage announced in 2013, if necessary energy storage mandates will be implemented.	54 MW Li-Ion batteries and 100 MW CAES; mostly for reliability and UPS systems.
Canada	Direct mandate, market evolution	Announced first frequency regulation installation.	–
UK	Support of demonstration projects	6 MW multi-use batteries and other small R&D and demonstration projects.	Mainly for load shifting and frequency regulation.
EU	International collaboration, policy framework development	EU funded *stoRE project* with the aim to create a framework to allow the development of energy storage infrastructure to help accommodate higher VRE penetrations.	VRE integration.

Source: (BMWi, n.d.-a, n.d.-b; Electricity Storage Network, 2014; IEA, 2014a; Martinez & Hughes, 2015; U.S. Department of Energy, 2013)

2.4.1 Policy Support for BESS in the USA

As of today, the USA is probably one of the leading countries in terms RD&D as well as other direct and indirect incentive mechanisms for electricity storage, and in particular battery storage, flywheels and supercapacitors. This development is mainly driven by regional initiatives in the States of California and New York dating back as far as in the 1990s, as well as the more recent national energy storage programme (Gyuk et al., 2005). As stated before, the main reason for this is the rather poor grid stability in some parts in the USA (particularly T&D constraints in urban areas) combined with the increased uptake of renewables in recent years that further accentuate the situation (Batistelli, 2013; Biello, 2013). Due to the fact that the focus of these policy support initiatives are primarily directed to grid-scale storage applications, as opposed to other support policies in some countries that focus mostly on distributed end-user installations, the California State mandate will be outlined briefly.

The U.S. DOE launched an electricity storage funding programme totalling around US$ 772 million with the goal of deploying more than 500 MW of installed storage capacity (JRC, 2014a). The U.S. DOE (2013) reasons that the "grid expansion to meet this increased electric load face growing challenges in balancing economic and commercial viability, resiliency, cyber-security, and impacts to carbon emissions and environmental sustainability. Energy storage systems (ESS) will play a significant role in meeting these challenges by improving the operating capabilities of the grid as well as mitigating infrastructure investments." (p. 7). Hence, the electricity storage is seen a central part of the future power grid, not only to increase the system flexibility, but also to reduce costs.

Example in California

In 2010, California enacted a legislation that requires the *California Public Utilities Commission (CPUC)* to mandate certain penetration levels of electricity storage in different parts of the power system. In October 2013, the CPUC determined that one of the biggest utilities is required to install 50 MW of electricity storage capacity by 2021 in the region grid around Los Angeles. Furthermore, the CPUC determined storage procurement targets totalling 1 325 MW of installed storage capacity for the three biggest utilities by 2020 (U.S. Department of Energy, 2013). As California has also mandated a renewable energy target, including net-metered generation from end-users, the grid is expected to face challenges due the variable nature of RET from wind and solar power. Therefore, the regulators perceived the need to enhance grid stability and flexibility in order to prevent power system blackouts and help to accommodate larger shares of VRE through electricity storage and mandated the deployment of significant storage capacity (Batistelli, 2013). The purpose of the CPUC's mandate is to "assist electrical corporations, electric service providers, community choice aggregators, and local publicly owned utilities in integrating increased amounts of renewable energy resources into the electrical transmission and distribution system in a manner that minimizes emissions of greenhouse gases." (Assembly Bill No. 2514, 2010, p. Section 1a). Furthermore, the energy storage mandate is considered to lower costs and reduce price volatility for VRE generation and grid integration. In this sense, the electricity storage procurement mandate in California is unique, as it is the first large-scale support programme for storage that serves as a real-life testing ground and if successful could have profound implications for the future power system integration of renewables (ASU Energy Policy Innovation Council, 2014).

2.4.2 Policy Support for BESS in the EU

Energy plays a crucial role within the EU's policy considerations, mainly due to the fact that it is highly dependent on energy imports from around the world. Despite its diverse energy mix across the continent, this energy import dependency comes at a price tag of roughly € 350 billion per year (European Union, 2014). Therefore, the EU's energy policy goals are to ensure security of supply while remain competitive, protect the environment and fight climate change, as well as improve the power grids and develop interconnections. The EU's energy strategy is primarily built upon three pillars: reduce GHG emissions through the *EU Emission Trading Scheme (EU ETS)* (Directive 2003/87/EC, 2003), improve energy efficiency (Directive 2012/27/EU, 2012), and increase the share of renewables (Directive 2009/28/EC, 2009) via clear targets (e.g. increase the share of renewables to 20 % by 2020, and at least 27 % by 2030). Moreover, the *Energy Roadmap 2050* (Commission Communication COM(2011)0885 final, 2011) laid out the long-term decarbonisation path to reduce overall GHG by 80-95 % compared to 1990 levels. The *Strategic Energy Technology Plan (SET-Plan)* (Commission Communication COM(2007)0723 final, 2007) for the uptake of low-carbon and efficient energy technologies provides the basis for the transition pathway, and was further refined and reinforced with the *Future Energy Technologies and Innovation* strategy (Commission Communication COM(2013) 253 final, 2013) of an integrated roadmap for the SET-Plan. There are additional energy related EU policy measures concerning the internal energy market and issues such as liberalisation of the electricity market (Directive 2009/72/EC, 2009), transparency on electricity and gas prices (Directive 2008/92/EC, 2008), security of electricity supply and infrastructure investment (Directive 2005/89/EC, 2005), and several other regulations that are rather fragmented. Having said that, all EU Member State, including Sweden, are free to develop their own energy mix as long as they respect the above mentioned legislation and implement it into national policy alongside their own strategic and political choices. However, the overall direction of the EU's energy strategy is pointing towards increased energy market integration with stronger and more interconnected grids. Recently, the European Commission has proposed the formation of the *Energy Union* package (Commission Communication COM(2015)080 final, 2015), a fully integrated internal energy market to better align and harmonise the formulated policy goals towards a more resilient, efficient, sustainable, low-carbon, and competitive energy future. Given this integrated approach of promoting a low-carbon and renewable based energy infrastructure in Europe, energy storage has up until now received relatively low recognition.

Under the *Energy Roadmap 2050* together with the *SET-Plan* and the *Future Energy Technologies and Innovation* strategy, the EU has launched a multi-billion research and innovation funding programme, called *Horizon 2020* (Commission Communication COM(2011)0808 final, 2011), that runs from 2014 to 2020. Bearing in mind the overall climate change, energy efficiency and renewable energy targets, a large share (€ 5.931 billion) of the money from the *Horizon 2020* funding programme has been allocated to promote the research and development of non-nuclear, clean and efficient energy technologies (European Commission, n.d.-b). The three main research areas are energy efficiency, smart cities and communities, and low-carbon technologies such as RET, whereof the latter also includes energy storage. Enhanced energy storage technologies on various scales to provide energy system flexibility is one specific area that is specifically researched (European Commission Decision C (2015)2453, 2015). The *Strategic Energy Technologies Information System (SETIS)* led by the EU's *Joint Research Centre's (JRC)* Institute for Energy and Transport identified (among others) *Electricity Storage in the Power Sector*, *Smart Electricity Grids* and *Wind Energy* as some of the main strategic technology areas where further RD&D activities are underway (JRC, 2014a). Although, direct public funding from the EU in energy storage technologies accounts only for € 1 million (the lowest number among all SET-Plan technologies), Member State's national public funding mechanisms (€ 59 million) together with corporate R&D investments (€ 1.5 billion) make electricity storage technologies the best funded SET-Plan technology (JRC, 2015). These numbers are interesting, as the EU itself only allocates a very small share of the total research funds, but RD&D activities from private businesses contribute with more than 95 % to future research. Having said that, the EU strategy is much more focused on market integration with smarter and more interconnected grids between the different countries. Therefore, energy storage plays only a subordinate role so far. In the *2013 Technology Map* of the SET-Plan (JRC, 2014a), which evaluates the different strategic technology areas for future research, it was stated that "the way to future electricity storage is not clear-cut as many questions arise concerning markets and regulations. There is no universal answer to whether storage is a profitable investment or adds value to a system" (p. 102). The same report also cast doubt on the potential needs for flexibility solutions that could be met with electricity storage. Therefore, it comes to no surprise that publicly funded research by the EU on electricity storage is lagging behind other markets, such as the USA. From the official EU documents and reports (JRC, 2014a, 2014b, 2015) it seems that electricity storage, with the exception of PHS, is regarded as rather immature afflicted with high uncertainty about the future. Many technologies are still considered to be in early research stage with only a few demonstration and pilot projects. Hence, it is also not surprising that there is no direct market support or incentive scheme on EU level for electricity storage and most of the effort and R&D is carried out through the private sector.

Example in Germany

A few EU Member States, such as Germany and Italy have some policy instruments in place that directly foster the uptake of electricity storage. Germany is also the country where most of the private sector research funds (65 % of total EU-wide corporate investment) are allocated, and the lion's share goes actually into battery storage applications (JRC, 2015). The Federal Government of Germany has launched the *Funding Initiative for Energy Storage* in 2012 with the goal to further develop storage technologies via RD&D and bring down technology costs while improving performance and exploring application areas in the power system in order to help accommodate larger shares of VRE. So far more than 250 projects in the areas of batteries in distribution grid, wind-to-hydrogen storage systems, and thermal storage systems have been supported with more than € 200 million (BMWi, n.d.-b). In addition, there is a *Funding Programme for Decentralised Battery Storage Systems* in place since May 2013, which subsidises small-scale BESS in conjunction with household solar PV installations (BMWi, n.d.-a). During the first two years, already over 10 000 BESS totalling € 163 million have been subsidised through the support initiative (Enkhardt & Beetz, 2015). A study on batteries in the EU electricity network (Normark & Faure, 2014) highlighted that such solar PV installations with BESS can be profitable without support schemes in Germany already in 2016 due to relatively high end-consumer electricity prices. The same study also found that similar application in Sweden would have significantly longer payback times due to the low electricity prices, but if local storage applications could be aggregated to participate in the balancing market, the profitability could be improved considerably.

Example in Italy

The situation in Italy is a little different from the one in Germany, but the main reason for battery support mechanism is also the rapid expansion of VRE with the help of support mechanisms. This however, has caused some stability issues on the power grid and has led the Italian TSO *Terna* to install electricity storage applications for transmission and distribution grid support. Even though the Italian regulatory authority for electricity and gas has implemented rules that BESS are considered production facilities, there is a clear distinction between distributed storage systems for domestic use and electricity storage installation for grid support, which essentially allows the TSO and DSOs to use such BESS systems (Cecchini, 2014; Electricity Storage Network, 2014). The Italian TSO has therefore launched a research and innovation project with the objective to install 40 MW of storage capacity (primarily batteries) in order to explore the development and implementation of electricity storage systems for transmission grid support (Terna, n.d.).

3 Framework & Methodology

This chapter identifies and presents a suitable and relevant method in the form of theoretical framework and justifies methodological choices. First, a brief review on *sustainability transitions* is presented and used to explain the why the Multi-level perspective (MLP) after Geels (2002b, 2004, 2006, 2010, 2011; Geels & Schot, 2007) has been chosen as a framework to structure the findings. In a next step, the relevance and the main characteristics and mechanisms of the MLP are described. Then, it will be elaborated what method has been selected for data collection. And lastly, some methodological choices, related to the data analysis and the identified framework, are justified.

3.1 Sustainability Transition Frameworks Examined

As this thesis departs from the background of the issues and risks associated with climate change and the need for a decarbonisation of energy systems and entire economies, the assumption is that the structural change related to renewable energy technologies is just the beginning of a system-wide transition towards low-carbon economy over the first-half of this century. Energy and electricity storage in general, and BESS in particular, are only a part of the system transformation based on more distributed renewable energy sources.

Henning and Palzer (2014) describe the technological development of energy transition towards a renewable based energy system in a 3-step process. It first starts with the installation of some RET without major effects on the overall structure of the incumbent system, which many countries are currently experiencing or have already completed. It is then followed by a conversion process of the overall system with increased supply and demand side flexibility, an increased push for efficiency, first deployments of short-term energy storage, and the emergence of new business models (e.g. Germany or Denmark). In the third and last step, long-term storage applications and the replacement of natural gas by synthetic fuels from renewables will complete the transition.

In the context of this thesis with an emerging energy system based on decentralised RET gradually replacing the incumbent fossil fuel and nuclear based one, it can be seen as transition towards sustainability, as described by Markard, Raven and Truffer (2012). In their extensive literature review on sustainability transition concepts, they identified that existing industry sectors (e.g. transportation, water or energy supply) manifest strong lock-ins and path-dependencies that are highly intertwined with established social, political, organisational, institutional and economic structures and norms. It can be seen as a broad network of different actors (e.g. individuals, companies, organisations), institutions (e.g. technical and societal norms, standards, regulations), products, and knowledge that is summarised as a socio-technical system. Therefore, sustainability transitions of incumbent socio-technical systems usually come along with incremental and long-term, rather than radical and quick, changes in patterns of production and consumption. It is not only the technological level that undergoes changes, but it also includes transition processes along multiple other dimensions, such as organisational and institutional structures, as well as user practices. Those fundamental and long-term changes raise the issue of how to promote and govern transitions towards more sustainable socio-technical systems. The same authors (Markard et al., 2012) identify mainly four prominent theoretical approaches to navigate and foster sustainability transitions: *transition management (TM)*, *strategic niche management (SNM)*, the *multi-level perspective (MLP) on socio-technical transitions*, and *technological innovation systems (TIS).*

While there are also numerous other theoretical concepts and frameworks that deal with analysing and guiding transitions of technical, social and economic systems in a more coordinated way towards more innovative and/or sustainable pathways, the four frameworks mentioned above embrace more systemic and integrated views of far-reaching transformation processes (Markard et al., 2012). In some instances, these frameworks are also somehow connected to each other, as they originate from similar theories and ideas. The field of sustainability transitions merges ideas of system innovations, socio-technical transitions and the uptake of sustainable technologies and has seen increasing interest in the area of social sciences over the last decade. Therefore, all four approaches are somewhat relevant and would to some degree be suitable for this study. However, when examined in more depth, it should become clearer why the MLP on socio-technical transitions has been chosen.

Transition Management

Active interventions form the basis of the transition management framework (Kemp & Loorbach, 2006; Kern & Smith, 2008; Loorbach, 2010; Rotmans, Kemp, & Van Asselt, 2001; Smith, Stirling, & Berkhout, 2005) and combine ideas from complex system theory, technological transitions, and governance approaches. The main focus lays in top-down steering and how ongoing transitions can be managed and influenced via policy interventions in an evolutionary and practice-oriented way towards more sustainable directions. While this concept might be useful in certain local and regional contexts, it has also been pointed out by some researchers (Kern & Howlett, 2009; Kern & Smith, 2008) that the transition management approach, especially in relation to energy system transitions, may not be very effective in the context of nationally administered policymaking.

Strategic Niche Management

Strategic niche management (e.g. Kemp, Schot, & Hoogma, 1998; Raven, 2007; Raven & Geels, 2010; Rip & Kemp, 1998; Smith, 2007) departs from the idea that novel technologies and innovations evolve from protected market spaces, so-called niches, in a way that they are not directly threatened by the incumbent market regime from the onset. Continuous learning through multiple experiments together with heterogeneous niche networks then gather momentum and as the influence of such niche innovation systems grows, they start to compete with established market structures and eventually replace the incumbent market regime. Hence, the SNM framework focuses mainly on a bottom-up perspective that analyses such niches and tries to better coordinate their resources. While this is certainly valuable in some circumstance, it risks neglecting the developments and implications on existing market structures as well as on a wider socio-technological landscape, as pointed out by some scholars (Berkhout, Smith, & Stirling, 2004; Geels, 2002b).

Technological Innovation Systems

The concept of TIS (e.g. Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Carlsson & Stankiewicz, 1991; Edquist, 1997; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000) deals with the emergence of new, potentially game-changing technologies and how actors, networks and institutions of the innovation system contribute to the development, diffusion, and use of such novel products. Therefore, the perspective is neither bottom-up nor top-down, but rather focuses on the prospect and dynamics of a particular technological innovation in a certain socio-technical *innovation system* and how it creates new structures and processes (so-called *functions*) within the system. A number of scholars (Bergek & Jacobsson, 2003; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000; Jacobsson & Lauber, 2006) have applied the TIS approach for technological innovation in the context of energy systems at different levels of aggregation. However, a drawback of this approach is that is quite limited around the development and diffusion of an innovative technology or product and its functional structures within the innovation system. The TIS concept does not focus on the transition process per se, but rather on the emergence of one particular (or generic) innovation and therefore lacks a broader analytical perspective across different dimensions (Markard & Truffer, 2008; Smith, Voß, & Grin, 2010).

Multi-Level Perspective

Concerning the MLP (Geels, 2002b; Geels & Schot, 2007; Rip & Kemp, 1998; Smith et al., 2010), as the name suggests, this concept focuses its analysis on several levels of a socio-technical system and takes a more comprehensive and dynamic approach. The framework consists of three different levels: niche, regime and landscape. The idea is that bottom-up developments from niches and top down pressures from the landscape destabilise the incumbent regime and ultimately replace it with a new one (see also *Figure 3-1* below). In that sense and simply speaking, it combines the bottom-up and top-down approach from SNM and TM and also allows for multiple technological innovations, as compared to the TIS. Hence, the focal unit of the MLP is the dynamics and prospect of the socio-technical transition itself, which allows for more flexibility and can capture the interactions between the multiple actors and levels.

