Balancing Supply and Demand in an Electricity System - the Case of Sweden

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Balansera produktion och konsumtion i ett elsystem – en studie av Sverige

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Abstract
In an electrical system there needs to be a constant balance between supply and demand of electricity and this is measured by the frequency in the grid. Due to the increasing awareness of climate change, more renewable energy resources have been introduced in the Swedish electricity system. This is, however, not solely positive since renewable energy sources are often of intermittent character which entails more imbalances between supply and demand. In addition, statistics and data show that the deviation in the frequency in the Nordic system has increased during the latest years. Thus, in this thesis, the issues regarding the frequency have been addressed by examining the demand for frequency control in the Swedish electricity system and what balancing efforts that can be carried out on a local level to contribute to a better balanced system. This thesis has been conducted at KTH Royal Institute of Technology with collaboration with the commissioner Mälarenergi AB.

A case study of the Swedish electricity system has been carried out to gather empirical material and this material has been analyzed using Geels theory on technical transitions, the multi-level perspective. The results indicates that it is likely the demand for frequency control will increase, and this is due to factors as more intermittent energy, current market design for trading electricity, overseas transmission connections, decommissioning of nuclear power and limited internal transmission capacity. Three other developments have been identified, which could have a large impact on the demand in the future, as an increasing use of electric vehicles, prosumers and the deployment of IoT in the energy sector. These developments have not been integrated to a large extent yet in the energy sector and thus have a more uncertain impact.

In terms of resources, the thesis has identified that it is likely that hydropower will continue to be the main resource for frequency regulation. Another source that could be used more
frequently than today and possibly compete with hydropower is combined heat and power plants. Furthermore, the study has found that local actors can contribute by advertising smaller local resources on a market for trading regulating power called “reglerkraftmarknaden”, that balance providing companies collaborate, that the load is controlled in the local grids or that smaller local production facilities are operated in stand-alone mode during extreme situations.

**Keywords:** Electricity System, Intermittent Energy Sources, Balancing Supply and Demand, Frequency Control, Local Balancing Efforts, Socio-Technical Approach, Multi-Level Perspective
Sammanfattning

För att uppnå ett välfungerande elektrisk system så måste det vara en konstant balans mellan produktion och konsumtion av el i systemet. Den här balansen mäts genom att mäta frekvensen i elnätet. Eftersom allt fler har blivit mer medvetna om de klimatförändringar vår planet står inför har det successivt införts mer och mer förnybara energikällor i det svenska elsystemet. Den här utvecklingen har inte enbart varit positivt, eftersom förnybara energikällor ofta är av intermittent karaktär, vilket har medfört att balansen mellan produktion och konsumtion av el har försämrats. Flertalet undersökningar har påvisat att det förekommer mer frekvensavvikelser i det nordiska elsystemet idag än tidigare. Denna rapport har således undersökt dessa problem genom att analysera efterfrågan på frekvensreglering i det svenska elsystemet och vilka initiativ som kan tas på lokal nivå för att förbättra balansen i elsystemet. Rapporten har genomförts på Kungliga Tekniska Högskolan i samarbete med uppdragsgivaren Mälarenergi AB.

Rapporten har genomfört en fallstudie av det svenska elsystemet för att samla in empiriskt material, och detta material har i sin tur analyserats genom Geels flernivåansats. De resultat som har framkommit i undersökningen visar på att det är troligt att efterfrågan av frekvensreglering kommer att öka. Denna ökning beror på faktorer som att mer intermittent energi integreras i elnätet, hur marknaden för att handla elektricitet är utformad, fler utfärdade överföringsförbindelser, nedrustning av kärnkraft och begränsad överföringskapacitet inom det nationella elnätet. Tre andra utvecklingar har identifierats som möjliga kan ha en stor påverkan på behovet av frekvensreglering. Dessa är ett ökat antal elektriska fordon, prosumenter och att energisektorn integreras av IoT och smarta objekt i större utsträckning än idag. Dessa faktorer har inte integrerats i det svenska elsystemet nämnvärt ännu och deras påverkan är därmed mer osäker.
Denna studie har också kommit fram till att vattenkraft troligtvis kommer fortsätta att vara den resurs som används mest för frekvensreglering, men även att kraftvärmeverk har potential att användas mer för reglering än idag. Vidare har rapporten även identifierat att lokala aktörer kan bidra till en bättre balans i systemet genom att antingen annonsera mindre lokala resurser på reglerkraftmarknaden, öka samarbetet mellan balansansvariga företag, kontrollera lasten i lokala elnät eller att mindre lokala produktionsanläggningar drivs i o-drift under extrema situationer.

**Nyckelord:** elsystem, intermittenta energikällor, balansera produktion och konsumtion, frekvensreglering, balansering på lokal nivå, socio-teknisk ansats, flernivåsåsats
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Oskar Mared
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Glossary

**AFK** - Automatisk Förbrukningsfrånkoppling (A system that automatically disconnects the supply of electricity)

**aFRR** - Automatic Frequency Restoration Reserve

**CAES** - Compressed Air Energy Storage

**CHP** - Combined Heat and Power

**CO2** - Carbon Dioxide

**COP 23** - The 23 session of Conference of Parties (to the UN Convention on Climate Change)

**Ei** - Energimarknadsinspektionen (Swedish Energy Markets Inspectorate)

**FCR-N** - Frequency Containment Reserve – Normal

**FCR-D** - Frequency Containment Reserve – Disturbance

**G2V** - Grid-to-Vehicle

**Hz** - Hertz

**IoT** - Internet of Things

**KTH** - Kungliga Tekniska Högskolan (The Royal Institute of Technology)

**KTHB** - The library in The Royal Institute of Technology

**kV** - kiloVolt

**kW** - kiloWatt

**kWh** - kiloWatt-hour

**mFRR** - Manual Frequency Restoration Reserve

**MFK** - Manuell Förbrukningsfrånkoppling (A system that manually disconnects the supply of electricity)

**MLP** - Multi-Level Perspective

**MW** - MegaWatt

**MWh** - MegaWatt-hour

**NEPP** - North European Power Perspectives

**PHES** - Pumped Hydroelectric Energy Storage

**RKM** - Reglerkraftmarknaden (A market for trading regulating power)

**R&D** - Research and Development

**RQ** - Research Question

**SEK** - Swedish krona

**ST-systems** - Socio-Technical Systems

**SvK** - Svenska Kraftnät (The TSO in the Swedish electricity system)

**TWh** - TeraWatt-hour

**TSO** - Transmission System Operator

**UK** - United Kingdom

**V2G** - Vehicle-to-Grid
1 Introduction

This chapter introduces a background to the investigated phenomenon which includes how an increasing usage of intermittent energy sources is causing issues for the electricity system in Sweden. Further, the problematization, purpose and research questions are presented followed by the delimitations and the contribution of the thesis. Lastly, an overview of the disposition of the thesis is presented.

1.1 Background

Climate change is one of the biggest challenges the human race faces today and it can be illustrated as an alternation in a normal state of weather in a specific region. For example, it could be a change in the seasonal average temperature or changes in the annual rainfall in a given location (Hansen et al., 2012). Changes in the earth’s overall climate is also a climate change, and research shows that the yearly average temperature has increased for the last decades on earth (Hansen et al., 2012). This “global warming” has resulted in more extreme weather events, such as tropical cyclones and flooding, than usual and has a large human impact (Rosenzweig et al., 2001). It is not only that people in specific regions suffer, for example because of persistent droughts, but it also involves economic damage. Single events that have occurred in Sweden, such as the storm “Gudrun”, has caused financial losses of SEK 1.5 Billion (Andersson and Keskitalo, 2016). Hansen et al. (2012) argue that this global warming is, mostly, due to the human-made greenhouse gases.

Governments and administrations have developed several renewable energy policies to mitigate these climate changes (European Commission, 2017). The EU has developed a policy called “The Renewable Energy Directive” which implies that 20 percent of the total energy need should be produced by renewable energy sources by 2020. There are also country specific targets and Sweden has, for example, a long term goal of 100 percent of the electricity production should be produced by renewable sources by 2040 (Regeringskansliet, 2016). To increase the living standard without leaving ecological footprints is of global interest and climate change conferences, for example COP 23 in Germany, indicates this endeavor (Regeringskansliet, 2017).

Climate change and politically set targets have forced the energy market to change and move towards using more renewable energy sources. This is an ongoing development which has started to introduce more solar and wind power to the grid system (Energimyndigheten, 2017). Solar and wind power are examples of intermittent energy sources, meaning that the energy from these sources is not continuously available to generate electricity (SvK, 2015a). They are highly dependent on factors such as wind speed and sunlight. The increasing use of renewable energy sources means that more intermittent energy is connected to the grid and that entails several challenges for the electricity network (SvK, 2015a).
A prerequisite for the electrical system to work is that there is a constant balance between supply and demand of electricity, this applies for every hour, minute and second of each and every day (SvK, 2015a). One way of measuring this balance is to measure the frequency in the system. In the Nordic electricity system, a frequency of 50 Hz indicates that there is a perfect balance between supply and demand (SvK, 2018a). If the frequency drops, the consumption is higher than the production and if the frequency goes up, the production exceeds the consumption (SvK, 2018a). The deviations in frequency in the Nordic electricity system have increased and it has been concluded that an increasing usage of intermittent energy sources is one factor for these increased deviations (SvK, 2015a).