However, once again it is argued that the uptake of energy storage technologies is part of the broader socio-technical transition towards a decentralised and RET based energy systems, with particular focus on Sweden. As the energy system forms wide socio-technical system with interactions of both internal and external processes, the transition also brings about far-reaching consequences and does not only encompass technological changes but also modifications in institutions and organisations, infrastructure, as well as in political, social, cultural, and behavioural aspects. Within this context the MLP approach seems to be more relevant for this study. Geels, Hekkert and Jacobsson (2008) support this as they argue that "the MLP has progressed further in conceptualising interactions between internal and external processes. The energy domain […] is particularly complex in this respect, because of influences from multiple regimes." (p. 530). For instance, Verbong and Geels (2007) have also argued and demonstrated that the MLP suits well for analyses of energy system transitions. What is more, the thesis aims to provide insights from and for different market actors and policymakers in Sweden in order to map drivers and barriers for the future deployment of battery energy storage and ultimately advance the energy system transition. While the MLP does not specifically focus on agency and has been criticised for this (Smith et al., 2005), the multi-level structure of the socio-technical system and the interactions between these different dimensions implicitly include actors, which are unveiled as shared rules and coordinated actions (Geels, 2011; Geels & Schot, 2007). Geels (2011) further elaborates that "the MLP accommodates agency in the form of bounded rationality (routines, search activities, trial-and-error learning) and interpretive activities" (p. 30). It is argued that both niches and regimes can be seen as some sort of networks or communities of organised actors that collaborate and coordinate their doings. Whereas in regimes these interactions and the coordination of rules and activities are more or less stable, in niches they are fragile and still evolving. These structures and ties are influenced by several internal and external factors. For instance, the behaviour of actors and how they influence others, or how they coordinate the interplay with technology and infrastructure ultimately determines the stability of such structures.

While there are also some other criticisms to the MLP (e.g. Berkhout et al., 2004) regarding the focus and boundary setting of the regime level or bias towards bottom-up change, some scholar (Bulkeley, Broto, & Maassen, 2014; Bulkeley, Castán-Broto, & Maassen, 2010) argue that the MLP approach and other transition theories (such as TM, SNM, or TIS) neglect the changes of infrastructural components that are also needed in order to successfully transition to a new regime. While this aspect is certainly relevant, especially with respect to the energy system under analysis, the main focus is on the diffusion of a technological niche innovation as well as the interactions of market actors and their structures. Therefore, the MLP framework is deemed to be most suitable in order to fulfil the research purpose.

3.2 The Multi-Level Perspective (MLP) on Socio-Technical Transitions

By applying this conceptual lens through the MLP framework, this thesis seeks to identify potential drivers and barriers for BESS for the grid integration of wind power in Sweden. In other words, it is not the technology development as such that is analysed, but rather the objective is to seek for evidence of certain patterns and mechanisms of a technology diffusion process in a large actor network within the context of a wider energy system transition. As explained above, the various actors on different level interact and collaborate with each. In this way, they share common rules and behaviour, shape (or are being shaped by) the environment they operate in and create certain structures, which ties them together. However, even if these interaction processes and structures between the actors are stable, they can evolve over time. Therefore transitions entail more than just technological innovations, it is a wide and complex interlinkage of factors, such as regulations, standards, infrastructure, behaviour, user practices, social and cultural meanings, as well as material artefacts that changes and evolves over a period of time. It is exactly those mechanisms and configurations between market players on different levels that will be analysed in order to identify certain patterns that can be interpreted as drivers or barriers for change. Therefore, the MLP framework by Geels (2002b, 2004, 2005b, 2006, 2010, 2011; Geels & Schot, 2007) was deemed to be most suited for carrying out this research as it helps to structure the findings by describing structures and processes between actors on different levels, as well as analysing the results.

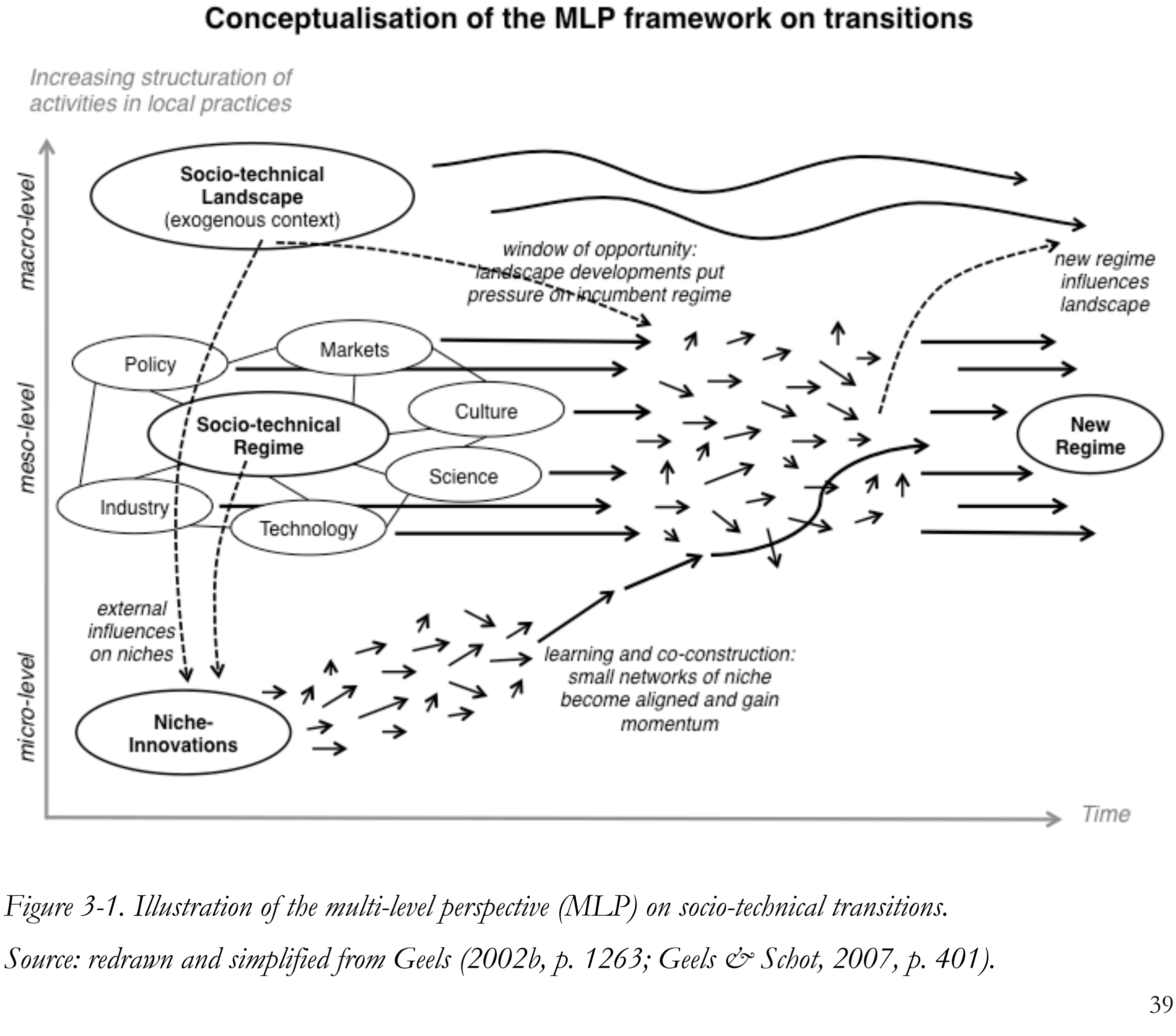

Figure 3-1. Illustration of the multi-level perspective (MLP) on socio-technical transitions.

Source: redrawn and simplified from Geels (2002b, p. 1263; Geels & Schot, 2007, p. 401).

3.2.1 Conceptualisation of the MLP Framework

The MLP framework on socio-technical transitions was originally developed by Geels (2002b) and builds upon evolutionary economics, technology studies, as well as earlier research on multi-level perspectives (e.g. Kemp et al., 1998; Rip & Kemp, 1998). Since its first publication in 2002, it has been gradually refined and expanded (Geels, 2004, 2005a, 2005b, 2006, 2010, 2011; Geels & Schot, 2007; Smith et al., 2010). As it has already been briefly explained above, the MLP consists of three main building blocks: technological niches, the socio-technical regime and the overarching socio-technical landscape. The niches form the micro-level and can be described as small, heterogonous places or networks protected from the mainstream market that act as an incubator space where technical, social, and organisational innovations are created, tested, and start to develop and emerge. The regime level is seen as the deep-rooted, stable structure of a socio-technical system accommodating the broader community of social groups and aligning established technology, infrastructure, user practices, markets, specific knowledge, behavioural patterns, cultural and symbolic meanings, sectorial policy, industrial networks, material artefacts, etc. The landscape forms the overarching, exogenous environment with deep cultural patterns as well as macro-economic and macro-political trends where change normally takes place very slowly.

The idea is that transitions come about via dynamic, quasi-evolutionary processes and interactions between these three different levels that ultimately result in the establishment of a new socio-technical system. The gradual transition process under the MLP approach includes four somewhat overlapping phases. At the very beginning, an innovation on the niche level emerges and after some time gathers momentum through processes of learning, experimentation, and improvement together with some form of external support. Then, when exogenously induced change on the landscape level evokes some pressure on the existing socio-technical regime, this may lead to the destabilisation of the incumbent regime and eventually creates a *window of opportunity* for niche innovations to break through. This in turn enables a wider diffusion of the novelty and leads to competition with the established regime. Eventually, the gradual realignment of a new socio-technical regime with various sub-regimes around the novel technology causes the gradual replacement of the incumbent regime and induces wider impacts on society as a whole (i.e. landscape level). An illustration of the MLP and the different interactions and processes across the various dimensions can be seen in *Figure 3-1* above. In summary, the phases of system innovation under the MLP framework (Geels, 2005b) somewhat differ from the ones initially proposed by Rotmans, Kemp, and Van Asselt (2001). While the latter approach departs from the concept of TM with the aim to actively navigate transitions in a desired direction, the MLP framework takes a more comprehensive and evolutionary approach that goes beyond the transition process itself, but aims to depict actor relations and interactions on various levels.

Although, the overall transition course of a socio-technical system shows similar phases and patterns, the pathways may differ depending on several factors and processes, such as e.g. the timing and nature of interactions between various dimensions. This is will briefly been taken up in the subsequent subsection.

3.2.2 Processes and Trajectories of the MLP

The MLP does not only help to identify certain structures and actor relations in a socio-technical system, such as the electricity market in Sweden, it can also be used to analyse transition pathways as well as technology diffusion patterns, processes, and phases. This does not only help to better understand the system interactions (i.e. drivers and constraints on different levels) but can also be used as a tool to strategically direct certain developments and transition processes.

Unlike some other approaches (e.g. Berkhout et al., 2004; Smith et al., 2005), Geels and Schot (2007) combine the two criteria *timing of interactions* and *nature of interaction* in order to better describe transition processes. Timing in transition is important as it highlights the fact that a sequence of interactions can take different trajectories depending on when things happen. In particular, the timing of landscape pressure on the incumbent regime (i.e. window of opportunity) together with the development state of niche innovations will steer the transition on different pathways. Not only when, but also how things happen determines the outcome of a transition. For instance, landscape developments and niche innovations can either have a disruptive and competitive relationship with the existing regime, or also more reinforcing and symbiotic one. While the first relationship is likely to destabilise the incumbent regime, the latter has more of a stabilising effect on the regime and makes transitions slower and harder. Moreover, it is also important to consider the type such external landscape pressures, e.g. whether the change is more gradual, or disruptive, or even takes the form of a specific shock. According to those criteria, Geels and Schot (2007) then propose several different transition pathways. However, for the purpose of this study it is of less relevance which specific pathway is likely to be followed (usually it is also only possible to determine the pathway after the transition is completed), but rather which processes and patterns can be observed.

Relating these theoretical explanations to real events and as it has been elaborated in the introductory chapter, today we can see increase landscape pressure on the incumbent fossil fuel based energy system as a consequence of the increasing climate change and human health related risks linked to the emissions of GHGs and other particles. Thus, the intensified debate on internalising climate related externalities and limiting CO_2 and other GHG emissions as a solution to mitigate the climate crisis we are facing. Inevitably this means a transition towards clean, low-carbon RETs energy systems (IPCC, 2014). However, the current socio-technical energy systems, including various subsystems, can be characterised by a strong lock-in effect and path-dependency on carbon intensive energy supplies and are therefore difficult to escape (Unruh, 2000). Nevertheless, the accelerated uptake of RETs in recent years with decreasing costs and improved performance for these technologies indicate that a transition is underway. While global solutions to advert the climate crisis have still not been reached, the rhetoric on national and regional level is gradually changing with more and more policies putting a price on carbon and supporting RETs, as the example of the EU and various other countries shows. However, as it was also made clear above, the transition requires coordinated action across multiple dimensions and also includes changes in behavioural practices, social and cultural norms, infrastructure, as well as the co-evolution of complementary functions and applications, such as for example energy storage, that eventually form a new socio-technical system.

Notwithstanding these recent developments, it is important to clarify a few specific aspects of the MLP concept. First of all, not all innovations will make the transition and evolve from niche level to form a central part of a new socio-technical regime. In fact, many niche innovations fail early and there is no guarantee for success. Secondly, there is also a chance that many different niche innovations compete against each other and ultimately a *winner* will be brought forward that then challenges the incumbent system. And last but not least, whether transitions will occur depends also on the timing and circumstances of events – i.e. how external influences and expectations from the regime and landscape level are shaping and/or dictating the perceptions of niche actors and their support networks (Geels, 2002b, 2004, 2005a, 2006, 2010, 2011; Geels & Schot, 2007). This is one of the main differences to the concept of SNM, where the internal niche processes are analysed and described (e.g. Kemp et al., 1998; Raven & Geels, 2010; Rip & Kemp, 1998). While in the SNM theory protected spaces are actively nurtured from above (Kemp et al., 1998; Rip & Kemp, 1998), the

MLP departs in a way that the emergence of niches is an evolutionary process of learning on multiple dimensions that is influenced by external aspects (Geels & Schot, 2007).

Having said that, the transition process under the MLP follows the path of co-evolution across the different levels and combines two views of evolution processes, as described by Geels (2002b): "(i) evolution as a process of variation, selection and retention, (ii) evolution as a process of unfolding and reconfiguration" (p. 1257). In other words, co-evolution can be understood as the emergence of a novel technology as such but together with a new user environment, new markets, policy dynamics, and socio-cultural norms. In the same way as an existing socio-technical regime is a more or less coherent network of sub-systems, actors and rules (i.e. regulative, normative, and cognitive rules) where the structure and stability is manifested by the degree of alignment or tension, a niche innovation must also build up its own new system through gradual alignment and co-construction of new sub-systems, actors and rules. This co-evolution usually happens via learning processes in various niche markets where the novelty is searching and testing new functions and applications, which can then be linked-up. Such learning and development processes also help to further improve the price/performance ratio. Geels (2005a, 2005b) basically identifies three patterns in system innovation, which are briefly described in *Table 3-1*.

Table 3-1. Identified patterns in system innovation under the MLP concept.

Co-evolution/diffusion pattern	*Underlying processes*
Fit-stretch pattern in the co-evolution of form and function	1. Fit new technology in existing regime 2. Explore new technical forms and design options 3. Explore new functionalities 4. Wider diffusion and eventually establishment of a new socio-technical regime
Co-evolution of multiple technologies	Linkages and interactions between multiple technologies as a process of co-evolution via e.g.: • interlocking, alignment, positive feedback, • cross-sectorial clustering, • complementarities, • cumulative effects of many incremental innovations to substantially improve product performance.
Diffusion as a trajectory of niche-accumulation	Technological diffusion occurs not all at once, but in successive steps via gradual development and learning processes involving multiple actors. Breakthrough from niche to regime as new technology diffuses or penetrates multiple sectors and domains.

Source: own elaboration based on (Geels, 2005a, 2005b).

Patterns and processes like these are particularly relevant for this study as they can contribute to better understand interactions, constraints and opportunities, not only the niche level but also on regime and landscape levels. It is important to note here that the patterns and processes for diffusion and co-evolution are being used as an explanatory, strategic transition tool, rather than market introduction strategy. Going back to the research question and objectives, the aim is to identify potential market drivers and barriers among various levels and market actors in Sweden for grid-scale BESS in combination with VRE from wind power. This may then help to delineate potential market opportunities for the future deployment and use of such BESS on the Swedish electricity market.

3.3 Method and Methodology

For this thesis, as it takes the form of exploratory work, a deductive approach was used to guide the research. First, an extensive literature was performed in order to better understand the topic and formulate the specific research problem. This then supported the identification of a relevant and suitable conceptual (theory based) framework and the formation of certain assumptions, which helped to refine the research problem and structure the study. Backed by this theory base, it was possible to outline potential interview targets for collecting the primary data. Using the conceptual framework for structuring and then analysing the observations, deductive reasoning was utilised. References, data, variables, diagrams, and hypotheses as such explain which empirical patterns were observed, but theory helps to explain why empirical patterns were observed (Sutton & Staw, 1995). Patterns in the pieces of information collected via interviews and literature have been determined using the MLP framework and institutional theory, which at the same time also help to identify why certain patterns are prevalent and if can be classified as drivers or barriers for the future deployment of BESS in Sweden.

3.3.1 Data Collection

As outlined in the introductory chapter, this thesis focuses on investigating market drivers and barriers for BESS in the context of VRE wind power grid integration in Sweden. For this reason data has been gathered both from primary sources via interviews and secondary sources through existing literature. Firstly, in order to specifically define the applications and benefits for BESS (both for Sweden and more in general terms) and further refine the scope, an extensive literature review, based on academic and industry resources, has been carried out. On the basis of this review, which helped to thematise and design the primary data collection, semi-structured interviews with selected electricity market actors in Sweden were carried out. As this research has exploratory character and is a first attempt to scope the market feasibility for BESS in Sweden, this method of *semi-structured interviews* with industry experts and market actors has been deemed as most suitable in order to obtain relevant, qualitative data (Hakim, 2000; Kvale & Brinkmann, 2009). The idea of semi-structured interviews is to state broad and easy-to-understand questions (with some more specific questions towards the end as a backup if needed), and to spontaneously respond to certain answers/statements (e.g. for probing, specifying, clarifying, confirming, etc.). Nevertheless, a detailed interview guide has been developed, including specific interview questions (can be found in *Appendix III*), in order to adopt certain questions to the specific context of the interview target and allow for more flexibility during the interview.

In order to identify and localise potential interview partner, an actor landscape with different actor spheres has been drawn (see *Appendix IV*). Electricity and wind power industry associations (i.e. Svensk Energi and Svensk Vindergi), research networks (i.e. SweGRIDS, Power Circle, Energiforsk, Nordic Energy Research), and governmental institutions (i.e. Swedish Energy Agency) have been consulted first. In order to get valuable information from various technology and industry experts across different levels and identify further actors, the *snowballing method* was used where interviewees where specifically asked if they can recommend additional experts with knowledge and experience in the field. As suggested by literature on qualitative research (Kvale & Brinkmann, 2009), the initial goal was to get around 15 interviewees, with actors and experts all across the Swedish electricity market. Having that said, a pre-selection of interview targets had to be made, especially on the level of utility companies where only the five biggest ones were contacted. In the end, a total of 20 semi-structured expert interviews were carried out via phone or Skype, mainly during the period between June and July 2015. A full list of all interviewees can be found in *Appendix V*. It should be noted here that more than those 20 interview targets were contacted initially, but some of them did not respond or were not available.

All interviewees were initially contacted via email and when requested by the interviewee a shorter version of the interview guide with some background information, research questions, as well as the main interview questions (a shorter version of what can be found in *Appendix III*) were also sent to them. The majority of the interviews have been recorded, only after obtaining permission from the interviewee, for more accurate transcription of the information. Already during the interview, some notes were taken and then after the interview and with the help of the recordings, they were transcribed.

3.3.2 Data Analysis

As it has been stated above, the secondary data was summarised in a literature review (see *Chapter 2*). This review has then been used to support and analyse the findings (see *Chapter 4* and *Chapter 5*).

Regarding the primary data, after all interviews were transcribed, a preliminary summary highlighting the most important findings was compiled. In order to better understand the semi-structured content of the interviews and identify certain patterns, the interview data was coded (i.e. drivers, barriers, uncertainties) according to what was specifically pointed out as important by the interviewee or what seems familiar (or contradicting) with theories/concepts from the reviewed literature. As the step, the coded information was clustered/categorised (into landscape, regime, and niche development) to enable better conceptualization and utilization for the chosen framework and analysis. Such an approach was also suggested by the literature on qualitative research interviewing (Kvale & Brinkmann, 2009).

In order to allow for better analysis and discussion of the findings, the results are presented and structured according to the functional components (i.e. the three levels niche, regime, and landscape) of the MLP. Geels (2005b, p. 101) suggests to work from landscape to regime to niche and points out the dynamics and themes (slightly adopted for the purpose of this thesis and inspired by a similar study (Wangel, 2015)) shown in *Table 3-2* below.

As it can be seen, many of the listed signal and ongoing processes in *Table 3-2* are somewhat overlapping, and therefore a strict division is neither possible nor desired. The above presented structural and functional components of the MLP should be seen as a support tool to better cluster certain dynamics and observations. This will be useful to analyse the prevailing patterns. As it has been mentioned before, the agency and how the different actors operate and respond to dynamics and rules (formal, normative, cognitive) is a central part of the MLP framework. Drawing on institutional theory and based on Oliver's (1991) seminal paper on *Strategic Responses to Institutional Processes*, it is argued that organisations (i.e. market actors) respond to external dynamics and pressures, such as e.g. formal rules and regulations or innovations, in different ways. The presumption is that there is "variation in the degree of choice, awareness, proactivness, influence, and self-interest that organisations exhibit" (Oliver, 1991, p. 146) to take up external pressures on various dimensions and seek legitimacy of their actions. However, organisations have bounded capacities to adapt, respond, influence or defy such external pressures. Hence, whether organisations choose a strategy to resist or comply with such external pressures depends on the anticipated legitimacy and outcome of their actions. Ultimately, organisational strategies and choices to adapt to such institutional pressures are closely linked to the anticipated outcome for organisations. Oliver (1991) proposes ten hypotheses how organisation respond to external pressures, which help to identify potential drivers and barriers from the observed processes and structures via the MLP. For instance, whether an organisation will resist or comply with certain institutional pressures (e.g. new rules and regulations) depends on how it affects their future economic bottom line. Whilst certain institutional pressures are likely to negatively affect organisation as there are perceived not to be in line with their values and practices (e.g. business models), others are more likely to positively impact them. Thus, it becomes obvious that regime actors usually act strategically and try to defend their status quo by resisting institutional pressures that are not in their favour. Such patterns and processes can be seen as barriers for novel technologies and niche actors. On the contrary, certain institutional dynamics might be too strong to defy and organisations will try to adopt. At the same time, these new institutional developments might then open up opportunities for innovations and new actors, which eventually constitutes drivers for niche applications and their actor network.

Table 3-2. Structural and functional components of the MLP framework on socio-technical transitions.

What to look for?	*Examples of patterns and processes*
Landscape developments	
What are the relevant external landscape signals? And how do they influence regime processes?	Landscape dynamics that can direct regime processes in certain ways are e.g.: • broad societal and political support/resistance to mitigate climate change risks, • large-scale deployment of a renewable energy infrastructure.
Regime developments	
What are the main dynamics in the socio-technical regime? And to what extent are they driven by landscape signals?	Specific attention towards internal regime processes, structures, and actors: • **formal institutions and policy actions (**e.g. formal rules such as law, regulations, or policies that institutionalise cognitive and normative rules and if well aligned can act to stabilise the regime dynamics but also destabilise when tensions emerge; • **market dynamics** (e.g. normative and cognitive rules such as behavioural norms, values, relationships, belief systems, innovation agendas, investment decisions, problem definitions, and guiding principles of regime actors and how they understand their role in society); • **actor network and interactions** (e.g. cooperation, legitimacy, problems, or tensions between actors that are strongly influenced by formal, normative, and cognitive rules and act either in an constraining or enabling way); • **technology development** (e.g. technological innovations such as smart grids, demand response technology, or RET in general that can act both as a driver or barrier for energy storage).
Niche developments	
Which novelties emerged in which niches and which actors are involved? Also, what issues (i.e. regime actor structures and interactions) were encountered by niche actors and how are they related to ongoing regime processes?	Specific attention towards ongoing learning processes on various dimensions (co-construction): • R&D programmes and funding, • demonstration/test/pilot projects; • complementary niche applications and functions; • networks with and expectations from incumbent regime actors on niche markets.

Sources: own elaboration.

4 Drivers and Barriers for BESS in Sweden

This chapter presents the findings and results from the collected data with the help of the MLP framework. The structure follows the MLP approach from landscape level to regime level and finally down to niche level. At a first step, important process and developments among various actors across different levels are described with relevance to battery storage in Sweden and then it is determined whether they can be seen as drivers or barriers for the future deployment of BESS.

4.1 Landscape Developments

The landscape can be seen as the exogenous environment that depicts the broader societal, political, and economic context (e.g. paradigms) where change usually happens very slowly (Geels, 2002b, 2005b; Geels & Schot, 2007).

As it has already been highlighted at the outset of this study, the necessity to mitigate climate change related risks has become an important aspect, not only on the global level but also particularly in Europe and Sweden. Actions to seriously tackle the issue have been rather moderate, but both on EU level (European Union, 2014) and in Sweden (Naturvårdsverket, 2013) there are policies in place that somehow try to address the issue through GHG emission cuts, improved energy efficiency, and increased shares of renewable energy. Many of the interviewees, did not mention this explicitly, but as a matter of fact it was pointed out by the majority that Sweden is currently undergoing a transformation process of its electricity mix. As Sweden already today has an almost carbon neutral electricity mix, mainly based on nuclear and hydropower with a small but growing share of VRE from wind, there is little indication that this could change in the near future. Quite on the contrary, nuclear power has been a highly controversial issue over the last years (IEA, 2013) and most of the actors interviewed indicated that a gradual phase out and decommissioning (rather then updating and renewing) of the remaining ten nuclear reactors within the next decades seems very likely. Nuclear power in Sweden is indeed facing some headwind, with two of the major nuclear power plant operators, E.ON and Vattenfall, having indicated that even earlier close-downs of some reactors are in the planning (The Local, 2015).

At the same time the societal acceptance of RETs in Sweden, especially the expansion of wind power, is perceived as favourable (Ek, 2005). There is also sufficient political support towards a more distributed and renewable based electricity system, as the existing electricity certificate scheme to further expand renewables and wind power shows (Swedish Energy Agency, 2012). Moreover, this is further underlined by almost all interviewees who expect the penetration of VRE from wind power, and to a lower extent solar PV, to increase significantly over the next decades.

On a broader societal level, there can also be witnessed an increasing trend towards distributed and self-produced renewable energy by households and industrial businesses in order to reduce their exposure to fluctuating electricity prices. This is especially the case in countries with relatively high electricity prices (either on the retail market or both wholesale and retail) where individual rooftop solar PV installations provide an option for cost savings. Such developments fundamentally alter the energy system backdrop, as electricity customers are not solely customers anymore but also producers, so-called *prosumers*. The emergence of energy storage systems (e.g. batteries) in combination with smart energy usage solutions (e.g. smart grids and demand-side management) will only exacerbate the situation for traditional utility companies (Bronski et al., 2014, 2015). More than a handful of the interviewees acknowledged that this trend can already be experienced in some European countries and will be further accentuated through support policy measures, such as feed-in tariffs (e.g. in Germany) or other incentive mechanisms.

From an European perspective, there can also be identified some dynamics in the direction of a more integrated energy market (i.e. the completion of a single Internal Energy Market and the proposed the EU Energy Union) focusing on increased energy security, competitiveness, as well as sustainability and renewables (European Union, 2014). It can be expected that such developments will also have an effect on the Nordic and Swedish power markets, as it was pointed out by some representatives from the regulatory and policy sector who have been interviewed. Therefore, it can be argued that the broader societal and political environment in Europe and Sweden shifts rapidly away from the centralised electricity generation model towards a more decentralised renewable based energy system as the legitimacy of renewables steadily grows. This rapid trend induces some sort of landscape pressure on the incumbent regime. As it will be elaborated further below, the established regime is rather reluctant to such changes due to incompatible values, norms, as well as technology and infrastructure lock-ins with the emerging low-carbon socio-technical system.

4.2 Regime Developments

The regime level consist of the currently incumbent socio-technical system including formal, normative and cognitive rules, market actors and their networks, established technologies, user practices and behaviour, as well as material artefacts. Due to the various dimensions and aspects on the regime level, it can be further divided into four sub-categories: formal institutions and policy actions, market dynamics, actor networks and interactions, technology development (Geels, 2005b; Wangel, 2015).

4.2.1 Formal Institutions and Policy Actions

As explained earlier, landscape dynamics gradually, or sometimes even rapidly, influence regime structures through exogenous pressure in the form of changing societal, macro-economical and macro-political developments. Such externally induced changes on the regime level create a window of opportunity for a de-alignment of established regime structures and re-alignment of new ones from niche innovations. First and foremost, such exogenous landscape pressure will affect the institutional context and how policies and regulations are shaped in the new environment (Geels, 2002b, 2005b; Geels & Schot, 2007). Whether landscape developments coincide with emerging niche applications to form a new socio-technical regime essentially depends on the timing and nature of the interactions. Even though it is important to bear that interplay of landscape and niche developments in mind, it will be left as food for thought for the discussion and analysis section.

Now the focus will be specifically on institutional processes and developments and how they might impact the current electricity market and ultimately the future investment and deployment of BESS in Sweden. However, it is important to remind the reader again that this is only a presentation of the policy aspects related to electricity storage deemed to be most relevant. The scope of this study does not allow for a complete policy mapping, but the findings presented here could provide an entry point for future research.

Developments on the EU Level

Starting from a broader EU perspective, it can be said that the EU policy actions influence Member States' actions and policy requirements to a significant degree, as Member States have to translate such legislation into national policy. As it was already highlighted earlier (see *Section 2.4.2*) and when describing the landscape dynamics, the EU has not only adopted quantifiable energy related policy targets for 2020 and beyond (e.g. for the share of renewables, GHG emission reductions, or increased energy efficiency), but also mandatory legislation in order to facilitate higher penetration of renewables and further integrate and harmonise the European energy market (so-called *Internal Energy Market*). The *Third EU Energy Package* in 2009 introduced a number of new pieces of legislation (notably (Directive 2009/72/EC, 2009) and the (Regulation (EC) 713/2009, 2009; Regulation (EC) 714/2009, 2009)), which supersede and amend prior legislation from the *First* and *Second Energy Package.* The Directive is of special relevance here, as it stipulates the common rules for EU Member States for the further harmonisation and liberalisation of energy markets with the aim of creating a single Internal Energy Market in the EU. Essentially the Directive 2009/72/EC (2009) legislates unbundling of the transmission and distribution network operation from generation and supply activities. In simple terms, the aim of unbundling is to prohibit any network operators from owning and operating any form of electricity generation in order to eliminate the risk of discrimination by vertically integrated utilities (Normark & Faure, 2014). Normark and Faure (2014) who analyse electricity storage in an EU context, conclude that "*Article 9 of Directive 2009/72/EC related to unbundling constitutes the main barrier to large scale storage development* on the grid because TSOs acting on the wholesale generation market could be a source of market distortion and interference with system wide responsibility" (p.33, with own emphasis). In combination with *Article 12* of the same Directive, which aims to ensure that TSOs provide the necessary means (including ancillary services) for balancing the grids, this creates a rather perverse situation for operating storage as a tool to provide power system stability. Furthermore, the same scholars (Normark & Faure, 2014) also emphasise that the current EU legislation framework (i.e. the Third Energy Package, plus the *Energy Efficiency Directive 2012/27/EC* (2012) and the *Renewable Energy Directive 2009/28/EC* (2009) "recognises storage as a strategic asset of the power system" (p. 33), but crucially the unclear definition of storage constitutes another major barrier for the deployment of storage assets. Whether storage assets qualify as a power generation units remain largely unclear. But the fact that no storage technology is further specified or defined leaves big leeway on how to own or operate electricity storage units, especially in conjunction with network operations. In theory TSOs are allowed or even encouraged to provide the necessary ancillary services for the proper functioning and stability of the power system, but they may not own or operate any power generating assets. Nevertheless, Normark and Faure (2014) also point out that Directive 2009/72/EC puts less stringent unbundling restrictions on DSOs, which would allow them to own and operate storage applications under certain conditions. These ill-defined or missing specifications on how to use and operate storage applications were also something that numerous interviewees specifically addressed, especially when asked about concrete market barriers.

Hence, it can be concluded that the EU legislation that is currently in place generally discourages the utilisation and operation of electricity storage applications for providing power system services, despite their strategic role of providing useful ancillary services and grid flexibility. Thus, the institutional situation on EU level today can be seen a major barrier for electricity storage, and particularly BESS.

Apart from the above, *EU Regulation (EC) 347/2013 (2013) on Guidelines for Trans-European Energy Infrastructure (TEN-E)* aims to further develop the energy infrastructure for the completion of the Internal Energy Market and the integration of the increased share of renewables. The Regulation includes storage as one of the asset categories besides transmission lines, smart grids and others that could receive EU funds or streamlined planning decisions under certain conditions. However, given the projects (referred to as *Projects of Common Interest, PCI*) currently in the process of being developed under this legislation (European Commission, n.d.-a), it shows that either interconnections is given a higher priority or there is a lack of suitable storage projects. Also, the fact that none of the interviewees referred to this piece of EU legislation highlights that market actors may be unaware of such support mechanisms.

However, the Third Energy Package was adopted in 2009 and in the meantime the EU has introduced the *Energy Roadmap 2050* (Commission Communication COM(2011)0885 final, 2011) in combination with the *Future Energy Technologies and Innovation* strategy (Commission Communication COM(2013) 253 final, 2013), which laid out the opportunities and challenges of the decarbonisation pathway (overall GHG emission reduction by 80-95 % compared to 1990 levels). Such an energy transition not only requires a higher share of renewable energy but also well-aligned and synchronised policies. In 2014, the EU and its Member States agreed on a renewed policy framework on climate and energy with updated and binding targets for 2030 for GHG emission reduction (40 % to 1990 levels), increased share of renewables and energy efficiency (at least 27 %) (Commission Communication COM(2014)015 final, 2014). What is more and, in 2015 the European Commission proposed the formation of *Energy Union* (Commission Communication COM(2015)080 final, 2015) to further complete the integration and harmonisation of the Internal Energy Market and align the strategic climate and energy policies mentioned above (European Union, 2014). While the currently implemented EU energy legislation still leaves some flexibility to Member States on how to translate it into national policy, it also creates a rather heterogonous patchwork that provokes some discrepancies among different Member States. Therefore, the Energy Union is once more step further towards a fully integrated Internal Energy Market. The proposal highlights the fact that more flexibility in the grid is needed to accommodate larger volumes of VRE from wind and solar power that are needed to reach the renewable targets. However, energy storage and smart grids seem to play only a subordinate role and a well interconnected and integrated European electricity market seems to remain the main priority (Commission Communication COM(2015)080 final, 2015). This is not very surprising, given the present and past focus on more interconnection and integration, as already pointed out in *Section 2.4.2* and above. Several interviewees further emphasised that, given the support mechanisms for RETs, direct incentives for complementary options to enhance grid flexibility (e.g. via electricity storage) for accommodating higher variability in supply are somewhat missing.