In Sweden, Svenska Kraftnät (SvK), acts as the transmission system operator (TSO) and thereby has the overall responsibility for the Swedish transmission system (SvK, 2015a). The frequency is the same in the entire Nordics but SvK has the overall responsibility for balancing supply and demand in the Swedish part of the system (SvK, 2015b). SvK does not possess resources to handle this balance themselves instead they purchase balancing resources from different companies and usually companies that produce electricity (SvK, 2016a). Today, the balancing resources mainly consist of production capacity from large hydropower plants located in the north of Sweden (SvK, 2015a). Increasing deviations in the system, however, puts pressure on using other alternatives as balancing resources as the capacity from the large hydropower plants is not unlimited (SvK, 2015a).

The commissioner of this study, Mälarenergi AB, is a utility company owned by Västerås stad and has around 700 employees (Mälarenergi, 2018). Mälarenergi AB is a large company with several subsidiaries and the main areas of operation are within electricity, district heating, water supply and instalment of optical fiber (Mälarenergi, 2018). In terms of electricity, Mälarenergi AB produces electricity in CHP plants and hydropower plants; they own local grids for distributing electricity and trades electricity for the area around the city of Västerås (Mälarenergi, 2018). This study was initiated by one of the electricity production departments of Mälarenergi AB.

1.2 Problematization

Climate change and politically set targets have put pressure on the entire energy sector. As a result, the sector is undergoing major changes. An ongoing development is the increasing use of renewable energy sources for electricity production. These sources are often of intermittent character which is problematic for the electricity grid as there needs to be a constant balance between supply and demand of electricity. This balance is, to a large extent, handled with large-scale hydropower plants located in the north of Sweden but the capacity of these power plants is not unlimited (SvK, 2015c). Another issue is that the transmission capacity in the grid system is limited and the resources from the north can, when the maximum transmission capacity is reached, not be used to balance supply and demand in the system (SvK, 2015c).
is thereby important that other options as balancing resources are considered, and especially options that could be utilized on a local level\(^1\).

### 1.3 Purpose & Research Questions

The purpose of this report is to investigate the demand for frequency control in the Swedish electricity system and what could facilitate a better balance in the system. To operationalize the purpose, the following research questions will be answered.

**Main RQ:** What is affecting the demand for frequency control in the Swedish electricity system and what balancing resources and efforts could facilitate the balance?

**RQ1:** What are the underlying factors affecting the demand for frequency control?

**RQ2:** What resources could be used to control the frequency?

**RQ3:** What balancing efforts could be carried out on a local level?

### 1.4 Delimitations

The thesis will investigate the Swedish electricity system and other parts of the energy sector will not be considered. The investigated technologies in terms of production, energy storage and consumption will thus only include technologies regarding electricity. The thesis will investigate global trends and a short outlook on the development of intermittent energy sources for the three countries Germany, Norway and Denmark. Apart from this will the markets outside of Sweden not be furthered investigated.

In terms of balance for the electricity system, this study will focus on the frequency in the system. The voltage levels in the grid are discussed in the report but are delimited to include the concept of brownout where the voltage in the grid is altered to control the load.

The main area of focus for this thesis will be to determine different directions that are possible to pursue with in terms of what resources that could be used and what balancing efforts that could be carried out on a local level. Thus, the thesis will not investigate specific technical details on how different technologies can be used to control the frequency nor will the thesis investigate other details such as what equipment that is needed in the power plants to be able to control the frequency.

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\(^1\) A local level is in this report defined as within one or a few local grids in the electricity grid system. A local grid is further explained in section 3.3.2 in the report but shortly a local grid is usually owned by a municipality and is the part of the grid system that transmits electricity to the end consumers, such as households.
1.5 Contribution

This thesis aims to make two contributions. Firstly, an analytical contribution described by Blomkvist and Hallin (2015 p.40-41) as “by analyzing a problem from a new angle (...) show new ways of understanding empirical data”. The analytical contribution will be to map out the factors affecting the demand for frequency control in the Swedish electricity system using the different levels in the multi-level perspective framework developed by Frank Geels (2004). This contributes with a well-structured overview of the current situation for the demand for frequency control in Sweden.

Secondly, this thesis will make an empirical contribution by presenting efforts that can be carried out on a local level to contribute to a better balanced system. Other studies such as the work by Watson and Kimball (2011) and Årdal et al. (2012) investigated the possibility to use solar power and wind power plants to control the frequency, which are specific resources that could be used locally. There are several studies on how specific resources could be used for balancing purposes but there is, in our opinion, limited research on the efforts that could be carried out on a local level.

1.6 Disposition of the Thesis

The thesis starts with the introductory chapter, followed by chapter 2 which presents the theory, a socio-technical approach and Geels multi-level perspective that has been used as the analytical tool in the thesis. Chapter 3 contains of a description of the relevant parts of the Swedish electricity system and how the balance between supply and demand is handled. Chapter three, thus, provides the necessary insights needed for the reader to assimilate the findings in this thesis. Chapter 4 provides a more international perspective and briefly presents how three other countries work with frequency control and handle imbalances in their grids. Chapter 5 presents and argues about the chosen method to the thesis. It discusses chosen research design and also reflects upon the quality of the collected empirics and material.

In chapter 6, the findings are presented and analyzed in detail. This chapter is divided into three parts which relate to the research questions in this thesis. Chapter 7 will discuss and highlight the key findings and takeaways from the study. Finally, the concluding chapter, chapter 8, answers the posed research questions in a more precise manner. The chapter also presents implications for utility companies and the thesis limitations as well as suggestions for further work.
2 Theory

This chapter presents the theoretical base of the thesis. The theoretical approach is a socio-technical approach where both social and technological elements are considered in the analysis. This approach is first explained followed by the theoretical framework on technological transitions, the multi-level perspective, which is used as the analytical tool in the thesis and this framework undertakes the socio-technical approach.

2.1 Socio-Technical Approach

A socio-technical approach is when both social and technological aspects are taken into consideration and they are related to each other (Chai and Kim, 2012). Geels (2004) argues that in a socio-technical approach there should be an analytical distinction between the three dimensions; socio-technical systems, actors within the system and rules that coordinate the activities of the actors. There are connections between these dimensions. When performing a socio-technical analysis it could, however, be advantageous to differentiate the dimensions to be able to investigate the relations between them (Geels, 2004).

Geels (2004, p.900) defines a socio-technical system as “*the linkages between elements necessary to fulfill societal functions*”. In Figure 1 the elements and how they interact with each other is visualized. The basic elements in a socio-technical system are divided into three larger sub-functions; production, distribution and use of artefacts. Each sub-function consists of several smaller elements such as technology, natural resources and cultural meaning. The alignment of these elements thus creates a socio-technical system.

![Socio-technical system](image_url)

*Figure 1* Socio-technical system (adopted from Geels, 2004, p.900)
A socio-technical system also includes relationships of human individuals (Chai and Kim, 2012). To be able to fulfill a societal function there need to be activities from human actors, organizations and social groups. It is the actors and social groups that carry, maintain, and change the elements and how they are linked in the socio-technical system (Geels, 2004). The actor group in a socio-technical system is wider than just actors from the technology side, such as in industry structures or engineering communities. It includes actors both from the technological side and other societal groups relevant to the system, such as public authorities and the users of technology (Geels, 2004). Figure 2 visualizes the social groups included in socio-technical systems.

![Figure 2 Social groups within a socio-technical system (adopted from Geels, 2004, p.901)](image)

Figure 1 and 2 clearly differentiate a socio-technical system and the social groups within the system. The actors within the social groups can, however, not act just like they want. The activities of the actors are coordinated by certain rules. Geels (2004) describes three types of rules that coordinate activities from actors; regulative, normative and cognitive rules.

Regulative rules are usually associated with the legal systems and thus affect the behavior of actors (Palthe, 2014). These rules are often established by legally binding documents which include reward or punishments for certain actions. One example could be that government’s subsidies for using technologies with low emissions (Geels, 2004). Normative rules are associated with moral and norms that alters behavior (Palthe, 2014). Cognitive rules are
cultural factors, for example, when humans develop certain values and beliefs that are shared amongst individuals (Palthe, 2014).

The triad of socio-technical system, actors and rules has now been explained and distinguished from each other. As explained in the beginning of the chapter, these three dimensions interact with each other, and it is these relations that constitute the socio-technical approach (Geels, 2004). The dimensions are interrelated in six steps which are shown in Figure 3 below.