In summary, regarding electricity storage in general (and BESS in particular) the current EU energy legislation can be seen as a barrier to the future investment and deployment of storage solutions. However, it remains unclear whether there is currently a strong need for the promotion of electricity storage, given the prioritisation of interconnection and market integration. At the same time, institutional developments in the EU with ambitions to further incentivise RETs clearly point towards increased pressure on the existing regime, and which at the same time drives the need for more flexibility measures on the electricity grid in order to accommodate larger volumes of VRE. Nonetheless, grid flexibility options other than interconnection and market integration are not given the highest priority.

Developments on the Nordic Level

The Nordic countries have already a long history in collaboration in electricity market related issues, dating back to 1969 with the creation of *NORDEL*, which was wound up in 2009 due to one of the legislative measures mentioned above and transferred to *ENTSO-E*, the European Network of Transmission System Operators for electricity (ENTSO-E, n.d.-b). ENTSO-E is the association of the European TSOs legally mandated by the EU (through (Regulation (EC) 714/2009, 2009)) to oversee the proper functioning of a pan-European transmission system. ENTSO-E does not only coordinate the national TSO's actions, but its task is also to ensure the completion of a single Internal Energy Market through active participation in rule setting, policy advice as well as providing information to various stakeholders and the public at large. It produces a *Ten Year Network Development Plan (TYNDP)* every two years to identify crucial bottlenecks in the pan-European grid and outline investment priorities to ensure security of supply. Normark and Faure (2014) mention that ENTSO-E already in its first TYNDP in 2012 identified major issues regarding the definition, ownership and operation of storage. Although no regulatory changes concerning the unclear handling of storage have been mandated, positive developments for the future could be identified in the 2014 TYNDP (Normark & Faure, 2014). However, it would be highly speculative to predict any future developments at this point and no interviewee was able to provide any information with reference to this ongoing process.

Another EU mandated institution (through (Regulation (EC) 713/2009, 2009)), the *Agency for Cooperation of Energy Regulators (ACER)*, has the aim to ensure compatible electricity market regulations across the EU Member States. ACER and ENTSO-E are currently in the final process stages of updating and harmonising the European Network Codes in order to align the electricity market rules with the overall energy policy under the EU's Third Energy Package (Regulation (EC) 714/2009, 2009). According to ENTSO-E (n.d.-a), this process is still ongoing with ten Network Codes approaching the final steps before adaption. Once again, it can be seen here that the EU is willing to align it institutional and regulatory capacity towards a renewable-based electricity market infrastructure. Whether energy storage applications and BESS will receive special treatment within these updated regulations remains rather unclear at this point. Normark and Faure (2014) found that some of the proposal for the new Network Codes contain mixed signals as to whether storage assets can be used to provide grid support services. One interviewee engaged in the regulatory area pointed out that the aim is to align and harmonise the rules and it is expected that energy storage will most likely be mentioned in the new energy market design proposal but probably not treated separately. Furthermore, one interviewee also highlighted that NordREG is currently in the process of formulating a common position on energy storage, but no further information was given. Nevertheless, the fact that the EU is continuing its way in transitioning the energy system and aligning its policies ultimately requires other actors and institutions to align their positions too. Whether electricity storage will play a major role in the EU's future considerations remains highly doubtful as the strategic considerations point in the direction of increased market integration and interconnections.

Developments on the Swedish National Level

Turing focus to the national Swedish level, the Swedish Parliament adopts energy related regulations that are relevant within the context of this study. The Swedish Energy Agency, mandated by *The Ministry of the Environment and Energy* and regulated by the Government, has the mission to promote the development of an energy efficient and renewable based energy system in Sweden. However, its work is to a large extent guided and regulated through EU policy measures presented above. For instance the green electricity certificate scheme to promote and expand the amount of renewables in Sweden is based on the *Renewable Energy Directive 2009/28/EC* (2009) The Swedish Energy Agency's task is to ensure the effective and efficient functioning and regularly reviews the scheme. Earlier, Svenska Kraftnät administered the operation of the electricity certificate scheme but that falls now also under the jurisdiction of the agency. Despite the large influence of EU law, Sweden can still set its own priorities within the frame of EU Directives (and to a lesser extent also Regulations). Hence, the Swedish Government has assigned the Swedish Energy Agency with the mission of promoting the sustainable development of wind power and preparing other agencies and society for up to 30 TWh by 2020 and onwards (Swedish Energy Agency, 2015b). Given nuclear and hydropower production remain the same, 30 TWh of annual wind power output would result in a penetration level of around 20 % of total power production. What is more, Sweden has been taxing electricity since the 1950s and also has in place taxes on fossil fuels and CO_2 (IEA, 2013). These taxes provide additional environmental incentives for the efficient use of low-carbon technologies. Many of interviewees pointed out that they expect the wind power penetration to rise significantly during the upcoming years, both driven by the governmental support, economic reasons, as well as favourable geographic conditions. Therefore, RET support policies with expected higher shares of VRE energy are expected to increase the need for additional grid flexibility, which can be seen as a potential indirect driver for BESS.

As it was outlined earlier, the Swedish electricity market consists of various actors, but ultimately the Swedish TSO Svenska Kraftnät has the balancing responsibility of the Swedish transmission grid. It was also Svenska Kraftnät that divided the Swedish electricity market in four bidding areas in order to ensure better operation of the power system and accentuate bottlenecks in transmission system. The national TSO closely works with the regional and local DSOs in order to ensure the proper and efficient functioning of the Swedish electricity system via planning and monitoring of supply and demand. The role of the TSO, and to some extent also of the regional and local DSOs, is not only to manage grid operation through balancing of supply and demand, but also to plan and develop grid investments and maintenance. As both TSO and DSOs are natural monopolies but electricity trade is deregulated in Sweden, the *Swedish Energy Markets Inspectorate* oversees and regulates the grid operators in order to ensure their compliance and prevent market abuses.

The overall functioning and operation of the electricity market in Sweden is regulated under the *Electricity Act* (SFS 1997:857, 1997) and for instance requires the TSO and DSOs to connect all electricity generation installations in a non-discriminatory way (as long as the developers pay for the connection lines). Thus, renewable generation units, such as wind turbines have guaranteed electricity network access through this connection obligation. Hence, wind power installations are neither prioritised nor discriminated against from this perspective. However, when it comes to energy storage solutions, the situation looks considerably different. The majority of the interviewed market actors, ranging across various sectors from the regulatory area to utilities, stressed the need to clearly specify grid-storage installations, which is in line of what has already been identified above on the EU level. Unless for *behind-the-meter* storage units, the use and ownership of grid-storage application units is rather unclear and confusing under the Swedish Electricity Act. Moreover and due to the ill-defined status of a storage unit in a legal context, it remains unclear whether a storage unit classifies as consumption or production unit or both (i.e. when charging or discharging the storage device). Thus, electricity consumption and production tax may be charged, supplementary to the connection fees that would occur anyway.

In fact, the Swedish Coordination Council for Smart Grids (Samordningsrådet för smarta elnät, 2014) concluded in its final report to the Swedish Government that the use of energy storage is not explicitly dealt with under the existing law, but the use and operation of such storage units is rather disincentivsed. According to the act's requirement for legal separation of electricity generation, trade and network operation (SFS 1997:857, 1997, chapter 3, § 1a), a legal entity that conducts network operations may not engage in any operation related to the generation of or trade in electricity. The only exemption for network operators occurs when the electricity generation is solely used for the purpose to cover network losses, or if the generation is conducted temporarily to compensate for the lack of electricity during power shortages. In addition, the network operator may buy power to cover eventual network losses only in a non-discriminatory, transparent and market-oriented way. This specification in the law basically excludes networks operators to own and operate storage devices and also limits the possibility to acquire electricity from storage installations. However and as presented above, this is in line with *EU Directive 2009/72/EC* (2009) on market liberalisation and unbundling of network operation from generation and supply. On the contrary, electricity producers, third-party actors and end-users in Sweden are free to operate and use energy storage units; given they account for eventual connection fees and taxes that might occur (depending on the location, i.e. *behind-the-meter* or not). Such additional costs, plus potential energy losses from storing electricity, cast doubt on whether electricity storage applications can be operated on a profitable basis. A study by the Swedish energy think-tank *Power Circle* (Hansson, Johansson, & Normark, 2014) came up with similar findings and proposed some changes in the regulatory framework. Given these mainly legal restrictions in relation to electricity storage units, it is not really surprising that a number of interviewees expressed concerns whether battery storage units would be a valuable and profitable option. The majority of the interviewed actors also stressed that they see regulatory obstacles as one of the major constraints in the current and future deployment of electricity storage installations. What is more, some experts that have been interviewed expressed their uncertainty whether for instance BESS could be placed within the vicinity of a wind farm for integration support. For this reason, it can be said that the unclear regulations have been identified as one of the main obstacles for grid-scale battery storage solutions, which was further support by many interviewees.

Additionally, given the formal role of Svenska Kraftnät to constantly balance the grid, all electricity produces (so-called *balancing responsible parties, BPRs*) can submit their bids from dispatchable power generators to the TSO for handling intermediate and peak loads and frequency response, as it was explained during an interview with a representative from the Swedish TSO. Those reserve bids are then activated (automatically or manually) by the TSO when needed based on prices on the Nord Pool Spot intraday market. Hence, the BPRs optimise their portfolio according to demand and supply (merit-order effect). The interviewee explained that such bids could technically also be submitted from electricity storage installations and will probably be used in the future with the need for more flexibility. Especially with expected higher price volatility due to increased penetration levels from VRE, battery storage options could prove a viable option for short-time, fast-response frequency regulation. In fact, several other interviewees, including also many of utility representatives, highlighted the fact that higher electricity price volatility will most likely be a driver for battery storage as it increased the profitability of such storage solutions. The rational behind this argument is that storage installations as of today have relatively high investment cost and need quite high price spreads between charge and discharge in order to recoup the initial installation costs. Whether higher price volatility on the Swedish and Nordic electricity market due to larger volumes of VRE will become reality remains to be seen, but the ample interconnection capacity speaks rather against such developments. As it has been presented earlier in the literature review (Holttinen, 2004; NordREG, 2014), the Nordic grid currently experiences relatively low price volatility compared to other European regions. Hence, this fact could be a significant barrier for the future deployment of BESS in the Swedish context, at least in the near future with VRE penetration levels below 30-40 %.

Summary of Institutional and Policy Related Developments

In general, there were no direct formal rules and policies identified, neither on EU level nor in Sweden, that would promote or incentivise the deployment of electricity storage assets. In summary, it can be concluded that the promotion and integration of renewables is guided from the EU and policies as well as institutions are quite well aligned to increase the penetration levels. When it comes to specific regulations affecting the deployment and use for energy storage and batteries as a means of grid flexibility and VRE integration tool, it has been found that the regulatory conditions are fairly unclear and render high uncertainty, which can be see as a hurdle. However, due to market mechanisms on the electricity reserve market, increased price volatility due to higher shares of VRE could become driver for BESS in the future. The most important formal institutions and regulatory actions are once again summarised in *Table 4-1*.

Table 4-1. Summary of drivers and barriers of formal institutions and policy actions on regime level.

Formal institutions	*Regulations & policies: DRIVERS*	*Regulations & policies: BARRIERS*
European Union		
• European Parliament • Council of the European Union • European Commission (DG Energy)	• Policy support for increasing the share of VRE • Reduce GHG emissions	• Unclear regulatory framework regarding storage • No direct incentives for grid flexibility and storage • Strategic policy towards market integration and interconnections
• ACER • ENTSO-E	• Have identified the regulatory issues for storage • In the process stages of updating the network codes	• Focus on completing an Internal Energy Market
Nordics region		
• NordREG	• Formulating a common Nordic position on storage	
Sweden		
• Swedish Parliament • Swedish Government (Ministry of Environment and Energy, Swedish Energy Agency)	• Policy support for increasing the share of VRE • Reduce GHG emissions	• Unclear regulatory framework regarding storage • Energy tax and grid connection fees
• Swedish Energy Markets Inspectorate	• Collaboration with NordREG and ENTSO-E	
• Svenska Kraftnät (TSO) • DSOs	• Needs to integrate larger share of VREs (eventual grid bottlenecks)	• May not directly engage in electricity generation and trade (and thus not use storage assets)

Sources: own elaboration.

4.2.2 Market Dynamics

This subsection deals primarily with normative and cognitive rules – that is how the market actors interpret the formal regulations and policies. Normative rules are rather implicit and can be seen values, role relationships, and behavioural norms of market actors. Cognitive rules define how market actors define their problems, make investment decisions and formulate innovation agendas (Geels, 2002b; Geels & Schot, 2007). Utility companies and system network operators have been identified as the key regime actors in this aspect. Besides Svenska Kraftnät as the Swedish TSO and the four biggest utilities (i.e. Vattenfall, E.ON, Fortum, and Statkraft) there are obviously numerous other markets actors, such as regional and local DSOs and smaller utilities, which are relevant and interesting to include here. However, it would go beyond the scope of this study to consider all these actors here and they can be seen as an entry point for future studies.

Electricity Network Operation

Svenska Kraftnät (2013b) has developed a long-term perspective plan in 2013 (*Perspektivplan 2025 – en utvecklingsplan för det Svenska stamnätet*) for the future development and investment in the national grid. It is based on the main political and regulatory framework from the EU and Sweden outlined above. One of the main aspects is the increased integration of additional wind power capacity. In collaboration with ENTSO-E and based on the EU regulation and proposed market integration strategy, Svenska Kraftnät's planning practices mainly concern the identification and elimination of bottlenecks, the expansion of the Swedish grid as well as further interconnections to its neighbouring countries. Therefore, Svenska Kraftnät's transmission grid development is primarily driven by new power production from wind power, reinvestments, and the European and Nordic market integration (Wangel, 2015). However, it was found by the same study (Wangel, 2015) that some discrepancies exist between Svenksa Krafnät's planning scenarios (assumed 17 TWh by 2025) and ongoing wind power projects that are either being constructed or have been granted permits (Svensk Vindenergi estimates 18 TWh by 2017). This could pose a real risk as it could not only delay the connection of wind power projects due to unsynchronised planning practices and lead times associate with grid expansion, but it could also create further bottlenecks in the power system. Having said that, uncertainty related to wind power projects further adds to the problem. As the differences in the two future predictions somewhat illustrate the problem: it is rather unclear whether all planned wind power projects will get installed, when they get installed and when. Furthermore, Wangel (2015) argues that "there is also a risk that large-scale wind power projects will end up in a catch-22 situation due to parallel, paradoxical and unsynchronised processes for gaining approval from the Environmental Courts and signing connection contracts with the TSO" (p. 29). Thus, it can be argued that those developments constitute both a driver and barrier for electricity storage. On the one hand if the deployment of new wind power production creates bottlenecks on the T&D grid system, electricity storage solutions such as mobile BESS could temporarily provide a remedy and defer direct grid investment or expansion. On the other hand, when wind power projects get delayed or even abandoned due to insufficient grid capacity it hampers the overall deployment of additional wind power capacity and therefore reduces the need for flexibility options such as electricity storage to support the integration of VRE from wind power. Which trend will prevail in the future remains to be seen.

Other than that, it could not be determined whether Svenska Kraftnät specifically considers that options of electricity storage options in order to overcome such challenges with increased wind power production. The interview with the TSO representative further underlines this finding as it was only mentioned that reserve capacity bids for grid balancing could be used. Moreover, the same informant also said that BRPs could potentially aggregate several storage units (which are usually quite small compared to bids from e.g. dispatchable hydropower) to place their bids on the market. In a study on how battery can support the EU electricity market (Normark & Faure, 2014) it was found that "one benefit of battery storage could be to improve liquidity in the balancing markets, while reducing volatility of balancing, therefore improving system adequacy" (p. 50). But BESS could not only be used for balancing services, but also by providing short-term ancillary services such as frequency response or voltage support services (JRC, 2014a; Normark & Faure, 2014), as presented in earlier in *Chapter 2* (see e.g. *Figure 2-7* & *Figure 2-8*). Similarly and in line with the information provided in *Figure 2-7* and *Figure 2-8*, BESS (either grid-scale or aggregated distributed residential batteries) could also be used for the provision of ancillary services to improve distribution network stability and/or reduce distribution network congestion (Normark & Faure, 2014). In fact, most of the interviewees shared the similar opinions on where BESS could provide useful benefits and services. However, the current legal situation, as elaborated before, essentially prohibits the direct ownership and operation of storage units for any TSO or DSO because of the unbundling of network operation and generation activities. In addition to the regulatory uncertainty, high investment costs for storage applications coupled with relatively low and invariable electricity prices in Sweden and an already large flexible capacity provided by hydropower in the Nordic system might further be hindering the deployment of BESS assets. Although network operators could possibly make good use of electricity storage options, the current legal framework does not allow for it, which clearly constitutes a barrier.

Utility Companies

Turning the focus towards the other identified key actors, the bigger utilities in Sweden currently only pursue limited activity in the area of electricity storage and battery storage. Essentially all representatives from those companies stated that they are investigating the situation and are running some RD&D projects related to electricity and battery storage.

According to statistics by Svensk Energi (2015a), the four biggest utilities in Sweden own and operate more than 70 % of the total installed power capacity, mainly nuclear and hydropower. Wind power only represents a small share of their portfolio the large majority of installed wind power capacity in 2014 and the largest volume of installed capacity falls under other entities. However this statistic might not reveal the full picture, as many larger wind power projects are carried out in joint ventures. For instance, the only bigger actor with no assets in nuclear power, Statkraft owns and operates most of its wind power installations in Sweden together with the Swedish forestry, pulp and paper product companies *SCA* and *Södra Cell* (Statkraft, n.d.). Despite the favourable institutional developments in Europe and Sweden towards transitioning the energy system, those actors still have large assets invested in incumbent power generation units, such as nuclear and hydropower plants, and this lock-in might be hindering a quicker transition towards investments into renewable technologies. In fact many studies on energy transitions point out that this path dependency and the technological and financial lock-ins are one of the main blocking mechanisms for change (Berkhout, 2002; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000; Kemp et al., 1998; Unruh, 2000). European utilities, including E.ON and Vattenfall, have been struggling to keep up with the ongoing transition and many of them have seen their market valuation plummeting as they are left behind with their incumbent business model on centralised power plants and lower electricity prices from renewables (The Economist, 2013). Only recently, Vattenfall (2015) announced that the continuous operation of two nuclear reactors in Sweden (which are owned together with E.ON) after 2020 seems questionable due to the bleak financial prospects. In fact, there is a risk for incumbent utilities of being left behind the current transition dynamics towards a more decentralised and renewable based energy system and eventually in extreme scenarios they could find themselves again in the so-called *utility death spiral*. Several studies (e.g. Bronski et al., 2014; Costello & Hemphill, 2014; Hervey, 2014; Newbury, 2013) have analysed such sudden and radical changes in the energy sector and concluded that with innovative solutions around (e.g. the participation in distributed RETs, smart pricing mechanisms, or service-based solutions), such threats can be avoided. Given this situation, some of the biggest European utilities are desperately looking for new solutions and some have made radical decision in order to keep up with the current market environment. One of them, E.ON has recently announces to completely change its strategy to focus entirely on renewables, customer solutions and distribution networks by splitting off the incumbent nuclear and fossil fuel based power generation parts (E.ON, 2014). However, it would go beyond the scope of this study to analyse the full effect of their incumbent business model on the effect of future BESS investment and deployment.

Nonetheless, it is not surprising that the incumbent utilities are somewhat reluctant to invest in new technologies, such as electricity storage. As further cost reductions and performance improvements for battery storage units are expected by many market actors, this might in some ways act as a barrier rather than a driver. Because if most market actors think further cost and performance improvements can be expected, then they rather wait until they can get a better deal and therefore such expectations could be contra productive for the future development of battery storage technologies. Almost all of the informants of these major utilities revealed that they are actively monitoring the market situation and developments for energy storage options. Among the various storage technologies, battery storage technologies and in particular Li-Ion and NaS batteries are expected by those actors as the ones to have the highest potential for the future, but none of the utilities solely focus on batteries. This can be seen as somewhat sensible, given the still relatively high uncertainty of batteries and their price and performance status. A study from EU's Joint Research Centre (JRC, 2013) on the valuation of electricity storage further supports this finding, as "storage investors or developers of technology aim at understanding revenue streams over the economic life of the investment in support of the decision making. Uncertainty of future earnings is often referred to as one of the main barriers to technology deployment and further development" (p. 27). This resonates with the facts presented in *Section 2.4*, where the gap between early technology innovation stages and market introduction is considered as the *technology valley of death*. Many emerging electricity storage technologies, especially batteries, are caught somewhere between R&D and niche market applications, as it will be further elaborated in *Section 4.3*.

It was also emphasised by the interviewed utility actors that, given a realistic business case would be there, they would already deploy more batteries for various applications, but as of today they do not see strong enough market signals that would justify such investments. From the four biggest utilities, which are also operating in an international business, several have test and pilot projects in operation or planning, which are all located in Germany (see also *Section 4.3* below). The experts interviewed from those companies once more stressed that Sweden has no need at the moment for grid-scale battery storage application due to it already high flexibility from hydropower and due to the relatively good interconnection to its neighbouring countries. An interesting statement was made by two of the utility representatives pointing out that they actually have started modelling the future of the energy system based on scenarios with high penetration levels of VRE and it turns out that storage applications are rather a complementary option to increased grid development. As energy storage competes with other grid flexibility options (see *Chapter 2*), most market actors expect that electricity storage will have its role for certain applications and services alongside or in combination with other options (i.e. T&D grid reinforcement and demand-side management). However, it was also pointed out by those interviewees that every business case would need individual evaluation based on the specific needs, costs and benefits and their future scenarios should rather be seen as indicative trends.

Summary of Market Dynamics on the Regime Level

In summary, grid electricity storage applications from the perspective of the bigger utilities are not yet mature and profitable enough, compared to other flexibility enhancing solutions. Additionally, the overall uncertainty related to RETs and complementary flexibility solutions, as well as the threat to their incumbent business model that originates from these emerging technologies, constitutes somewhat a barrier for investments in electricity storage options. However, the fact that all of them are closely monitoring the storage market, where further price decreases plus performance improvements can be expected, and testing the viability and functionality of storage application, could be a weak indicator for a market driver.

4.2.3 Actor Networks and Interactions

The interaction of market actors, their respective networks and legitimacy are strongly influenced, either in a positive or negative way, by formal, normative and cognitive rules (Geels, 2002b; Geels & Schot, 2007). Therefore, in this subsection the inter-regime dynamics and processes are presented. However, it should be noted here once again that the list is far from complete and should only be seen as an entry point for future research in this field. Only the ones which deemed to be of most importance in the context of this study and which could be directly associated with wind power and/or electricity storage were selected. It would go beyond the scope of this work to present a complete actor network here and what is more, for some actors it is rather difficult to determine their specific role.

Many actors and networks have been identified by studies (e.g. Albrecht, 2012; Wangel, 2015) in a slightly different context on grid development, while some other were detected during the process of finding interview targets. Most of the involved actors are governmental institutions, interest groups and organisation, research and innovation networks, and private companies. A list has been compiled that summarises the main actors and networks as well as their role in relation to electricity storage in more general terms (see *Table 4-2* below). It is important to highlight the fact that the majority of those actors are somehow involved in the electricity market and thus their relationship and influence specifically towards grid-scale BESS is not always very clear and therefore a more broad perspective on electricity storage was chosen.

Table 4-2. Summary of regime actors and networks.

Actor or actor network	*Role and actions in relation to battery energy storage*
European Union	
• European Parliament • Council of the European Union • European Commission (DG Energy)	• Formulate and adapt policy and legislation (e.g. GHG emission reduction, promotion of renewables and energy efficiency) • Strategic focus is on energy market integration and increased interconnections • No direct support policy for storage (except RD&D funding)
• ACER • ENTSO-E	• Formulating new Network Codes • Have identified the regulatory issue(s) around storage
• Grid+Storage consortium • StoRE project • eStorage	• Research and innovation activities on the integration of energy storage applications into the electricity networks (at various levels) and smart grids
• EWEA • Euroelectric	• Industry organisations (advocate industry interests)
Nordics region	
• Nordic Energy Research	• Research on smart grids and VRE integration
• NordREG	• Promotes legal and institutional frameworks in the Nordic markets • Formulating common position on electricity storage for the Nordic electricity market
Sweden	
• Swedish Government • Ministry of the Environment and Energy • Swedish Energy Agency	• Formulate and adapt policy and legislation (e.g. GHG emission reduction, promotion of renewables and energy efficiency) • No direct support policy for storage (except some small RD&D projects)
• TSO & DSOs	• Operating and developing the T&D grid infrastructure • Looking for new ways to better integrate VRE from wind power
• Swedish Coordination Council for Smart Grids (Samordnigsrådet för smarta elnät)	• Regulates the Swedish TSO and DSOs, ensures a well-functioning energy market, and suggests changes in laws and regulation • International collaboration (NordREG, CEER)
• SweGRIDS	• Research and innovation programme on smart grids (includes also energy storage solutions to some extent)
• Energiforsk (former Elforsk)	• Research on electricity market (including VRE integration)
• Power Circle	• Research on smart grids and VRE integration (including storage)
• Svensk Energi • Svensk Vindenergi	• Industry associations (advocate industry interests)

Sources: own elaboration.

It can be said that several of the identified actors act on different levels and peruse different interest. Although this list might not grasp the full picture of all market actors and their interactions, it gives somewhat an overview of the variety and complexity on the market. They all act on different levels and pursue different interests. While some of them are clearly a driving force for electricity storage and better grid integration of variable wind power, other might peruse other goals, and still others take a more neutral stance. Nevertheless, it is merely not one actor, except for governmental institutions with their policy actions that determines the future of electricity storage, but rather their interaction and the prevailing overall market dynamics, as it has been shown above. Another important aspect is the technological development that influences regime process and which will be presented in the next section.

4.2.4 Technology Development

Technological development and the existing infrastructure are closely linked to the coherence and stability of the socio-technological regime. For this reason, the technological development on the regime level and how the infrastructure is aligned to the market players' practices has a strong influence on overall regime dynamics. While some technological change is induced by policy and regulatory developments, other innovations may emerge from niches. Once again, the interlinkage of several parallel processes in the MLP framework may disrupt regime actors' operations and functions in a wider sense and at the same time allow for the formation of a new socio-technological regime through niche market developments (Geels, 2002b, 2005a; Geels & Schot, 2007).

However, as BESS are considered a niche technology, the specific dynamics of batteries are examined in the next subchapter, even if certain regime actors may engage in RD&D activates for electricity storage. The focus in the following section is on the development of the overall regime technologies and infrastructure, such as for instance the evolution of wind power and grid infrastructure that might affect the future development of BESS. A major aspect of the technology related development on an EU level can be associated with the overall EU energy and climate policy, such as the *Energy Roadmap 2050* and the *SET-Plan*, and the multi-billion research and innovation funding programme *Horizon 2020* mentioned earlier. These policy initiatives somewhat drive and guide the future energy infrastructure.

Technology Development Related to Wind Power

What concerns the technological development for wind power, it can be said, that it is already a relatively mature technology, especially for onshore wind installations. As part of the SET-Plan and the EU research and innovation programmes, the aim is to further decrease technology costs and improve the performance (JRC, 2014b). For instance, it is expected that the average size of wind turbines will further increase, from around 2 MW today to about 4.5 MW in 2050 for onshore and around 4 MW to ca. 15 MW for offshore units. In addition the capacity factor is also expected to improve significantly until 2050 for both onshore and offshore turbines. Despite some remaining challenges, increased deployment of offshore wind power is expected in the future. On the one hand his will further amplify the need for investments in grid expansion in order to connect the additional capacity as offshore wind farms can usually not just be connected to existing power lines (JRC, 2014a). On the other hand, more offshore wind power coupled with higher capacity factors (both for on and offshore turbines) are expected to reduce wind power output variability, as a study on future wind power development in Sweden concluded (Olauson et al., 2015). Form this perspective it is not entirely clear weather such developments will constitute a driver or barrier for more grid flexibility and electricity storage.

However, the overall effect on the power system from increased wind power deployment might have wider technological implication on the power system, especially when some of the nuclear power reactors will be decommissioned. As presented earlier, such large synchronised generation units provide the necessary spinning mass to keep the grid at constant frequency, but with less synchronous generators and more asynchronous supply from VRE from wind there will be a loss in system inertia. Wind power turbines can also contribute to system inertia with certain technical control mechanisms in order to provide synthetic inertia (Ela et al., 2014), but wind power operators in Sweden are currently not incentivised to do so (Seyedi & Bollen, 2013). This could however change with the proposed new EU Network Codes, which are currently in the process of being developed. BESS could remedy this issue in providing synthetic inertia. In fact, a few interviewees, some with many years of experience in the electricity sector, pointed out that BESS would be well suited to provide such ancillary services in connection to higher wind power penetration scenarios. This would not only reduce the need for additional control instruments in wind turbines, but BESS could provide additional system inertia that will be needed with less synchronous generation from nuclear plants. Hence, the installation of larger amounts of wind power coupled with the planned decommissioning of some nuclear power plants can be identified as driver for BESS.

Technology Development Related to Power Grids

With regards to grid technology development, it can be seen that the trend is going towards more integrated, smarter, and bi-directional transmission and distribution systems. Especially for the transmission of bulk electricity over long distances (e.g. interconnectors) and undersea power lines (e.g. for offshore installations or intercontinental interconnectors), the emergence of *high-voltage direct current (HVDC)* multi-thermal power lines shows the potential to transmit electricity in a more efficient way than via conventional *alternating current (AC)* cables (IEA, 2014c; JRC, 2014a). However, the HVDC technology is considerably more expensive than AC power lines, and while the latter is synchronous the former is not. Whereas the asynchrony of HVDC lines makes it easier to adjust and control the power flows, but as it can be imagined it can pose a problem for system inertia. However, modern HVDC power lines can use so-called voltage source converters for providing valuable system services such as voltage support (IEA, 2014c). As HVDC technology is relatively new, the effects of such developments needs to be investigated further. However, electricity storage in the form of fast-responding BESS could provide certain system services here, such as voltage and/or inertia support.

What is more, the *European Electricity Grid Initiative EEGI* (2013), which is an EU industrial initiative under the SET-Plan, identified basically four challenges that are related to grid technology development:

- change from *supply-follows-load* to *load-follows-supply*;
- augmented real-time balancing;
- integration of aggregators (e.g. small and medium-sized prosumers); and
- a multi-layer control structure.

Hence, the transition towards a more distributed system will increase complexity and the numbers of actors involved. For instance, as it was also pointed out by many interviewees, distributed VRE from wind is not just connected to the transmission grid as it is usually the case for centralised power plants, but also on the distribution grid. Together with consumers that might increasingly install solar PV installations, which is then also sold and fed into the distribution grid (hence the name *prosumers* as electricity consumers also become producers), this changes the technical requirements and operational practices for TSO and DSOs. Particularly distribution grids used to be designed for one-way electricity flows (i.e. from generation units via transmission and distribution grid to the customers), but distributed RETs require a bi-direction flow of electricity and thus pose further challenges on the capacity of the transmission grid infrastructure. Local and maybe even mobile electricity storage applications could provide support services in order to reduce the expansion of distribution grids and/or temporarily defer further grid investments. One option could even be to aggregate customer-storage installations, which could provide and sell additional support services to DSOs. In particular with the emergence of a smart grid infrastructure and advanced demand-side management through smart meters, aggregated residential BESS could provide local distribution grid support services and reduce the need for additional peak load capacity for generators (Bronski et al., 2015). As already highlighted above under *Section 4.2.2*, many actors that were interviewed, including representatives from the Swedish TSO and researchers and consultants, expressed similar views in this direction on the application areas for batteries in the future energy system, which is also supported by literature (e.g. Normark & Faure, 2014)

All together, the implications of increased volumes from VRE sources means that probably the way we used to think about the electricity system that *supply-follows-load* will be challenged and in the future it is more likely to be *load-follows-supply*. A few interviewees also shared this point of view. Ultimately the consequences are that smarter grids with more flexibility, both on demand and supply side, will be needed (EEGI, 2013; IEA, 2014b; JRC, 2014a). It is also expected that batteries, among other options, may play a vital role within such smart grid infrastructure by providing valuable flexibility and ancillary services. Hence, the technological development from a grid distribution system perspective with the emergence of smarter grids can be seen as a driver for the future deployment of BESS. This is very much in line with the assessment of the situation from the majority of the interviewed actors and experts. Most of them identified distributed VRE generation, especially from residential solar PV installations, as one of the main drivers for smaller-scale BESS that could eventually also drive grid-scale BESS through improved learning curves (i.e. better performance and reduces technology costs).

4.3 Niche Developments

In general terms, novel technologies, such as BESS, emerge from more or less protected market niche, where they are tested and improved regarding to their performance, price, new functionalities and applications. Usually it is not just one single niche market, but rather a dispersed cluster of various smaller niche markets that gradually evolve and align their interactions, interests, and applications through processes of co-construction and co-evolution (Geels, 2002a, 2005a; Geels & Schot, 2007).

Grid-Scale Battery Storage Developments in General

As highlighted already before, most battery technologies are still rather expensive and on the verge of becoming cost competitive compared to other grid flexibility solutions (EPRI, 2010; IEA, 2014a, 2014b; IRENA, 2015b; JRC, 2014a). Most interviewees clearly pointed out that the currently high cost for storage assets, such as BESS, coupled with the some uncertainty related to performance and reliability, are the most evident barrier to the investment grid-scale. However, essentially all of the interviewees also expect significant cost declines in the upcoming years due to increased R&D activities and augmented deployment of batteries in various applications areas at different scales. Hence, and as elaborated in *Section 2.4*, as well as supported by literature (Normark & Faure, 2014), support mechanisms and incentive schemes might be needed to further bring down technology costs through increased deployment.