![Figure 3 Relation between system, rules and actors (adopted from Geels, 2004, p.903)](image)

2.2 The Multi-Level Perspective

A socio-technical system does not stay the same for all eternity, the systems changes over time (Geels, 2004). The multi-level perspective is a framework for analyzing technological transitions in the context of a socio-technical approach (Geels, 2002). The framework is developed as an integration from findings in various other studies and Geels (2002) states that the framework is not a perfect representation of reality but rather an analytical tool for investigating the complex developments involved in socio-technical transitions. This framework is not a simple linear model that works with simple drivers but instead a relative complex model which makes it possible to grasp the complexity of reality in a good way (Geels, 2002).

The multi-level perspective consists of three analytical levels called niches, regimes and landscape (Geels, 2012). Shortly, niches can be seen as the development of new revolutionary technologies and other innovations, the regime as the established practices in the current socio-technical system and the landscape as slow-changing external factors such as climate change (Geels, 2002). All of these analytical levels affect each other and the relationship
between them is described by Geels (2002, p.1261) as a “nested hierarchy”. The relationship between the levels is visualized in Figure 4. It can be seen that the landscape is the top part and the regimes are located under the landscape and the niches are the bottom part under the regimes (Geels, 2002).

![Figure 4 The levels of the multi-level perspective (adopted from Geels, 2002, p.1261)](image)

2.2.1 Niche-Level

Niche is the bottom part of the multi-level perspective framework and can be seen as protected spaces (Geels, 2012) where it is possible to do or create something entirely different called radical innovations (Tidd and Bessant, 2013). Examples of these kinds of protected spaces are R&D departments or smaller markets that encourage radical innovations, like the army, where innovations such as the digital computer and the radar have emerged (Geels, 2002). The protected spaces are not part of the regular market and radical innovations need that kind of protection to be able emerge (Geels, 2002).

The radical innovations that emerge in the niches are usually called novelties and they are developed since a specific problem in the current regime or landscape is discovered (Geels, 2002). The novelties developed in the niches are different compared to the currently existing innovations in the regime, and the actors within the niche have the ambition that their new radical innovation sooner or later reaches the regime and is used frequently. The niches are important in this socio-technical approach since they provide a first starting point to enable a change (Geels, 2002).

Geels (2012) describes three processes that are important within niches:

1. Learning processes: Actors need to learn about several aspects such as imperfections of the technology, how it can be solved, user behavior and market demand.
2. The articulation of expectations and visions: Actors need to get their vision accepted by the broad market. If the vision (novelty) is aligned with some of the learning
processes there is a possibility that the vision obtains momentum and comes out as the
dominant design which means that a specific product design is the one that the broad
market approves and uses (Srinivasan et al., 2006).

3. Social networks: Actors need to build a strong social network around their novelty to
be able to attract powerful stakeholders that can provide more resources.

2.2.2 Regime-Level

The regime level is located in the middle, between the niche and the landscape, in the multi-
level perspective. As explained in section 2.1, the alignment of elements that fulfill a societal
function is defined as a socio-technical system. These elements are carried and changed by
certain actors, organizations and social groups. The socio-technical regime is defined by
Geels (2004, p.905) as “the deep-structure or grammar of ST-systems, and are carried by the
social groups”. Which is further explained as the established practices within a socio-
technical system.

Geels (2004) has developed the concept of socio-technical regime from Rip and Kemp’s
technological regime as: “the rule-set or grammar embedded in a complex of engineering
practices, production process technologies, product characteristics, skills and procedures,
ways of handling relevant artefacts and persons, ways of defining problems; all of them
embedded in institutions and infrastructures”. A technological regime thus only includes
the activities related to an engineering community. In a socio-technical regime, this view is
expanded by adding the other social groups that interact within a socio-technical system
(Geels, 2004). Social groups sharing rules that coordinate their activities can be recognized
as, for example, science regimes, socio-cultural regimes and user and market regimes. A
socio-technical regime is thus a combination of these different regimes which is visualized in
Figure 5 (Geels, 2004). It can also be seen in Figure 5 that the regimes included in the socio-
technical regime needs to be interrelated and be relevant for the socio-technical system. Thus,
the socio-technical regime does not include every existing regime, there needs to be some
kind of relation between them (Geels, 2004).

![Figure 5 A socio-technical regime (adopted from Geels, 2004, p.905)]
The regime level has its base in the elements of a socio-technical system and the social groups interacting in that system. The elements in a system are tangible and can be things such as market shares and infrastructure. These are important to describe to get an overview of the regime that is going to be analyzed (Geels, 2012). The difference between a system and a regime is that the concept of a regime adds intangible elements to this level of the framework and thus investigates the “deep structures” of a societal function (Geels, 2012, p.473). Intangible elements on regime level can, for example, be norms or developed practices for doing certain things. This further expands the analysis from only looking at the tangible elements in the system (Geels, 2012). The regime that this thesis will investigate is the Swedish electricity system and how supply and demand are balanced in that system, which is further described in chapter 3.

2.2.3 Landscape-Level

The landscape is the top part of the multi-level perspective framework and the regimes and niches are located within the landscape meaning that the landscape affects the dynamics of the niches and regimes (Geels, 2012). Geels (2002, p.1260) describes a socio-technical landscape as “an external structure or context for interactions of actors” and “beyond the direct influence of actors” (Geels, 2004, p.913). The landscape includes factors such as oil prices, emigration and environmental problems (Geels, 2002).

The landscape consists of technology-external factors that are considerably hard to change. It is possible to change the landscape, but changes on this level develop even more slowly than changes in the regimes (Geels, 2002).

2.2.4 The Dynamics of Change in a Multi-Level Perspective

The most important thing to understand with the multi-level perspective framework is that, for radical innovation to be able to move from the niche-level and reach the regime-level, it is dependent on the dynamics of all three levels in the framework (Geels, 2002). A good development for an innovation at the niche-level is thereby not enough for further success for the innovation. Kemp et al. (2001 p.277) describe this as: “it is the alignment of developments (successful processes within the niche reinforced by changes at regime level and at the level of the sociotechnical landscape) which determine if a regime shift will occur”. Geels (2012) has developed a model which illustrates the dynamics of change in a multi-level perspective and that model is shown in Figure 6.
The niche-level is mostly illustrated with small short arrows in Figure 6, the arrows indicate new radical innovations. Since the development of the radical innovation is unknown at an early stage, these arrows are small and point in all different directions (Geels, 2002). Some innovations can seem hopeful but it is hard to be successful. If a radical innovation gains momentum through, for example, an extensive social network with powerful actors, the innovation may reach dominant design. An innovation that has reached dominant design is illustrated with fatter arrows emerging from the small arrows at the niche-level (Geels, 2002).

On the regime level, Geels (2012) has illustrated several dimensions such as; technology, user preferences and markets. The horizontal arrows from these dimensions indicate incremental processes, and as seen in the figure, they are all linked together and co-evolve (Geels, 2012). Long horizontal arrows indicate stability in the regime and shorter arrows indicate instability.

Stability in the regime is created by factors that make the regime hard to change. That can be, for example, lock-in mechanisms and path dependence (Geels, 2002). An example of a lock-in mechanism is sunk investments and path dependence can be established user patterns that
make change more difficult. These types of factors make it hard for a radical innovation to reach the current regime (Geels, 2002). When the regime is stable it is thus mostly incremental developments that occur which entails small improvement on something that already exists (Tidd and Bessant, 2013).

Instability in the regime is factors that could open up for change and is caused by tensions in the regime (Geels, 2002). Tension may arise from changes on the landscape level, for example, concerns regarding climate change may cause tension in the current regime (Geels, 2002). Tension can also be created within the regime (Geels, 2002). It can be, for example, that user preferences have changed and the established technologies cannot meet these new preferences. The tensions will make the linkages in the regime weaker which causes the regime to be unstable (Geels, 2002).

When the regime is stable, it is extremely hard for a radical innovation in the niche to reach the regime. For a radical innovation, that has reached dominant design, to move from the niche to the regime a “window of opportunity” has to be created through tensions in the regime which has caused the regime to be unstable (Geels, 2002). The window of opportunity can be created either through internal dynamics or developments on the landscape causing the regime to be unstable (Geels, 2002). If a radical innovation manages to use this window of opportunity, the socio-technical regime will change (Geels, 2002).