Again, as mentioned in *Section 4.2.4* above, the *Energy Roadmap 2050*, the *SET-Plan*, and the multi-billion research and innovation funding programme *Horizon 2020* pave the way for future energy infrastructure. Over € 1 billion public and private funds are currently put into RD&D activities and projects for electricity storage in the EU and it Member States (JRC, 2014a, 2015). However, it is also highlighted that "most of these projects are in the research stage, and very few are demo or pre-commercial projects" (JRC, 2014a, p. 103). It is also worth pointing out that electrochemical storage technologies, such as batteries, receive almost one third of the available funding and are therefore the biggest beneficiary. Additionally, significant investments in R&D activities for electricity storage are taking place in the USA, where the U.S. DOE has allocated over US$ 700 million. It is interesting to mention here, that many interviewees were aware of the fact that the U.S. is currently investing and incentivising electricity storage, but almost none mentioned the EU funding activities for RD&D in electricity storage.

Some larger energy industry companies, such as *ABB*, *Siemens*, *Alstom*, or *General Electric* (among others) are already providing some large-scale battery storage products for grid applications and larger industrial facilities. Representatives from ABB and Siemens, which have been interviewed, specifically pointed out that they are already providing such solutions that are being used in several parts of the world for various applications. None of the interviewees could reveal where most of their large-scale battery products are being used, but one hinted that the application area at industrial facilities seems very promising, as such BESS can be used as backup power device for UPS systems (e.g. data server centres) or a support tool for internal demand-side management (e.g. peak load shaving to avoid peak electricity prices). Additionally, BESS for providing grid support services (especially for island systems or micro-grids) were also named by those interviewees as possible application areas for their products. However, as it seems from their responses, most of those units are being installed elsewhere than Sweden. Nevertheless, the information from these representatives coincide with what other interviewees also mentioned several times, especially what concern the above mentioned application areas.

As presented earlier, interviews with representatives from the bigger utility companies revealed that all of them are actively engaged in R&D activates related to electricity storage and are monitoring the market. Although all of them said that they would not commit or bet their strategy on one single storage technology, most agreed that batteries show the most promising developments for the future. All but one of the four utilities interviewed said that they have already started to set up pilot and demonstration projects, all of which are located in Germany. Interestingly, most of these test installations are based on battery storage systems. For instance, E.ON (in collaboration with the local university and with support through the governmental *Funding Initiative for Energy Storage*) has recently started with the construction of a modular large-scale 5 MW battery storage project (called *M5BAT*, combining different battery technologies) in Aachen, Germany for providing additional system stability and testing various potential other application areas (E.ON, 2015). Similarly, Statkraft is building a 3 MW battery storage system in Germany for the provision of reserve power to the grid as well as balancing power to the TSO (Statkraft, 2015). In addition, Vattenfall currently operates a 1.6 MW BESS in combination with a large-scale solar power plant in Germany and has already previously gained experience with two other battery storage pilot-projects in Germany for providing reserve power and grid stability services (Vattenfall, 2014).

Grid-Scale Battery Storage in Sweden

As of today in Sweden, only a few test and pilot projects have been deployed. More than half of the interviewees, some of whom were directly involved in the project, highlighted the *Falbygdens Energi* project in Falköping where a small 75 kW battery was installed. The pilot project was carried out in collaboration between the local DSOs Falbygdens Energi and Göteborg Energi, as well as the battery unit supplier ABB with the aim to integrate higher volumes of VRE from wind power to the local grid. The project also served as a test ground for several studies to evaluate application services and investigate business models. One of these studies (Borg, 2012) specifically investigated the benefits of battery storage in connection with increased wind power deployment. The study concluded that the deployment of battery storage units alone to accommodate more wind power production would not be feasible due to the unrealistic large dimensioning of the battery units. This view was also shared independently by many of the interviewed experts and actors. Most of them see the role of battery rather as complementary power application for short-term ancillary services (e.g. voltage control, frequency regulation) instead of storing large amounts of electricity for time-shifting. The main reasons for this, as further elaborated by these interviewees, are the high technology costs as well as the technological specifications of batteries that would make batteries uneconomical for only energy storage applications. One interviewee with many years of experience in the area and also directly involved in the Falbygdens Energi project pointed out that it would make much more sense to stack several benefits of batteries for short-term power applications and then provide such different services when needed or requested by the local DSOs. Hence, these interview statements are largely in congruence with what has been discovered through the literature review.

Besides this first pilot installation of a BESS for grid applications, there are also some smaller electricity storage and BESS projects that focus mainly on distributed energy storage applications in connection with for instance household solar PV installations, off-grid applications or EVs. As it was mentioned by a few of the persons interviewed (including one representative from a bigger utility company), the *Glava Energy Center* in Western Sweden is one of these test centres where such small-scale projects are being tested and carried out. Additionally, there are also some other ongoing research programmes and projects mainly related to smart grid solutions, and to a lesser extent also include electricity storage (e.g. *SweGrids*, *Smart Grid Gotland*, *Smart Grid Hyllie*), which receive funding from the Swedish Energy Agency and other corporate actors and are carried out in collaboration with universities and industry partners (European Research Knowledge Centre, n.d.). Furthermore, other research organisations, such as Power Circle or Energiforsk, as well as Nordic Energy Research, also conduct research in the areas that are (at least to some extent) related to electricity and battery storage (e.g. VRE grid integration and power system flexibility, smart grids. The author has conducted interviews with some representatives from the above mentioned research and innovation projects and essentially all of them revealed that electricity storage in general, and battery storage in particular, is something that they are actively looking into. However, it does not seem to be of the highest priority as most of them take more of a systemic approach to the entire energy system (i.e. electricity, transport and heating). Most of them also shared similar views on electricity storage and BESS that have already been presented above: batteries can provide valuable power system services (e.g. ancillary services) for the local distribution grids or for residential houses or industrial facilities.

Other Battery Storage Related Developments

Alongside the gird applications of BESS presented above, there are several other niche markets related to BESS emerging that are worth noting here briefly to put the development on the niche level in bigger perspective. However, it should also be stressed that this is only a snapshot in order to make some connections of the rather dispersed niche clusters for BESS.

One very innovative product currently on the market, is General Electric's BESS that can be directly integrated into wind turbines in order to provide ramp control for smoothing/firming wind power output through the interplay with smart software (General Electric, n.d.). It is interesting to mention that only a few interviewees were aware of this niche product directly in combination with wind power. However, most of the interviewees said they were rather sceptical towards BESS applications directly in connection to wind turbines or wind farms for various reasons. Firstly, wind turbines (and even more so wind farms) produce a significant amount of energy, thus a rather large BESS (several MW) would be required to manage the power output of wind turbines, especially if the battery would be used for time-shifting and arbitrage (i.e. store excess electricity output and feed it into the grid during peak hours or low wind power output times). Secondly, some interviewees also expressed concerns regarding legal issues, whether BESS connected to wind would be considered a part of the generation unit or if the battery would be part of the grid infrastructure. This discussion is tightly connected to the unclear regulatory specifications of storage assets, but no definite answers could be found for this specific case (possibly the upcoming new EU Network Codes might create some clarification here). Nevertheless, a few interviewees also pointed out that, given BESS can be used as an integrated part of a wind turbine or wind park, they could provide ramp control services for capacity firming, which is exactly what General Electric is marketing.

What is more, there are several other applications areas for BESS, but rather on a smaller, more distributed scale. As it has been mentioned and pointed out by interviewees, BESS can be used for UPS systems (i.e. as backup energy instead of diesel generators), for black-start services in weak grids in order to restart the power grids, or in micro-grids or on island systems for providing backup power or peak capacity. Most of these application areas were also mentioned in the literature review (see *Chapter 2*).

In addition, small-scale BESS for home installations in combination with rooftop solar PV systems are becoming increasingly popular, especially in areas around the world with relatively high end-consumer electricity prices and/or locations with favourable solar insolation (Bronski et al., 2014, 2015; IRENA, 2015b). If such small-scale BESS can be aggregated (either trough the DSO or a third party actor), the combined storage capacity of all distributed residential BESS could be used for the provision of local distribution grid support services, whereas the DSO buys such services from individual prosumers who then get compensated. In certain circumstance such a solution might be less costly than investing in additional grid infrastructure or flexible generation units. The Independent System Operator in California (CAISO, 2015) has only recently released a draft proposal that would exactly allow so-called *Distributed Energy Resource Providers (DERPs)*, such as battery, solar PV system, EVs, smart meters and thermostats, and other integrated energy assets, to be aggregated and dispatched in order provide the same grid support services as grid-scale BESS. Some interviewees also pointed out similar ideas for the future, given regulatory challenges and infrastructure related issues are resolved. With the rollout and uptake of residential BESS and EVs (see e.g. *Tesla*), such scenarios could become reality sometime in the future.

Summary of Niche Developments

The technology development of electricity storage on an EU level is still in a rather early phase and there are only a few smaller BESS projects in the EU as of today with some demonstration and pilot projects in Germany. The market in Sweden is almost non-existent or very low. Whilst some of the regime actors have started implementing RD&D programmes and pilot projects regarding electricity storage solutions and batteries for grid-scale applications and can therefore be considered a regime dynamic, it is also part of the niche market developments. There are of course other niche market actors, one of which in Sweden has been interviewed, however, it would go beyond the scope of this study to examine all niche players and dynamics in full detail.

4.4 Summary of Findings and Results

The following *Figure 4-1* is a visualised account of the main findings and results of drivers and barriers for BESS in Sweden:

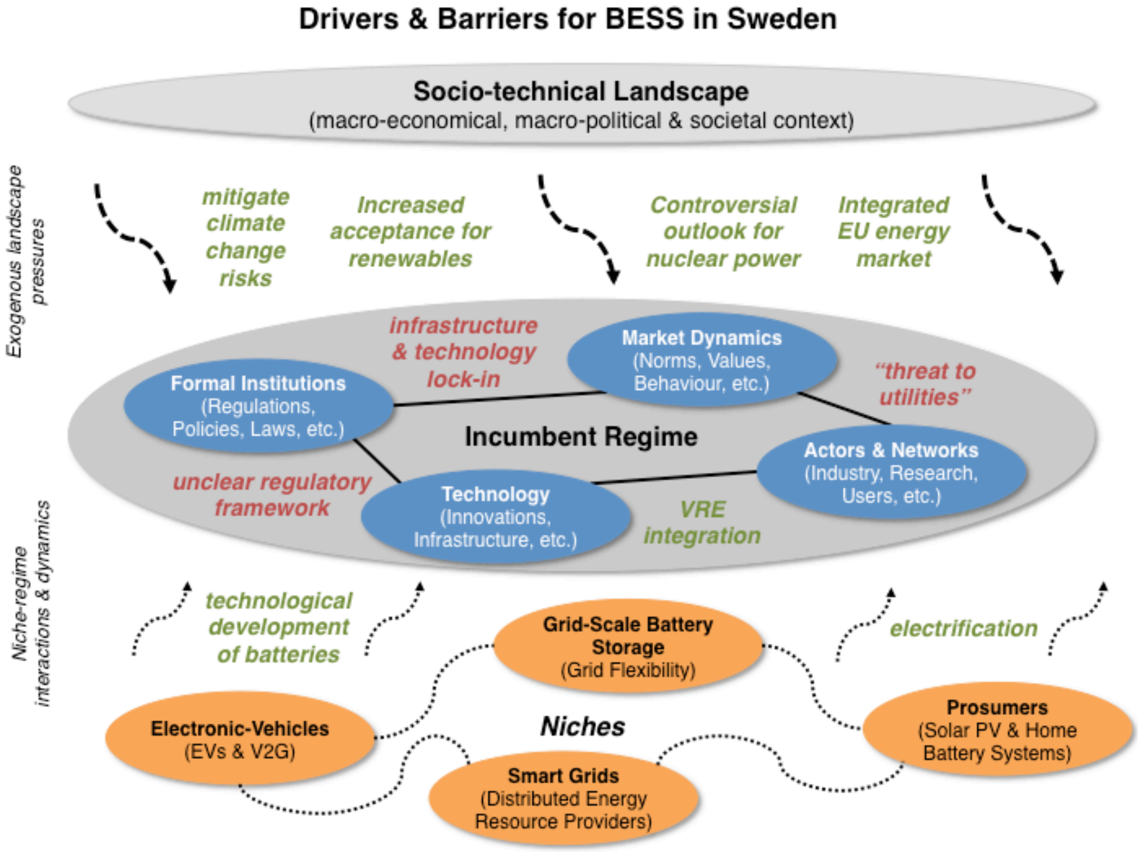

Figure 4-1. Summary of the findings (i.e. drivers & barriers for BESS in Sweden) structured and visualised with the help of the MLP framework.

Source: Own elaboration.

5 Analysis and Discussion

This chapter will analyse the findings of the previous chapter, mainly the identified drivers, barriers and uncertainties related to BESS in Sweden. Additionally, the pertinence of the applied framework and theory, as well as methodological implications will be discussed.

5.1 Interpretation of Drivers and Barriers for BESS in Sweden

On a landscape level it was found that the developments are clearly directing towards an increasingly renewable-based and distributed electricity system in the EU and Sweden with more integrated electricity markets across Europe. This implies higher penetration levels of VRE from wind and solar power and ultimately increases the need for flexibility. These dynamics can generally be seen as a *window of opportunity* (as with reference to the MLP framework (Geels, 2002a; Geels & Schot, 2007)) for electricity storage applications and in particular BESS. However, such drivers alone might not be enough to make the case for BESS in Sweden, as the needs for and introduction of additional power system flexibility is highly system specific and depends to a large degree also on the existing infrastructure.

What concerns the regime developments, the situation becomes slightly more complex. On the one hand it has been identified that the general institutional direction is clearly pointing towards and increased uptake of VRE from wind power in Sweden and the economic outlook for large centralised generation units, such as nuclear power plants, is in limbo and a gradual decommissioning of the ageing nuclear power reactors over the next decades seems to be likely. On the other hand, Sweden as a part of the Nordic power system, which is well interconnected and has large hydropower capacities, is already quite flexible. Thus, the increased penetration of VRE from wind power does, at least in the near term future until higher shares of more than 30 % (or annual production exceeding 30 TWh) will be reached, not provide a major problem to the grid flexibility and stability. Only on a more regional and local level on the distribution gird, which have initially not been designed to handle the bi-directional flow of electricity, this might constitute an issue. For this reason, it can be seen that increased investments in local grid infrastructure might be needed, and BESS could provide a remedy there. But once again, the situation is different from region to region, and with a large share of the power generation capacity located in the Northern parts of Sweden, but most of the load occurring in the Southern part, these regions in the South might be more in need of distribution network reinforcement, either through investments in additional power lines or with the help of flexible assets such as BESS. Yet, an EU study on electricity storage (JRC, 2013) concluded that "the market integration of RES-E [i.e. VRE] can be decisive about the prospects of electricity storage as this can strongly affect all value streams for storage, i.e. power prices, reserve market prices and needs" (p. 61). Thus, the future penetration level and integration of wind power in Sweden can definitively be seen a one of the main drivers for BESS in Sweden.

What is more, it has been found that regulatory environment constitutes a major barrier for the deployment of grid-scale electricity storage assets, not only in the EU but also in Sweden. The current legislation, which aims to unbundle network operation from electricity generation and supply, does not clearly specify which market actors can own and operate electricity storage. Especially TSOs and DSOs, who would probably be the first to install storage assets due to their balancing responsibility, are essentially prohibited from making use of it. Additionally, the current regulatory framework in Sweden rather disincentivises the use of storage assets due to connection fees and energy taxes that would have to be paid when operating storage systems, which further diminishes the business case (due to relative high costs which are however expected to decrease over time). As shown in *Section 2.4.2*, the Italian TSO *Terna* already makes use of batteries in order to improve grid stability and flexibility despite the de-facto prohibition from the EU legislation to do so. Without going too much into details, the Italian legislators have found a way to somehow allow the TSO and DSOs to own and use battery storage assets that contribute to power system stability and provide valuable services (JRC, 2013; Normark & Faure, 2014). A report issued by the EU's *Joint Research Centre* through *SETIS* (JRC, 2013) further analysed the impacts of regulation on electricity storage and stressed that "the issue of ownership and right of access is closely linked to the question of efficient power markets" (p. 52) and whether regulated TSOs and DSOs should own and operate storage or if it should be left to the open market and other third party players. But ultimately, the unclear and controversial regulatory situation stemming from *Article 9 of Directive 2009/72/EC* (2009) on unbundling in combination with the Italian example might need to be revised and clarified in order to incentivise the utilisation of electricity storage solutions and create a level playing field across Europe (JRC, 2013). In Sweden, several studies (Hansson et al., 2014; Samordningsrådet för smarta elnät, 2014) have also advocated changes in the regulatory framework in order to make better use of electricity storage assets. In general, the impact of regulation on electricity storage is rather complex and encompasses not only issues regarding ownership and utilisation areas, but should be considered from various angles, such as (JRC, 2013):

- *technical rules and non-market regulation* (e.g. grid fees, taxes, environmental regulation, public acceptance);
- *power market design* (e.g. VRE integration, reserve market design);
- *aspects of ownership and right of dispatch* (e.g. unbundling rules, aggregation of DERPs);
- *direct financial support* (e.g. feed-in tariffs, capacity markets).

All these points have in one form or another been taken up during earlier chapters and once again show that a holistic approach is required in order to create a level playing field for the different flexibility technology options (e.g. storage, demand-response, grid reinforcement) and align policies in order to accommodate higher penetration levels of VRE. Even though regulatory changes seem necessary, such amendments can enable the effective and efficient utilisation of the various technological solutions at hand, without interfering too much into the market or prioritising any technology.