A short summary of the sequence of events in the technical change can be divided into three steps (Geels, 2012):

1. Radical innovations build momentum and reach dominant design
2. Tension builds in the regime caused by changes in the landscape or due to internal dynamics within the regime
3. The regime gets unstable which creates a window of opportunity for the radical innovation to move from the niche-level and thereby change the regime

2.3 Application of theory

The theory presented in this chapter will be further utilized throughout the report. Firstly, in chapter 3, a simple model is constructed to present the societal function of the Swedish electricity system based on the socio-technical approach. The model is based on the three sub-functions in a socio-technical system as production, distribution and usage of artefacts. In the model constructed in chapter 3 these correspond to electricity production, electricity distribution and the usage of artefacts correspond to consumption (usage) of electricity. Trading of electricity is also included in the model since this is a vital part of the interaction between the three sub-functions. The last part of the model highlights the balance in the electricity system as this is the part of the societal function that is in focus for this study.
Further, the multi-level perspective is used as a sorting tool to map out the different factors affecting the demand for frequency control. In chapter 6.1 the identified factors from literature and interviews are mapped out on landscape and regime level according to the levels in the multi-level perspective. Factors on landscape level is thus factors that is hard for single actors to control and factors on regime level is factors that could be controlled by different actors within the regime. This categorization of factors is carried out to provide a well-structured overview of the current situation.

In chapter 6.2 the different resources that are possible to use for balancing supply and demand is presented. In this chapter the theoretical approach is used to analyze why a specific resource is used in the regime for balancing supply and demand, why the resource is not used in the regime or what possibilities there are that the resource could be used in the regime.

In chapter 6.3 the possible efforts that could be carried out on a local level is presented. In this section the theory is used to analyze the identified efforts as “niches” and the possibilities for the niche to reach the regime. Further for the analysis in this report, a radical innovation trying to reach the regime level will be referred to as a niche.
3 The Swedish Electricity System

This chapter will present an overview of the Swedish electricity system based on the socio-technical approach. The electricity system is presented according to the sub-functions of a socio-technical system which are production, distribution and usage of artifacts (which in this chapter corresponds to production, distribution and consumption of electricity). How electricity is traded is also presented in this chapter as it is closely connected to all of the three sub-functions. Lastly a description of how supply and demand are balanced is described as this is the focus of the study.

3.1 Production

The sources used for electricity production and the total amount produced in Sweden has varied through the years and in Figure 7 this development is visualized (Energimyndigheten, 2017).

![Electricity production in Sweden from 1970 - 2016](image)

The electricity production has gradually increased from 1970 until around 2000 when the total production has been relatively stable with slight variations. The total electricity production in 2016 was 152.3 TWh in Sweden (Energimyndigheten, 2017).

Figure 7 shows that hydropower has been an important resource for the Swedish electricity production for a long time and a large part of the hydropower capacity is located in the north of the country (Energiföretagen, 2017a). In 1970, hydropower produced almost all of the electricity and has through the years continued to contribute with a large part of the Swedish
electricity production. During the latest years, hydropower and nuclear power have together accounted for the largest part of the production and can be considered to be the two main sources. In 2016, hydropower and nuclear power together accounted for about 80 percent of the total production (Energimyndigheten, 2017).

The nuclear power plants are, unlike the hydropower plants, mostly located in the southern parts of Sweden (Energiföretagen, 2017b). There are, however, ongoing changes regarding the nuclear power plants. A large part of the nuclear power in Sweden is being decommissioned. In 2015 a press release announced that the two reactors Oskarshamn 1 and Oskarshamn 2 shall be closed by the year 2017 (Okg, 2015). It is further announced that Ringhals 1 and Ringhals 2 are going to be closed in 2019 and 2020 (Vattenfall, 2017). The combined capacity of these four reactors accounts for about 30 percent of the total installed nuclear capacity in Sweden (Byman, 2017).

Figure 7 presents mainly four sources used for electricity production, apart from nuclear and hydropower, the used sources are combined-heat and power (CHP), which uses biomass to produce heat and electricity, and wind power. During the last years, wind power is the source that has increased the most. In 2004 the electricity production from wind power was just 0.9 TWh and in 2016 this number has increased to 15.5 TWh (Energimyndigheten, 2017). This is a development that is likely to continue due to politically set targets of renewable electricity production. There are a lot of wind power plants being installed in Sweden, as an example, 213 new wind power plants were installed in 2015 (Energimyndigheten, 2017).

Apart from the four main sources presented in Figure 7, there is one additional source that should be discussed and that is solar power. It is a source that has increased during the last years, but so far electricity production from solar power is remarkably small. In 2015, solar power produced only 0.06% of the total electricity in Sweden (Energimyndigheten, 2017). Solar power is a renewable energy source and could increase even more but the main obstacle for using solar power in Sweden is that it is mostly available between Mars and October, and not during the winter when the demand is at its highest in Sweden (Byman, 2017).

### 3.2 Distribution

In Sweden, the electricity is transmitted through a large grid network that can be observed all over the country. The electricity grid system involves a total of 559,000 kilometers of transmission lines and one part of the lines are located above ground while another part is located underground (Brodin et al, 2016).

The electricity grid system is usually distinguished as three different parts; the national grid (also called the transmission grid), the regional grid and the local grid (Brodin et al, 2016). One substantial difference between these grids is the voltage. The national grid has a voltage of 400-220 kV, the regional grid 130-40 kV and the local grids 40-0.4 kV (SvK, 2014). The differences in voltage results in that the grids have different functions. The national grid
transmits electricity through the entire country for large distances and the overseas connections for import and export capacity are connected to the national grid (SvK, 2014). The regional grids are connected to the national grid and the local grids are in turn connected to the regional grids. Most of the consumers, such as households, are connected to the local grids but there are some large consumers, such as industries, that are directly connected to the regional grids (SvK, 2014).

The national grid is owned and operated by SvK. Since SvK is acting as the TSO in the Swedish system, they have the overall responsibility for the transmission system (SvK, 2014). The regional grids are mostly operated by larger utility companies such as Vattenfall and several larger production facilities are connected to the regional grids (Fritz, 2013). The local grids have many different owners but several of them are owned by companies connected to the local municipalities (Andreåsson et al, 2014). The production facilities connected to the local grids are usually just smaller facilities, such as single wind power plants (Fritz, 2013).

In order to be an electric transmission company, the company needs to have a certain permission. This permission is called “network concession”, and it is compulsory to hold this permission if a company wants to engage in electric transmission (Ei, 2018). The network concession is created to secure that the use of the electric transmission is safe and that the constructing of the electric cables do not damage animals or nature. There are two classifications, “network concession for line” and “network concession for region”. The first classification, network concession for line, is for single electric wire that affects the national and regional grid (Ei, 2018). The other classification, network concession for region, impacts the electric transmission in a certain local grid. It shall be mentioned that some electric wires are allowed to be built without the network concession, but only if they are not harmful to individuals or human settlement (Ei, 2018).

3.3 Trading

In 1996, there were large changes on the Swedish electricity market as the market was deregulated. This implies that the electricity is at this moment traded on an open market with several competing actors involved (Andreåsson et al, 2014). The reason that the deregulation was carried out was to open up for competition and thereby offer more alternatives to the consumers (Brodin et al, 2016).

The market for trading electricity is called NordPool. It is a market which includes the Nordic and the Baltic countries and thereby Sweden is part of a market that includes several different countries (Brodin et al, 2016). Nordpool runs mainly two markets for trading electricity and the difference between them is the time horizon of the trades (Nordpool, 2017a).

Most of the electricity is traded on a market that is called the “day-ahead market” or “Elspot” (Nordpool, 2017a). On this market, around 360 actors trade electricity and the majority trade
every day. On the day-ahead market, electricity is traded for the upcoming day and the price is set hourly. This market is based on planning by the traders of electricity (Nordpool, 2017a). The suppliers need to plan (forecast) the amount of electricity they will need to cover the demand for the upcoming day and at what price they want to purchase the electricity (Nordpool, 2017a). The same planning goes for the producers who need to forecast the amount electricity they can produce the following day and at what price they can offer their produced electricity. The planning by both the suppliers and producers are conducted hourly. At 12:00 CET before the upcoming day the market closes and all the bids from the producers and suppliers must have been submitted (Nordpool, 2017a). The price of the electricity is decided at the point where the supply and demand prices intersect, as shown in Figure 8.

![Figure 8](image)

**Figure 8** How the electricity price is set based on electricity source (adopted from Ei, 2014, p.2 and translated by the authors)

Figure 8 illustrates that different energy sources have different production costs. It can be seen that two energy sources with low production costs are wind power and hydropower and they are the sources that are first used to meet the demand (Ei, 2014). If the demand is higher, more expensive production facilities with higher production costs, like nuclear and CHP, are used to meet the demand. A higher demand thereby makes the production more expensive and the price of electricity will be higher. Production costs vary between the facilities due to factors such as fuel costs and taxes (Ei, 2014).

The price of electricity in Sweden can be different depending on location since the market has been split into sub-markets called bidding areas or spot-price areas (Brodin et al, 2016). Figure 9 shows the different bidding areas in the Nordic-Baltic market. It can be seen that Sweden is divided into four areas, Norway in five areas and Finland in just one area.
The electricity price within each bidding area is uniform and is decided by the amount of electricity that is produced and the demand for electricity inside the specific area. An additional factor that affects the price is the ability to transmit electricity from other bidding areas (Brodin et al., 2016). The reason for this market split is to avoid bottlenecks when a large amount of electricity needs to be transmitted from one area to another. In Sweden, this is a rather usual situation since there is a large production capacity (mainly from hydropower) in the north which implies that the produced electricity needs to be transmitted to the southern areas while there is a limited transmission capacity (Brodin et al., 2016). This reflects on the price since the price variations are mostly occurring between the two northern areas compared to the two southern areas. Despite this, the price in all four areas was the same in 86 percent of the time in 2015 and that is usually the case when the demand is low (Brodin et al., 2016).

Apart from the day-ahead market, Nordpool has established an additional market called the “intra-day market” or “elbas” (Nordpool, 2017b). The intra-day market works as a complement to the day-ahead market and is used to handle deviations in the planning by the producers and suppliers. Different types of deviations can occur from the forecasted values, both on the production side and the supply side (Nordpool, 2017b). Examples are lower wind
speeds or a colder outdoor temperature than expected. The intraday market gives the actors a chance to correct their inaccurate forecasts before delivery of the traded amount on the day-ahead market as it gives the actors a chance to trade closer to real-time (NordPool, 2017b). Every bid needs to have a volume of at least 0.1 MW and the trade is conducted bilateral, meaning that the trades are conducted directly between the actors as they find matching bids for their new forecasts (Linnarsson et al., 2014). Most of the electricity that is traded on Nordpools markets is, however, traded at Elspot (Linnarsson et al., 2014).

3.4 Consumption

The last part of the electricity system is to consume the electricity. The electricity consumption in Sweden has varied throughout the years both in terms of how it has been consumed and how much that has been consumed (Energimyndigheten, 2017). Figure 10 is visualizing this development by showing the amount consumed by each sector from 1970 to 2016.

One trend that can be spotted in Figure 10 is that the electricity consumption has gradually decreased since 2001. This is something that differs from the production as that has stayed relatively stable during those years. In numbers, the total electricity consumption in Sweden 2016 was 140 TWh (Energimyndigheten, 2017).

The two sectors that have consumed most electricity through the years are the industry and the residential sector. The residential sector is the one that has increased most since 1970 and a part of that is the growth in population (Energimyndigheten, 2017). There are mainly three
other sectors, apart from industry and households, that consume electricity and those are distribution losses, district heating and transport. Distribution losses have increased but that is not really a form of consumption, it is just losses in the system. The transport sector has contributed with a small part of the consumption through the years and that number has stayed relatively stable. This is, however, a sector that may have large changes in the near future with the increasing popularity of electrical vehicles (Hadley and Tsvetkova, 2008).

Figure 10 shows that there is some variation in consumption between the years and that can be due to factors such as outdoor temperature, strength of the Swedish industry and economic or technological developments (Energimyndigheten, 2017).

3.5 Balancing Supply and Demand

The concept of balancing supply and demand in an electricity system was briefly described in section 1.1. For an electricity system to be well-functioning, there has to be a constant balance between supply and demand (SvK, 2015a). The balance is measured by measuring the frequency in the system. In the Nordic system, a frequency at 50 Hz, indicates a perfect balance. There will, however, always be small deviations in the frequency, it has thereby been decided that when the frequency is within the interval of 49.9 and 50.1 Hz, the situation is defined as “normal” (SvK, 2016a). When the frequency falls out of that interval, the situation is defined as “disturbed” (SvK, 2016a). In 2017 there was a goal of having a disturbed situation during a maximum of 10 000 minutes (SvK, 2018b). However, this goal was not reached in 2017 as the frequency was outside the allowed interval for 11 956 minutes (SvK, 2018b). In numbers, a deviation of 0.1 Hz from a perfect balance (50 Hz) is equivalent to a combined imbalance of about 600 MW in the entire system (SvK, 2015a).

As the TSO, SvK has the utmost responsibility that the electricity system is well-functioning and this includes balancing supply and demand in Sweden. SvK can, however, assign different tasks to other actors on the electricity market to facilitate a well-functioning system. One example of this is the “balance agreement” contract between suppliers of electricity and SvK (SvK, 2016b). Every supplier of electricity has a responsibility to make sure that they can balance the amount of electricity that their customers consume. This is called being a “balance provider” (SvK, 2016b). The supplying company can act as the balance provider themselves or hire a company to act as the balance provider for them. In both cases, the company acting as a balance provider has to sign a “balance agreement” contract with SvK (SvK, 2016b). The agreement makes the balance provider obliged to hourly balance the demand of the consumers in the area where the balance provider is supplying the electricity. This is, mostly, executed through trades at Nordpools markets, Elspot and Elbas, where the supplying company forecasts the hourly demand of their customers and trades to balance this demand (NEPP, 2016). If a company that has signed a balance agreement contract with SvK fails to be in balance, they have to economically compensate SvK what it costs them to correct their imbalance (SvK, 2016b). This system gives the balance providers economical incitements to keep their balance as well as they possibly can.
The remaining balance that the balance providers do not manage to keep is handled by SvK (SvK, 2016b). SvK does not possess resources themselves to handle the imbalances instead they purchase these resources from different companies that can contribute with available power. It is mostly power from the producing companies and from large hydropower plants but it also exists resources from consumers that can change their consumption (SvK, 2016a). These resources are divided into three different reserves called: the primary, secondary and tertiary control (SvK, 2016a).

3.5.1 Primary Control

The primary control acts as a base for the frequency control system and this system includes the first resources that are used to handle deviations (SvK, 2016a). The primary control consists of balancing resources that are equipped with control systems that can detect deviations in the frequency momentarily during the entire day (SvK, 2016a). When a deviation is detected, the system automatically activates the balancing resource to stabilize the frequency and it can react to changes within seconds. The balancing resources connected to the primary control are mainly hydropower plants which increase or decrease their production (SvK, 2016a). The objective of the primary control is not to bring the frequency back to 50.00 Hz exactly, but instead to mitigate the deviations (SvK, 2016a).

The balancing resources connected to the primary control are purchased in advance by SvK, usually one or two days before the day of operation. The primary control consists of two systems called (SvK, 2016c):

1. FCR-N (Frequency Containment Reserve – Normal)
2. FCR-D (Frequency Containment Reserve – Disturbance)

FCR-N is activated for minor deviations in the frequency while it is still within the limits of 49.9 and 50.1 Hz (SvK, 2016c). The demands for a balancing resource to be part of FCR-N is a minimum of 0.1 MW, it should be able to handle deviations above and under 50 Hz, 63 % of the capacity of the resource should be able to be activated within 60 seconds and a 100 % within three minutes and the resource needs to be equipped with real-time measurement devices (SvK, 2016c).

FCR-D is activated for larger deviations when the frequency falls out of the permitted limits (SvK, 2016c). The demands for a balancing resource to be part of FCR-D is a minimum of 0.1 MW, 50 % of the capacity of the resource should be able to be activated within 5 seconds and a 100 % within 30 seconds and the resource needs to be equipped with real-time measurement devices (SvK, 2016c).

3.5.2 Secondary Control

The secondary control is, like the primary control, balancing resources equipped with control systems to automatically handle deviations in the frequency. The main task for the primary
control is to mitigate the deviation and the secondary control has the task to bring the frequency back to 50.00 Hz (SvK, 2016a). The secondary control consists of just one system called (SvK, 2016a):

1. aFRR (Automatic Frequency Restoration Reserve)

The demands for a balancing resource to be part of the aFRR are a minimum of 5 MW and a full activation within 120 seconds (SvK, 2016c).

3.5.3 Tertiary Control

The last part of the balancing resources provided by SvK is called tertiary control and apart from the first two systems, the tertiary control is handled manually (SvK, 2016a). These resources are sometimes called mFRR (Manual Frequency Restoration Reserve) (SvK, 2016a). The reserves included in the tertiary control are:

1. Reglerkraftmarknaden (RKM)
2. Störningsreserven
3. Effektreserven

RKM is a market where SvK trade power to manually control the frequency (SvK, 2016a). SvK takes in bids from actors both from the production side and the consumption side. A bid on RKM has to include source (for example, hydro or wind power), volume (MW), price (SEK/MWh) and how fast it can be activated (Linnarsson et al., 2014). The volume has to be at least 10 MW in Sweden except for SE4 (the southernmost part) where the minimum is at least 5 MW and the activation time has to be at most 15 minutes (Linnarsson et al., 2014). An actor can change the bid until 45 minutes before delivery and after that the bid is economically obligated.

The other two systems act as reserves for more extreme events. The power in Störningsreserven is purchased through multi-year contracts and this reserve is activated manually when there are major disturbances in the system (SvK, 2016d). Examples could be that large amounts of electricity are lost due to issues with the national grid. Störningsreserven mainly consists of gas turbines that can be activated in a short period of time and they can reach full production within 15 minutes. It also consists of contracts with large consumers that can change their consumption of electricity within 15 minutes (SvK, 2016d).