However, it can be said that it also depends on whether there is an urgent need for electricity storage on the grid or not, which is again highly systems specific. For Sweden, there is currently no urgent need for increased system flexibility option and BESS. However, with the projected developments on the Swedish electricity market in the upcoming years (more VRE from wind and less nuclear power), Sweden might be well advised to integrate increased system flexibility into future planning activates and align incentive mechanisms for flexibility solutions in combination with support schemes for expanding VRE (Bird et al., 2013; Cochran et al., 2012; Normark & Faure, 2014). This goes not only for electricity storage options or BESS, but also for other flexibility solutions such as demand-side management, interconnections, or flexible generation units that may complement (or even compete with) storage solutions in order to accommodate larger shares of VRE (JRC, 2014a). As it has been shown on the niche level, there are several research projects actively investigating these VRE integration challenges and smart grid solutions. However, what concerns electricity storage, there are certainly other countries in the EU (e.g. Germany) and elsewhere (e.g. USA) that are ahead of Sweden. It is important to stress again that storage is by no means the only solution to the challenges with increased supply-side variability from renewables, but it might play an integral part, especially if other storage concepts, such as *power-to-heat* or *power-to-fuel* (specifically to handle excess electricity production from VRE generators), are also brought into consideration to combine the electricity system with the transport and heating sector.

What is more, the electricity storage technologies, such as batteries, are still relatively expensive and might only become competitive with other flexibility options in some years. However, it was also shown that when the benefits of certain grid application services can be *stacked*, electricity storage might already be an economic viable solution under certain circumstances. BESS can use on the power grid for the provision of valuable short-term power applications and ancillary services, such as frequency response (i.e. primary reserves), voltage and inertia support, VRE smoothing, as well as T&D network congestion management and investment deferral. Nonetheless, direct and indirect technology support mechanisms, for instance in the form of RD&D funding to further explore application areas and improve technology performance and costs, or even market pull policies, for instance through market-based incentives (e.g. removal of regulatory barriers, tax credits, investment grants, feed-in tariffs or other subsidies) help to foster the future deployment of BESS in Sweden (JRC, 2013; Normark & Faure, 2014). When looking at the frontrunner countries in terms of electricity storage solutions it becomes evident that all of them have favourable regulatory environments and some kind of support initiatives in place that allow market actors, entrepreneurs and investors to explore new applications areas and advance storage technologies and further bring down prices. There are certainly also other reasons for doing this, as for instance in the USA there is an actual need for more power system flexibility due to some grid failures in the past (Biello, 2013; Minkel, 2008). However, Germany, as the world leader in solar PV installations, provides yet another good example of how the right policy mix can create a great market opportunities while still fostering competitiveness. Exemplarily, the reason for Germany's success in solar PV is not because it is the blessed with extraordinary amounts of sunlight, but because it has created a stable, long-terms focused incentive programme. Installation costs and LCOE for residential solar PV systems in Germany are among the world's lowest today (IRENA, 2015a; REN21, 2015).

The Swedish TSO Svenska Kraftnät or the DSOs, who are mainly responsible for balancing, operating and developing the power system, are by no means the only potential actors to utilise other system flexibility services through electricity storage or demand-side management. Established utilities, third-party players, entrepreneurs or even residential and industrial prosumers might all play an active role and even benefit, as long as the energy market environment provides the right incentives and allows to exploit the full potential of abound innovative and smart solutions.

5.2 The MLP Framework Revisited

As described in detail in *Section 3.2.2*, the trajectory of the MLP can take on various trajectories along different patterns and processes. A central aspect of the MLP framework by Geels (2002a) is the transition processes and the emergence of new regimes from the diffusion of niche innovations follow the pathway of co-evolution, notably "(i) evolution as a process of variation, selection and retention, (ii) evolution as a process of unfolding and reconfiguration" (p. 1257). In the light of the dynamics and processes presented in *Chapter 4*, BESS can be seen as niche applications, which, together with the development of distributed RETs, are transforming the energy system.

Firstly, BESS and other electricity storage solutions are evolving at various scales and technologies, such as grid-scale electricity storage applications for providing ancillary services, residential and industrial storage systems for backup power or micro-/off-grid applications, as well as the emergence of EVs. Many of these applications are being tested and improved through pilot and demonstration projects and even consumer markets. Some technologies and functions are better suited than others and continuous testing and learning brings about winners and losers, following the evolution process of "variation, selection and retention" (Geels, 2002a, p. 1257). BESS, notably Li-Ion batteries, have experience significant cost reductions and performance improvements mainly brought about by the development of EVs and to some extent residential small-scale BESS in combination with rooftop solar PV installations (IEA, 2014a, 2014b; Nykvist & Nilsson, 2015). Secondly, the combination of these BESS with the increased deployment of VRE from wind and solar, together with the augmented electrification and uptake of EVs can be seen as an ongoing process of "unfolding and reconfiguration" of the energy and electricity regime. Additionally, when the smaller-scale BESS can be aggregated (i.e. DERPs) and combined with smart grid solutions, they can be used complementarily to larger-scale BESS and further support the integration of VRE while providing additional flexibility to the power system.

All together, when linking the processes just described above to the various co-evolution and diffusion patterns presented in *Table 3-1*, BESS in essence seem to follow most of these trajectories. *Table 5-1* below draws from *Table 3-1*, but summarises the most prevalent co-evolution and diffusion processes of BESS innovation dynamics described before.

Table 5-1. Identified patterns of co-evolution and diffusion in BESS innovation processes.

Co-evolution/diffusion pattern	*Identified processes*
Fit-stretch pattern in the co-evolution of form and function	• *Form:* different electricity storage technologies (e.g. various battery technologies, flywheels, supercapacitors, hydrogen); • *Function:* exploring new functionalities and application areas (e.g. in T&D grids, islands and micro-grids, industrial facilities or residential storage systems, EVs); Spanning across multiple sectors (e.g. electricity system, home applications, transport)
Co-evolution of multiple technologies	Linkages and interactions between multiple technologies: • in combination with VRE technologies to support grid integration of higher penetration levels (for energy and power applications); • use in electricity sector (e.g. ancillary services), industrial facilities (e.g. energy backup, UPS systems), end-user (in combination with solar PV systems and/or EVs), electrical consumer devices; • increased electrification (e.g. electro-mobility, EVs); Cumulative deployment and use, resulting in increased improved learning curve (lower costs and better performance).
Diffusion as a trajectory of niche-accumulation	• Gradual technological diffusion via positive feedback loops; • Penetration of multiple sectors and domains (electricity, industry, transportation, residential, consumer market, etc.); • From RD&D projects, to niche market applications, and towards increased uptake in commercial/competitive markets; Eventually breakthrough from niche to new regime through alignment and of various niche actors and networks.

Source: own elaboration, based on concepts from Geels (2005a, 2005b).

As a consequence of these findings, it can be said that the MLP frameworks appears to fit well with the examined market and innovation dynamics when forming to a broader picture. However, when zooming in on various single processes, patterns, and structures within the different levels of the MLP the situation becomes a little more complicated and it is not always obvious whether certain dynamics can be seen as driver or barrier. Additionally, the timing of landscape signals or shocks (i.e. window of opportunity) is equally important to the diffusion and breakthrough of niche innovations. If the timing and nature of the parallel developments do not concur optimally (e.g. when niche innovations are not yet mature enough or if they too easily fit into existing regime structures without substantially change the overall trajectory), then new niche markets might not be able replace the old regime structure and get rejected. While the MLP framework takes a dynamic and evolutionary approach, the analysed processes are nevertheless only a snapshot of the present and the final outcome of the ongoing transition processes is not certain. However, as the MLP concept allows for a multi dimensional analysis of the interactions and structures of various actors, this has the advantage of analysing and identifying enabling and/or hindering factors for a successful transition. Consequently, market actors and policymakers can influence, adjust or remove the specified barriers and use the drivers as leverage points to foster or accelerate change.

However, and as already mentioned in *Section 3.1*, a limitation of the MLP approach (Geels, 2002a; Geels & Schot, 2007), and also similar transition and innovation theories (e.g. TM, SNM, or TIS), is that the main emphasis is on the diffusion, evolution and governance of technological innovation processes and actor networks (social interactions). But the larger change in infrastructure, which is also necessary in order to complete the transition (Bulkeley et al., 2014, 2010), is mostly neglected. This is certainly a critical aspect when analysing the diffusion of innovative technology in the energy and electricity system, which manifest huge infrastructural artefacts (e.g. power plants, T&D power lines) that are further interconnected with other infrastructure (e.g. transport, industry). Hence, this can be seen as a major shortcoming of the MLP framework, which regards infrastructure as part of whole system rather then the regime (Geels, 2011), and therefore, does not explicitly include it into the analysis. However, as the main objective of this study was to analyse market drivers and barriers (i.e. the interactions and structures of market actors) for the future deployment of BESS in Sweden, this approach was deemed to be most suitable in answering the research questions. Further research on the infrastructural components of such energy transitions and in combination with electricity storage and other flexibility enhancing solutions might be needed, where Bulkely et al. (2014, 2010) could provide an entry point.

5.3 Discussion of Methodological Choices and Limitations

The methodological approach applied for this study was deemed useful insofar as it allowed the author to fulfil the research purpose and answer the research questions stated at the outset. The extensive literature review helped to better specify the research problem. In addition, the identification of a useful and relevant framework supported the scoping and formulation of the research questions. The information collected via interviews fitted well with the research context of battery storage and its relationship to the Swedish electricity landscape, which helped to formulate an answer to the first research question and also fostered the execution of the analysis. It is important to notice here that the analysis, due to its multi-dimensional and dynamic nature, was not a linear but rather an iterative process. The analysis and findings from the interview data were structured with the help of the MLP framework and the understanding from the literature. While the power system is a rather complex construct with various actors, networks and interlinkages to other socio-technical systems, the MLP framework was deemed to be quite helpful in this sense, as it allows capturing these dynamic interactions and structures. However, this comprehensive approach makes it hard to strictly define borders on the various levels of the MLP framework and poses the risk of deviating from the initial research focus. Indeed, the MLP approach has received criticism from some scholars (Berkhout et al., 2004; Smith et al., 2005) that it is somehow unclear how the multiple conceptual levels should be defined, scoped and separated. Geels (2011) does not clearly resolve this issue and even proposes to focus on a multi-regime approach. Consequently, author of this thesis feels that the shortcoming of setting clear boundaries within the socio-technical system of the MLP framework posed some difficulties in maintaining focus and not deviating too much into other areas (e.g. small-scale BESS and EVs) that are somehow connected to the research problem but outside the defined scope. Moreover, due to the broad and holistic approach, it was often not possible to investigate certain aspects in more detail, as this would have gone beyond the scope the study, which is clearly a limitation of this thesis. However, in general the selected theoretical approach via the

MLP was useful to determine the main barriers and drivers and therefore, to answer the research questions. What is more, the author is convinced that this study has revealed and touched upon some interesting areas and challenges that could provide an entry point for future research (see also *Section 6.2*).

With regards to the interviews, the author feels that the initial literature review and the chosen framework have facilitated the identification of the interview targets as well as the structuring and formulation of the interview questions. Furthermore, the interview data was deemed to be essential to gather specific insights for the Swedish context of the study and re-assess and substantiate findings from the literature review. What is more, the author feels that the quality and quantity of the primary data were appropriate insofar that the results and conclusion are substantiated, also because they are largely congruent with what has been found in the literature. The relatively high number of interviewees (in relation to recommendations from literature on qualitative research, see e.g. Kvale and Brinkmann (2009)) and the fact that some sort of saturation of the answers after about 12-15 interviews was taking place, further underlines this point. Nevertheless, the selection of interviewees, both in terms of selection and availability, could be seen as limitation of this study. As possible actors and experts in the field are numerous, a pre-selection had to be made and is likely to be biased in a way that those who are more inclined towards renewables and battery storage were chosen. On the other hand, the selection of these interviewees with a broad knowledge and understanding of electricity market in Sweden is also likely to have positively affected the validity of the interview data.

The overall generalisability of this thesis can be seen as a major limitation, as the study is mostly country specific. As already pointed out earlier, every electricity system is unique as it has its own power mix and energy policy, follows specific production and consumption patterns, and connects to neighbouring countries with other unique configurations. Hence, the analysis of certain aspects of a specific power system is only comparable to other system with more or less similar configurations, but even here caution is recommended as the interactions and structures of the market can still differ significantly. Whilst some comparisons concerning regulatory settings and market design options are possible in order to learn from success stories or failures, the local and regional context is essential and policies or strategic choices need to be adapted accordingly.

6 Conclusions

This study set out to examine the uncertainties and opportunities in connection to grid-scale electricity storage through batteries in Sweden in order help integrate increased volumes of VRE from wind power and provide additional power system flexibility. This section provides the final conclusions of the study and the main findings in relation to the initially stated research question (see *Section 1.2*). And finally, some recommendations for future research will be made.

6.1 Answer to the Research Questions and Main Findings

The guiding research question has been formulated as follows:

> *How is the market for grid-scale BESS for integrating larger volumes of VRE from wind power becoming a reality in Sweden?*

Furthermore, two sub-questions were stated in order to better operationalise the overarching question:

> *In which ways can BESS be integrated into the Swedish electricity grid?*
>
> *What are the perceived drivers and barriers for the future investment and deployment of BESS in Sweden?*

In order to answer these questions, an in-depth study on the electricity market development and configuration in Sweden with respect to its connection to the broader Nordic and European context was required.

It was found that the increased uptake of distributed VRE from wind power, mainly driven by policy support measures, challenges the incumbent electricity market regime based on centralised power generation units. The grid integration of VRE requires a more flexible power system in order to manage the induced supply-side variability. BESS, as a versatile electricity storage option, are one of several other solutions to enhance system flexibility by providing multiple benefits for different application areas at various scales. Batteries have shown promising technological improvements in recent years, mainly driven by the development in the automobile industry and the emergence of EVs, and are now becoming competitive with other flexibility solutions, such as more flexible generation assets, grid reinforcement and interconnection, or demand-side management. It was found that BESS are most suitable for quick-responding and short-term power services rather than bulk energy storage over longer time periods. Examples of grid application areas frequency response (for primary reserves), voltage control, inertia support and other ancillary services, ramp control and smoothing of VRE, T&D network congestion management and grid investment deferral. If several of these benefits can be combined (i.e. benefits-stacking), the value and profitability of BESS can be increased. Additionally, the aggregation of smaller-scale and distributed BESS (e.g. from industrial facilities or residential installations) could used to provide local grid support services and help accommodate higher penetration levels VRE.

Using the MLP framework to analyse findings from the literature and interview data, it was found that there are currently major obstacles to the deployment and investment in BESS in Sweden for various reasons. First and foremost, the regulatory framework for BESS, both in the EU and Sweden, is largely unclear with regards to ownership and right of dispatch (i.e. which actors may use it and where in the power system may it be used). This is mainly a result of the EU Directive 2009/72/EC (2009), which lays out the rules for the EU market liberalisation and particularly specifies unbundling requirements with the aim of prohibiting any network operator from participating in any form of electricity generation or supply. Therefore, TSOs and DSOs who are responsible for operating and developing the grid may not operate or own electricity storage assets for making use additional balancing services or as an alternative to eliminate bottlenecks in the power grid. The situation for utilities and other electricity market actors is less restrictive. However, grid connection fees and energy taxes may apply when charging or discharging storage assets. The reason for this is that the regulatory regime does not clearly specify electricity storage assets as a singular asset category, and thus it can be seen as an energy consuming or generation unit, or even both, due to their very nature of charging, storing and discharging electricity. However, the EU is currently in the process of updating the Network Codes, and given the multiple benefits of grid-scale electricity storage, which have been identified by various other studies, resolving this problem is recommended. In this sense, it is also somewhat understandable that Sweden is awaiting clear signals from the EU in order to update its regulatory framework with regards to electricity storage. However, with a clearer specification of storage assets, much uncertainty could be removed relatively easily, which would significantly improve the business case for providing grid services through storage assets.

Besides these regulatory barriers, the developments on the Swedish electricity landscape show more promising signs for the future uptake of BESS, although there is currently no imminent need for enhancing the overall power system flexibility. Generally, the Nordic power system is well interconnected and there is ample flexible generation capacity from hydropower, both in Sweden and Norway, thus reducing the need for electricity storage. Moreover, whilst a gradual phase out of nuclear power in Sweden seems likely (mainly due the weak economic outlook for the renewal of existing and ageing for nuclear capacity), increasing penetration levels of VRE from wind power look set to continue in the near future. Despite the current flexibility of the power system, electricity demand (mostly in the South) and power generation (mostly in the North) are unevenly distributed across the country, therefore increasing the risk of power system bottlenecks. In addition, as most wind power generators are distributed in nature and connected to the local distribution grid (as opposed to centralised power generation units that connect to the transmission grid), there may be additional challenges on the local network in the future. Hence, electricity storage for local grid support applications might be needed to enhance local power system flexibility and remedy certain issues. For this reason, it is even more important that the regulatory hurdles are cleared in order to maintain grid flexibility and network stability.

With the emergence of smart grid solutions, and to a certain extent also demand-side management, it was also found that the aggregation of smaller-scale BESS from residential or industrial prosumers (i.e. DERPs) could be used as a solution to provide additional and/or complementary local grid support services for enhancing power system flexibility. However, it is important to reinforce the fact that the regulatory requirements should be carefully evaluated in order to provide the right incentives for such solutions.