Effektreserven is a reserve to handle large peaks in demand during the winter and has to be available between 16 November to 15 Mars (SvK, 2016e). SvK is compelled by Swedish law lag (2003:436) om effektreserv to have a power reserve called effektreserven. The reserve has to include both agreements with producing companies to contribute with production capacity and agreements of changed consumption from consumers (Sveriges Riksdag, 2017a). Swedish law lag (2016:423) om effektreserv specifies that at least 25 % of the reserve has to
consists of agreements of changed consumption and during winter time 2017 the reserve could be at most 1000 MW (Sveriges Riksdag, 2017b).

3.5.4 Disconnect Power

In cases when the frequency in the system has extreme deviations, there is a possibility to disconnect the supply of electricity in some parts the Swedish electricity system to save the grid system and thereby restrict the extension of a power failure (SvK, 2017). By disconnecting a small part of the system, the rest of the system may remain intact and it will also make it faster to regain a normal electricity system (SvK, 2016f). The Swedish electricity law gives SvK the authority to determine if grid owners should disconnect the electricity supply. The most common reasons that there occur extreme deviations in the frequency are the primary control is malfunctioning or that there are not enough resources in the reserve systems and mainly in störningsreserven (SvK, 2017).

The disconnection can either be handled manually called “manuell förbrukningsfrånkoppling” (MFK) or automatically called “automatisk förbrukningsfrånkoppling” (AFK) (SvK, 2016f). The MFK is used for situations when there is a very high electricity consumption, for example, due to cold weather conditions and it is not possible to meet the demand. If this situation occurs, specific regional grid owners should be able to do a MFK within 15 minutes (SvK, 2016f). MFK is done by disconnecting the power in one region for a certain time and thereafter disconnect another area.

AFK can be utilized when the regular power plants malfunction or must be disconnected. The AFK is a much more rapid process compared to the MFK, and it reacts within just a few seconds (SvK, 2016f). Furthermore, AFK is activated directly (and automatically) as the frequency drops below 48.8 Hz (SvK, 2016f). Currently, MFK has never been used in Sweden and AFK has only been utilized a few times (SvK, 2016f).

In case of power shortage situation, the Swedish energy agency has developed certain methods were the electricity can be directed to specific electricity users. This is called "Styrel", and the intention is that key functions in the society can operate even if there is a power shortage situation (SvK, 2016f). It is the country administrative board together with the municipalities and the grid owners that organize and plan the "Styrel", and that is the information SvK uses to decide if a disconnection is needed (SvK, 2016f). Thus, it is not SvK that decides who is going to be disconnected, but only if a disconnection is necessary. It shall be mentioned that when the power is reconnected, it is a complicated process that is gradual and can last for several hours. It is SvK that has the overall responsibility for the reconnection on a national level, and it is the grid owners together with SvK that have the responsibility on a regional and local level (SvK, 2016f).
4 European Outlook

*Integrating intermittent energy sources into the grid system is something that is occurring worldwide and not only in Sweden. This chapter will, thus, present a short outlook of the development in three other countries in Europe and what issues they are experiencing. The selected countries are Germany, Norway and Denmark.*

4.1 Germany

Germany has been included in this outlook as it is a country that is undergoing a similar development of its electricity generation as Sweden. Renewable energy sources are subsidized by the government and all of its nuclear power capacity is planned to be decommissioned by the year 2022 (SvK, 2015a). The renewable energy sources Germany is using are mostly wind and solar power plants and this has, as for Sweden, lead to issues with the operation of the grid network (SvK, 2015a). The long term goal for Germany is that 80 percent of the electricity should be generated by renewable energy sources by the year 2050 (TransnetBW, 2018). This goal is an indication that the integration of intermittent energy sources in the grid will continue to increase and thus also the challenges for the balance in the grid.

Unlike Sweden, where SvK is the only TSO in the system, there are four TSO’s in Germany. The four TSO’s are collaborating under something called “Grid Control Cooperation” (GCC) regarding the balance in the transmission system (50Hertz, 2018). This cooperation has been successful since instead of balancing their own areas separately they are now benefiting from each other which have decreased the total volume needed for regulating power in the country (50Hz, 2018).

However, one balancing issue that is occurring in Germany is that most of its solar power plants are located in the south of the country and the wind power plants are mostly located in the north. This brings several challenges for the transmission system as this power needs to be transmitted to the rest of the country (SvK, 2015a). During days when there are good weather conditions for solar and wind power the maximum transmission capacity for the internal transmission network in Germany is reached and internal bottlenecks are created. To handle this, Germany transmits electricity to the grid systems of the neighboring countries (SvK, 2015a). This is disadvantageous as the import and export capacity for Germany is affected since import and export must be planned to handle the internal bottlenecks in the system (SvK, 2015a).
4.2 Norway

Norway has been selected in this outlook section since the world development of intermittent energy sources has not been applied much in Norway, even if they have good conditions for wind power plants, i.e. high wind speeds, along their coastlines (SvK, 2015a). Due to Norway's geographical conditions (high elevation and many fjords), it is suitable to use hydropower, which is another energy source that is considered to be renewable, for electricity production. In 2016, more than 96 percent of the electricity production in Norway was from hydropower plants (Ssb, 2017). Since almost all of the production comes from hydropower, Norway does not experience the same issues, with balancing intermittent energy sources, as many other countries do (SvK, 2015a).

The frequency in the electricity system is, however, the same in the entire Nordics. The capacity from the Norwegian hydropower plants is thereby used to regulate the intermittent energy sources in the other Nordic countries (SvK, 2015a). The Norwegian TSO, Stattenet, is currently planning to build overseas transmission lines from Norway to the UK and Germany so that their regulating capacity can reach those markets (SvK, 2015a). The Norwegian hydropower has started to be referred to as the battery of Europe, as it will be used to balance the intermittent energy sources in several European countries. This is a negative development for the Nordic system as a large part of the regulating resource will be transmitted to other European countries instead of to the Nordic system (SvK, 2015a).

4.3 Denmark

Denmark has been selected in this outlook due to it is a country that has integrated a large portion of intermittent energy sources in their electricity production and they are struggling to balance these sources. Denmark is well known for its deployment of wind power plants in their electricity generation. This is reflected in the statistics as 33 percent of the total electricity production in 2012 came from wind power and this is expected to be as much as 51 percent in the year 2020 (SvK, 2015a).

The TSO in Denmark is called Energinet and has the overall responsibility for the electricity transmission system (Energinet, 2018). Denmark’s electricity system is divided into two parts, “West Denmark” (DK1) and “East Denmark” (DK2) (Danish Energy Agency, 2015). DK1 and DK2 are linked together, however DK1 belongs to the European continental system and DK2 belongs to the Nordic system (Danish Energy Agency, 2015).

The geographical conditions in Denmark are very different compared to Norway and Sweden even if they are neighboring countries. Denmark has a very low elevation, where the highest natural point lays only around 170 meters above the sea level. Due to this geographical conditions, there are only a few and very small hydropower plants installed in Denmark and instead it is wind power that is one of the main sources for electricity (SvK, 2015a). Since a large part of its electricity production comes from an intermittent energy source, Denmark is
struggling to balance the production and consumption on its own. Instead, they are strongly dependent on transmission possibilities so that the Swedish and Norwegian hydropower can level out the imbalances (SvK, 2015a). Denmark has some CHP plants that facilitate the regulation of frequency (Danish Energy Agency, 2015), however they are still very dependent on foreign transmission possibilities as mentioned above.

Denmark is, like Germany, struggling during weather conditions when they produce high amounts of electricity. There have occurred situations in Denmark when the price of electricity is negative (SvK, 2015a). This means that the consumers get paid for using electricity and instead of earning money on their production, the producers have to pay for producing electricity. SvK (2015a) has concluded that the situation of negative prices for electricity is a clear signal that Denmark is not able to balance its intermittent sources, instead they are relying on the capacity of neighboring countries to take care of their problems. If more countries adopt the same strategy as Denmark and, to a certain extent also Germany, to rely on other countries to solve their balance, there will be massive issues for several European countries in the future (SvK, 2015a).
5 Methodology

This chapter presents the research approach and methods that have been used for data collection in the thesis. It also reflects upon the quality of the gathered material and critically evaluates the sources of material that have been used in the thesis.

5.1 Research Approach

The purpose of this report is to investigate the demand for frequency control in the Swedish electricity system and what could facilitate a better balance in the system. To fulfill this purpose a qualitative research approach has been adopted. A qualitative approach is suitable since it tries to capture real or perceived experiences (Williams, 2007). Further, a qualitative approach enables to investigate real problems in the social world, and it answers on "how things work in particular contexts" (Mason, 2002, p.1). It also allows to find "cross-contextual generalities", and explores the complex relations between social processes (Mason, 2002). The reason why this thesis has chosen a qualitative approach instead of a quantitative approach is, thus, because it yields deeper and more detailed knowledge which is suitable to fulfill the purpose and answer the research questions (Williams, 2007).

The thesis has also adopted an inductive approach, where theory has been used to get a deeper knowledge regarding the results and findings (Blomkvist and Hallin, 2015). According to Thomas (2006, p.238), an inductive approach can be described as “the researcher begins with an area of study and allows the theory to emerge from the data”. The inductive approach is suitable for qualitative studies. The advantage of this approach is that it allows the investigator to create and change the theory underway, without being restrained by earlier formally made up theses (Thomas, 2006). Therefore, the theoretical framework used in this thesis has emerged from the findings and from the empirical data. It is the empirical data that has influenced the choice of framework in this study.

Finally, the thesis has followed an iterative process which means that the material has been assessed several times (Kekeya, 2016). This entails, for example, that the background, the purpose and the research questions have been revised when new knowledge was yielded.

5.2 Case Study

To explore the purpose and research questions in this thesis a case study of the Swedish electricity system has been applied. The findings in terms of the investigated demand and what balancing efforts that can be carried out on a local level are, thus, based on the case of the Swedish electricity system.

According to Zainal (2007 p.2), a case study can be defined as “an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of
evidence are used”. Furthermore, Blomkvist and Hallin (2015) state that a case study allows to collect material when investigating complex problems. By investigating the demand for frequency control and what balancing efforts that can be carried out on a local level, the thesis tries to explore new areas which suits a case study approach (Blomkvist and Hallin, 2015). In addition, the thesis investigates a real-life phenomenon, and a case study approach enables to explode key variables (Blomkvist and Hallin, 2015). According to Crowe et al. (2011) a case study can capture information in “how”, “why” and “what” questions. Since all four research questions in the thesis starts with what it further proves that a case study approach is suitable.

5.3 Data Gathering

The collected data for this study contains previous research and literature, which has been reviewed and analyzed. Furthermore, data has also been gathered through semi-structured interviews. Below, the data gathering process is further described.

5.3.1 Pre-Study

A pre-study was done to get an overview of the studied phenomenon to give an insight of the balance between supply and demand of electricity and the need for frequency regulation in an electricity system. The pre-study only served as an introduction to the thesis and facilitated to get a broader understanding of the problem as well as to break the investigation into more concise parts. The information gathered to the pre-study contains reviewed literature, such as academic papers and articles. Also, attending lectures at KTH about how hydropower is used for regulating purposes gave relevant information to the pre-study. This part of the thesis also contains meetings/unstructured interviews with the commissioner and the supervisor at KTH to yield more knowledge relevant to the study.

5.3.2 Literature Review

To get a deep understanding and knowledge of the subject regarding the thesis, a literature review was done. The review consisted of searches in databases, such as KTHB Primo, ScienceDirect and Google Scholar. These databases can be regarded as trustworthy because the content is thoroughly reviewed and assessed. Furthermore, the literature in the thesis is articles and publications from the Swedish government and operators on the electricity market. Also, data and numerical values have been collected from different energy agencies such as the Swedish energy agency that provides that types of statistics.

The literature review includes mainly information about the Swedish electricity system and how to balance supply and demand. The review of the Swedish electricity system has focused on four aspects: production, distribution, trading and consumption. Regarding the balance of supply and demand, literature about primary, secondary and tertiary control has been reviewed. Furthermore, literature about what factors affecting the demand for frequency control and what resources that can be used to control the frequency have been reviewed.
5.3.3 Semi-Structured Interviews

In addition to the literature review, semi-structured interviews were conducted to collect empirical material and serve as the main primary source in this thesis. Semi-structured interviews were regarded suitable to the thesis because it allows to “gather systematic information about a set of central topics, while also allowing some exploration when new issues or topics emerge” (Wilson, 2014, p.24). This type of interviews also enables to collect information on complex problems (Wilson, 2014). The interviewees were selected after their knowledge about the Swedish electricity system and frequency control. To get a broader view and different perspectives, interviews with both senior managers and junior employees were conducted. Since SvK has the overall responsibility for the frequency control, it has been of the utmost importance to find interviewees within this company. In addition, interviews with researchers at KTH and other companies like Fortum have been conducted to get more opinions and more knowledge. Also, two former managers were interviewed due to that they both have had long careers within the energy sector and have a lot of knowledge regarding these questions. Before questions were asked in the interviews, the interviewees were informed about the purpose of the thesis and how the gathered material would be utilized. The interviews have followed the ethical codes and the four principal requirements provided by the Swedish Research Council (Blomkvist and Hallin, 2015). The four requirements and how these have been analyzed are discussed below:

- **The information requirement:** All the interviewees have been informed what the purpose of the investigation is about.
- **The consent requirement:** Everyone involved in the study have agreed to be studied. Everybody has voluntary participated and no one has been forced to be interviewed or to answer questions.
- **The confidentiality requirement:** The gathered material has been handled carefully. The interviewees names have been treated confidentially if they not voluntary wanted to be mentioned in the investigation.
- **The good use requirement:** Before every interview, the interviewee was informed about the study, what type of questions that were going to be asked and how the material would be handled. The gathered material was only used for the purpose that was stated before the interview.

During the interviews, some answers were written down and the interviews were also recorded if consent to record where given. Furthermore, the interviews were conducted in Swedish and then translated into English. In addition, the interviewee answers have been interpreted literally. Tone of voice and body language that could affect the interpretation, are perceived in a subjective way and must therefore be taken out of consideration. Table 1 below presents the conducted interviews. Due to confidentiality, the interviewees names are not mentioned. Furthermore, some of the interviews were conducted with face to face meetings while some other interviews were conducted by telephone.
Table 1 Interviewees in the study

<table>
<thead>
<tr>
<th>Interviewee/Title</th>
<th>Organization</th>
<th>Date of interview</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power system analyst</td>
<td>SvK</td>
<td>2018-03-29</td>
<td>90</td>
</tr>
<tr>
<td>Operations manager</td>
<td>SvK</td>
<td>2018-03-29</td>
<td>70</td>
</tr>
<tr>
<td>Senior power system analyst and part time researcher</td>
<td>SvK/KTH</td>
<td>2018-04-05</td>
<td>50</td>
</tr>
<tr>
<td>Former Manager</td>
<td>Växjö Energi</td>
<td>2018-04-13</td>
<td>30</td>
</tr>
<tr>
<td>Former Manager</td>
<td>SvK</td>
<td>2018-04-16</td>
<td>40</td>
</tr>
<tr>
<td>Senior Advisor R&amp;D</td>
<td>Fortum</td>
<td>2018-04-17</td>
<td>45</td>
</tr>
</tbody>
</table>

5.4 Research Quality

The research quality has an impact on the credibility of the thesis. Three factors that will have an impact on the data quality is the validity, reliability and the generalizability (Saunders et al., 2009). Apart from these three factors, this section will also provide a discussion on source criticism for the sources used in the study.

5.4.1 Validity

According to Blomkvist and Hallin (2015), validity is to study the right thing. This means that one should use literature, theories and other gathered material that are relevant to fulfill the purpose and answer the research questions posed in the study. To ensure that the gathered material through interviews can be considered valid to the study the interviewees have been selected based on their knowledge about the investigated phenomenon. Since SvK has the utmost responsibility for the electricity system and that supply and demand is balanced in Sweden several employees from this organization has been interviewed. Other actors from the electricity sector have also been interviewed based on their relevance for the study. The purpose of the study and several of the questions were sent beforehand to the interviewees to ensure that they could provide valid information that is aligned with the purpose of the study.

Validity is also about if findings (or information) are legit, accurate and if it really is credible (Saunders et al., 2009; George et al., 2003). By using a triangulation method (using at least two theories or literature to verify the authenticity) and collect empirics from several sources promotes the validity (Yeasmin and Rahman, 2012). Finally, the validity related the literature
that has been used in this thesis is regarded high since it is publicized from trustworthy databases and agencies.

5.4.2 Reliability
Reliability is, according to Blomkvist and Hallin (2015), that one studies the right things decently. This entails approaching theories and interviews in a suitable and a correct manner (Blomkvist and Hallin, 2015). Saunders et al. (2009), argues that reliability also relates to if a study yields the same result even though the study is conducted several times, and if the same result can be achieved by others. One identified issue with reliability in this research design is that by conducting qualitative interviews, it may be difficult to get the same answers continuously. The answers from the interviewee may alter due to, for example, mood and if more knowledge is obtained between several interviews. Another issue regarding qualitative interviews is that the answers may be interpreted differently from person to person, which also can make it more difficult to yield the same results repeatedly. The reliability relating to the literature review can be considered decent since the same articles and statistics used in this thesis can be studied and utilized repeatedly. It is also worth to mention that articles and statistics may be interpreted differently, which will have an impact on the reliability.

5.4.3 Generalizability
Generalizability is “whether your findings may be equally applicable to other research settings, such as other organizations” (Saunders et al., 2009, p.158). The chosen research design in this thesis is a case study which could have a negative impact and lower the generalizability. A case study will never lead to any statistical generalizability and the findings in one case may be hard to exercise on alternative cases (Blomkvist and Hallin, 2015). The case study will instead yield analytical generalizability which implies that the findings can be discussed for how they could be appropriate for other settings (Blomkvist and Hallin, 2015).