To sum up, BESS are certainly an emerging technology that could provide multiple valuable grid support services to enhance the overall power system flexibility, especially with the increasing shares of VRE. As of today, the market for BESS in Sweden is almost non-existent, despite the great potential in certain application areas. Whilst there are some drivers in the form of small niches for small-scale BESS applications and promising technological developments, regulatory hurdles and uncertainties coupled with still relatively high technology costs constitute the main barriers today. However, these obstacles do certainly not seem insurmountable and it remains to be seen how these will be managed in the future.

6.2 Further research and recommendations

The exploratory nature of this thesis aimed to give an account of the main uncertainties and opportunities for the introduction of BESS in Sweden. However, there is sill much more to be examined in relation to the uptake and usage of BESS in Sweden and the study still leaves various important issues and challenges open for future research.

Firstly, this thesis has only scratched the surface with regards to regulatory and institutional setting for electricity storage and BESS in Sweden and the EU. Whilst there are some studies that have provided some policy recommendations for the promotion and use of electricity storage (e.g. Hansson et al., 2014; JRC, 2013; Normark & Faure, 2014), this thesis indicates that there is a need to further evaluate and map the regulatory aspects affecting the deployment of storage assets on the grid. This includes not only legislation affecting ownership and right of dispatch but also the effects of the overall power market design, as well as support and incentive schemes.

Secondly, as this study has analysed the evolution of BESS as a niche application, future research could examine in more detail the interlinkage and accumulation of such niche dynamics in more details in order to assess how the different functions, application areas and technologies interlink and eventually for a new energy regime.

Thirdly, another relevant area is how regime actors (e.g. established utilities) can best respond to threads from the evolution of potentially disruptive niche innovations and the emergence a completely different socio-technical regime with distributed VRE sources, storage applications, and smart grids that is not compatible with the incumbent structures. Although some might want to resist change and try to delay the transition, some studies (Bronski et al., 2014, 2015) have already paved the way in this direction on how incumbents can best respond to such fundamental changes.

Fourthly, and connected to the third point above, new and emerging business model operate grid-scale BESS and sell valuable services to other markets actors (e.g. TSO, DSOs, or directly on the intraday or spot market) could also provide an entry point for future research in order to make effective and efficient use of such solutions. Such research is of course not only limited to the utilisation of grid-scale BESS, but could also include the operation of aggregated distributed energy resource providers (DERPs) and in combination with innovative demand-side management solutions.

Fifthly, the energy landscape is changing rapidly, and whilst many studies have assessed the expansion of VRE from wind power leaving other factors (e.g. the share of nuclear or hydropower) constant, and some system studies even assume that share of nuclear will at least remain the same over the next years, future research should assess the need for future system flexibility with decreasing generation capacity from nuclear. Moreover, and due to the high level of interconnection between the Nordic countries, such aspects are also worth considering when assessing the potential future need for flexibility options.

Lastly, if needs for additional system flexibility are identified, it is important to assess the various technological options that can be used, as well as their interplay. For instance, the expansions and reinforcement of power grid lines is one option, BESS or demand-side management are other, but the interlinkage or combination of these could provide another entry point for future research. What is more, the broader field of electricity storage technologies, in particular power-to-fuel or power-to-heat solutions could provide further solutions, especially with increased penetration levels from VRE.

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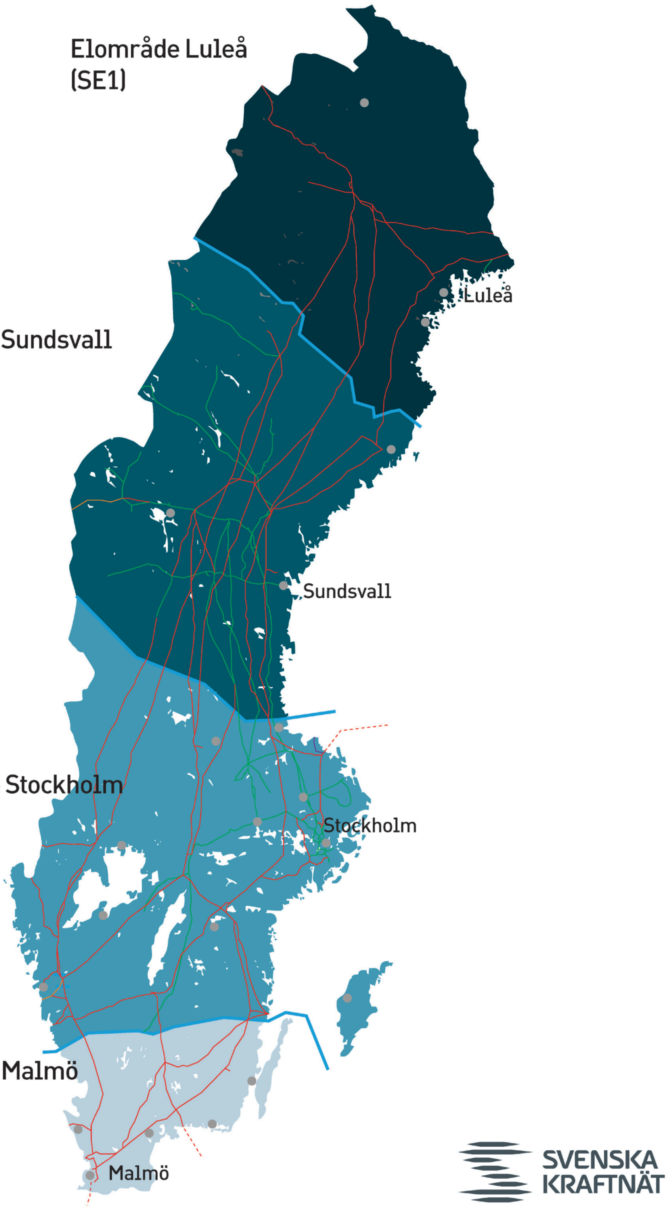
Appendix I

Illustration of the four bidding areas *SE1–SE4* of the Swedish electricity market:



Source: Svenska Kraftnät.

Appendix II

Present-values (PVs) of selected energy storage benefits (expressed as US$/kWh and US$/kW) along the power system value chain:

Value chain	*Benefit*	*PV US$/kWh*		*PV US$/kW*	
		Target	*High*	*Target*	*High*
End user/customer Energy management services	Power quality	19	96	571	2 854
	Power reliability	47	234	537	2 686
	Retail time-of-use (TOU) energy charges	377	1 887	543	2 714
	Retail demand charges	142	708	459	2 297
Distribution infrastructure services	Voltage support	9	45	24	119
	Defer distribution network investments	157	783	298	1 491
	Distribution losses	3	15	5	23
Transmission infrastructure services	VAR support	4	22	17	83
	Transmission network congestion	38	191	368	1 838
	Transmission network access charges	134	670	229	1 145
	Defer transmission network investments	414	2 068	1 074	5 372
Power system operation & ancillary services (including generation & bulk energy services)	Local capacity	350	1 750	670	3 350
	System capacity	44	220	121	605
	VRE integration	104	520	311	1 555
	Fast regulation (1 hour)	1 152	1 705	1 152	1 705
	Regulation (1 hour)	514	761	514	761
	Regulation (15 minutes)	4 084	6 845	1 021	1 711
	Spinning reserves	80	400	110	550
	Non-spinning reserves	6	30	16	80
	Black start	28	140	54	270
	Price arbitrage	67	335	100	500

Source: based on EPRI (2010, p. xvi).

The report *Assessing Storage Value in Electricity Markets – A literature review* by the EU's *Joint Research Centre* (JRC, 2013, p. 39) gathered data from several studies and came up with similar, but still slightly different values (illustrated and expressed as €/kW; see following Figure). However, numerous other studies identified much lower values for some selected energy storage benefits (JRC, 2013, p. 44).

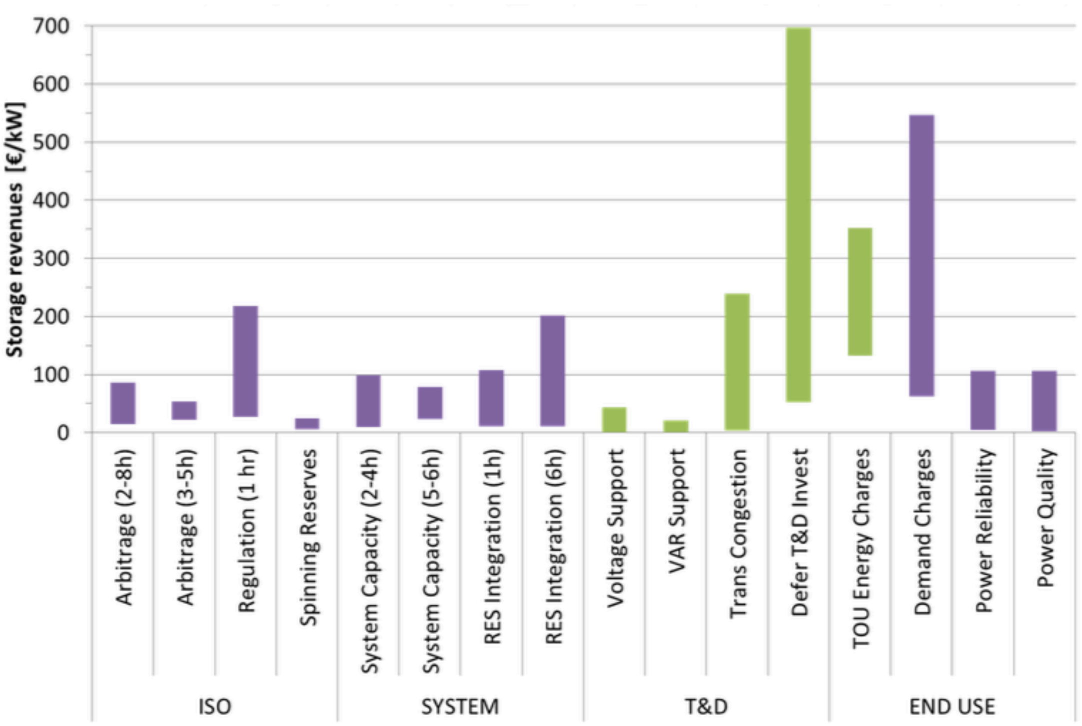


Figure 16: Cross value chain storage value pools, elaboration on EPRI 2010 [38], SANDIA 2010 [45]

Source: adopted from JRC (2013, p. 39).

Appendix III

Interview questionnaire for collecting primary data for this thesis.

General information/introduction

- Full name, job position, company name (e.g. subsidiary of…)?
- How long have you worked within this field/job position (personal and in the current company)?
- How and why did you get involved in this work field the first place (personal and in the current company)?

Part I – General questions

- Could you describe **the role battery energy storage plays in your company's strategies and considerations** (today or in the near future)?
    - What reasoning underpins your company's/personal view?
    - What activities (R&D, testing, pilot project, etc.) related to battery storage initiatives are you engaged in (today or planned in the near future)?
    - Which battery storage technologies are you are focusing on (or does your company view as most promising) and why (technology, price, R&D, etc.)?
    - More specifically, are electrochemical battery storage technologies (e.g. Li-Ion batteries or other electrochemical batteries) of any interest for your company? And if so, why or why not?
- On a bigger picture, what **functions and roles** do you think will battery energy storage systems (BESS) play in the near future on the energy/electricity landscape?
    - In comparison to and/or combination with grid development and interconnections?
    - In comparison to and/or combination with demand response management (e.g. pumped hydro storage (PHS), thermal power plants (peaker plants), etc.)?
    - In comparison to and/or combination to demand control?
- What **applications and benefits** do you consider that battery energy storage systems (BESS) have to integrate larger volumes of variable renewable energy (VRE) into the electrical grid in the (electricity market) value chain?
    - What about wholesale energy services on independent system operator (ISO) markets (bidding into energy services, capacity and ancillary services, spinning reserve, black start, frequency regulation, price arbitrage)?
    - What about variable renewable energy (VRE) integration on system level (ramp and voltage support, off-peak storage, time shift, rapid demand support)?
    - What about stationary/transportable transmission and distribution (T&D) support (defer transmission/distribution investment, transmission access

charges, transmission congestion, VAR and voltage support, distribution losses)?

  - What about end-user support (retail demand charges, retail time of use (TOU) energy charges, power reliability and quality)?

- Specifically **in combination with larger-scale wind farms**, what applications and benefits do you see for battery energy storage systems (BESS)?
  - Ramp and voltage support, off-peak storage, time shift, rapid demand support?
  - Anything else (e.g. grid access, transmission/distribution investment, transmission access charges, transmission congestion, power reliability and quality)?

Part II – Drivers, barriers and the current state of incentive/support mechanisms

- Which **specific market drivers** for the investment in or deployment of battery energy storage systems (BESS) can you identify that are currently in place or that you are anticipating in the near future?
- Which **specific market barriers/constraints** can you identify or anticipate that are currently (or in the near future) withholding the investment in or deployment of battery energy storage systems (BESS)?
- Which **market incentives and/or support mechanisms** for battery energy storage systems (BESS) can you identify that are currently in place or that can be anticipated in the near future?
  - What about capacity markets (for peak demand regulation and/or frequency/voltage support)?
  - Are there any energy storage regulations/mandates from the government in place to you know of?
  - Are there any subsidy schemes, tax rebates or R&D support mechanisms for energy storage technologies in place that you know of?
- What incentive/support mechanisms do you think **would (additionally) be needed for the future** consideration of battery energy storage systems (BESS) investment/deployment?
  - What about regulations/mandates/certificate schemes?
  - What about subsidies, tax rebates or R&D funding programmes?

Final thoughts and comments

- Is there anything else you would like to add?
- Do you have any further recommendations or comments for me?
- Do you know some other market actors or experts you think I should talk to?

Appendix IV

Actor landscape from where the various interview targets have been approached.

Sphere	*Organisations*
Policymakers & authorities	• Swedish Energy Agency (Statens Energimyndighet) • Swedish Energy Markets Inspectorate (Energiemarknadsinspektionen) • Other Governmental Agencies and authorities
Research networks & institutions	• Nordic Energy Research • SweGRIDS • Power Circle • Energiforsk (former Elforsk) • Swedish universities • Collaborative research programmes (e.g. industry and academia)
Electricity generation & utilities	• Vattenfall • E.ON • Fortum • Statkraft • Other utility companies (e.g. Skellefteå Kraft, Kraftringen Energi, etc.) • Industry associations (e.g. Svensk Energi, Svensk Vindenergi)
Electricity market	• Nord Pool Spot • Electricity traders and retailers • Advisors/Consultants
Transmission & distribution system operators	• Svenska Kraftnät (TSO) • DSOs
Battery storage & electrical components manufacturers	• ABB • Siemens • Alstom • Others (e.g. Tesla, Panasonic, etc.)
End-users	• Industrial customers • Household customers

Source: own elaboration

Appendix V

List of interviewees for personal communication data:

#	*Interviewee*	*Organisation*	*Position/designation*	*Date*
1	Sara Malmgren	Swedish Energy Agency (Energimyndigheten)	Programme Manager; Solar and Batteries	23.06.2015
2	Malin Hanson	Power Circle	Project Manager; Smart Grid and Integration of Renewables	23.06.2015
3	Jan Schelling	Statkraft	Senior Technology Advisor; Innovation Department	24.06.2015
4	Christer Bergerland	Fortum	Advisor; Corporate Technology and Innovation, Decentralised Generation	24.06.2015
5	Marielle Liikanen	Swedish Energy Markets Inspectorate (Ei)	Senior Advisor	26.06.2015
6	Fredrik Lundström	Swedish Energy Agency (Energimyndigheten)	Programme Manager; Smart Grids and International Coordination and Collaboration	26.06.2015
7	Lars Olsson	Seniorit AB	Founder, Owner and Consultant (former CEO of 3 Swedish DSOs)	26.06.2015
8	Mikael Dahlgren	ABB	R&D Manager; Corporate Research Sweden	29.06.2015
9	Erik Thunberg	Energiforsk (former Elforsk)	Area Manager; Electrical Grid, Wind and Solar Power	29.06.2015
10	Björn Jernström	Ferroamp Elektronik AB	Founder and CEO	29.06.2015
11	Stig Åhman	Nord Pool Spot	Region Market Manager for Sweden and Central Eastern Europe	02.07.2015
12	Karin Widegren	Swedish Energy Markets Inspectorate (Ei)	Advisor to the Director-General (former Head of Secretary of the *Swedish Smart Grid Council*)	02.07.2015
13	Nathalie Tietz	E.ON	Technology Consultant; E.ON Innovation Center for Energy Storage	02.07.2015
14	Göran Hult	Fortum	Vice President; R&D Sweden	03.07.2015
15	Fredrik Wik	Svenska Kraftnät	Market Designer; Market Integration and Balancing	07.07.2015
16	Jens Madsen	Vattenfall	Head of Wind Power R&D	08.07.2015
17	Lovisa Jönsson	Siemens	Technical Sales; Power Solutions for Energy Storage	08.07.2015
18	Johan Abrahamsson	SweGRIDS & Uppsala University	Area Manager STORAGE	10.07.2015
19	Pia Borg	Scio-Tech	Founder, Owner and Consultant (Author of the study *Förstudie Energilager anslutet till vindkraft*)	23.07.2015
20	Mikael Nordlander	Vattenfall	Head of R&D; Future of the Energy System	17.08.2015

Source: own elaboration.