Furthermore, due to the chosen research design, a qualitative study directed towards the Swedish electricity system, it may be hard to generalize it on other foreign markets. Other countries may have different rules, policies or infrastructure for their electricity system compared to Sweden. One specific example is that another country may not have the infrastructure of national, regional and local grids. In such cases, it would be hard to generalize the results regarding what can be carried out on a local level. The results regarding what resources that could be used, for example that household consumers could be used as a balancing resource, is an example of a result that would be easier to generalize as it is not dependent on the infrastructure to the same extent.

5.4.4 Source Criticism
An essential part of scientific research is to work with source criticism as it is a method for evaluating the reliability of the utilized sources in the research. In this research, the sources
have been categorized as primary or secondary sources and it is important that sources in both of these categories are critically evaluated and analyzed (Blomkvist and Hallin, 2015). A method to perform this evaluation of the sources is to analyze them with the source evaluation and criticism framework presented by Blomkvist and Hallin (2015) which consists of the following four parts:

1. Authenticity: Is the author trustworthy? Is it an expert? Can the information be verified by someone else?
2. Proximity and dependence: Is it based on firsthand information? Is it based on other sources?
3. Tendency: Does the source tend to be partial and present the information in a specific way? Do financial and political factors affect the assessment of the source?
4. Representativity: Does the material represent the phenomenon that is studied? Is the information equivalent to other sources?

Primary sources have been collected through interviews and these sources have been evaluated by the above-mentioned framework. The first, second and fourth part of the evaluation framework has been addressed by conducting interviews with different stakeholders, experts and employees with dissimilar positions. Conducting interviews with several stakeholders have also aided to verify the authenticity of their answers. When it comes to evaluating primary sources, and in particular interviews, partiality is very important to consider. As the interviewees may adjust their answers to their advantage, a triangulation method has been used. Reviewed literature and material from different sources has been triangulated with the information provided by the interviews to ensure an unbiased investigation (Yeasmin and Rahman, 2012).

As described in the literature review, secondary sources have been collected from trustworthy databases. Despite this, the secondary sources have been evaluated with the source evaluation and criticism framework to further ensure that they are reliable sources. While part one, two and four is quite straightforward to assess (the reference list provides a lot of information), part three may be more difficult to evaluate. It is not always easy to detect if there is some underlying meaning or partial information. However, this issue has been mitigated by combining and scrutinizing several secondary sources to confirm the legitimacy.
6 Results and Analysis

This chapter will present and analyze the results that the thesis has yielded and is based on literature and empirics gathered from interviews. The results are presented and structured according to the research questions posed in the introduction chapter. Firstly the identified factors affecting the demand for frequency control are presented followed by the possible resources that can be used to control the frequency. Lastly the identified balancing efforts that can be carried out on a local level are presented.

6.1 Identified Factors Affecting the Demand for Frequency Control

This section will present and analyze the results from the first research question; the underlying factors affecting the demand for frequency control in the Swedish electricity system. The factors are retrieved from literature and interviews and are mapped out on landscape and regime level according to the theoretical framework, the multi-level perspective presented in chapter 2.

6.1.1 Factors on Landscape-Level

The first identified factor on landscape level is an increasing use of intermittent energy sources. An increased awareness of climate change has forced the entire energy sector to undergo massive changes. Due to the increasing interest to reduce harmful emissions, governments have developed targets such as that a large part of the electricity should be produced from renewable energy sources. In Sweden, the two renewable intermittent energy sources that are currently being used are wind and solar power. This factor is located on the landscape level since an increasing usage of renewable energy sources is closely related to climate change, which is a factor that is beyond the control of actors.

An increasing usage of wind power is affecting the frequency control mainly because of its intermittent character, meaning that the production is highly dependent on weather conditions (SvK, 2015a). The weather conditions are hard to forecast, especially in time horizons that are longer than 24 hours, which leads to issues for the producers to decide how much electricity they can produce (SvK, 2015a). This volatile and unpredictable production causes an imbalance in the electricity system and thereby affects the frequency. As seen in section 3.1, the wind power production has increased a lot during the last decade and in 2016 the total production from wind was 15.5 TWh. This is likely to increase even more due to factors such as politically set targets. In future scenarios developed by both SvK and Energimyndigheten, the wind power production increases both in long term and short term (SvK, 2015b; Energimyndigheten et al., 2016).

Another renewable energy source that is also intermittent but that is not discussed as much as wind power, but is also increasing, is solar power (Brodin et al., 2016). In the same way as the wind power is dependent on wind speeds is the solar power dependent on sunlight and the
weather forecasts for these are just as hard (SvK, 2015a). As described in section 3.1, the production from solar power is today extremely small but has still increased during the last years. The production from solar power is not expected to increase as much as the wind power production in Sweden. This is because most of the power is available between March and October and that is when the demand is at its lowest (Byman, 2017). Despite this, it is still a factor on the production side that affects the balance in the system and thus affects the demand for frequency control (SvK, 2015a).

Another factor on the landscape level that affects the demand for frequency control is a trend discussed in section 3.1 as the decommissioning of nuclear power in Sweden. This is not a trend only in Sweden, it is a development that is occurring worldwide, with a few exceptions like Finland who is currently constructing more nuclear power plants (Statnett et al, 2016). According to the World Nuclear Association (2018), the most frequently occurring reason for the shutdown is that the power plants are no longer economically profitable and another considerable factor is safety concerns. This factor is located on the landscape level since the fact that a technology is no longer economically profitable and that there are safety concerns with the technology is factors that cannot be controlled by single actors.

For many years, a large part of the demand for electricity in Sweden has been produced from nuclear and hydropower, these two sources have served as a base for the electricity production. The decommissioning of nuclear power will force the hydropower to cover larger parts of the base production (NEPP, 2016; Energimyndigheten et al., 2016). This affects the capability to control the frequency as larger parts of the capacity from hydropower has to be used to produce electricity. The reason that hydropower has been such a good balancing resource is that nuclear power has covered a large part of the base demand, and has by that freed up capacity from the hydropower to be used as a balancing resource (NEPP, 2016). This development will increase the demand for frequency control as the conventional resource used for that purpose, i.e. the hydropower, will be needed to cover other types of demands.

6.1.2 Factors on Regime-Level

One factor on regime level that affects the demand for frequency control is the current market design for trading electricity. This factor is located on the regime level since the market design is a factor that can be affected by actions of certain actors. In the current market design (described in section 3.3) the electricity price is set by the hour as the producers and suppliers trade electricity at Nordpool based on hourly forecasts. This implies that the production facilities may change the produced amount heavily, between different hours of the day, to meet the amount that has been traded at Nordpool. The consumption, on the other hand, increases or decreases more slowly and varies during the hour. Thus, the consumption does not “jump” to the new demand at the start of a new hour, like the production does (SvK, 2015c). This market design thereby creates large balancing issues around the hour shifts (SvK, 2015c). SvK (2015c) has concluded that about 45 percent of the total frequency
deviations in 2014 occurred during hour shifts. During this investigation, a senior analyst at SvK, has explained that there are ongoing discussions to change this market design. The ongoing discussion is to change the trading period from having hourly trades to instead trade every 15 minutes. The senior analyst at SvK argues that since almost half of the deviations are connected to the market design, this development would have a large impact and thus decrease the demand for frequency control. This is, however, not a solution that will solve all the balancing issues regarding how the electricity is traded. There will be a “jump” in the production facilities at the start of every trading period. It is, however, argued by the senior analyst at SvK that the jump in production will be lower with trades every 15 minutes instead of hourly trades.

A second factor is the increased overseas grid connections. Transmission capacity is a factor located on the regime level since decisions regarding overseas as well as domestic transmission possibilities can be affected by specific actors. SvK (2015a) has concluded that the issues around hour shifts caused by the market design are further enhanced due to the increase in import and export capacity. Overseas transmission capacity is, for the market overall a good thing, since it allows for transmission of electricity from high production areas to low production areas. A disadvantage is that it increases the complexity of the system and the power direction can quickly turn from one side to the other (SvK, 2015a). The overseas transmissions do not consider the frequency in the system when they deliver the traded amount of electricity. During hour shifts, large amounts of electricity are transmitted overseas as it has been traded at Nordpool, which enhances the imbalances in the system at those moments (SvK, 2015a). The import/export capacity is a factor that is likely to increase in the future as there are several connections under construction at the moment (Statnett et al, 2016). One example of an ongoing construction is a transmission line from Norway to the UK which will affect the entire Nordic system.

A third factor, briefly mentioned in section 4.2, is that the Norwegian hydropower capacity will be used to cover balancing demands on other markets than the Nordic market. Norway is currently increasing its import and export capacity by building transmission lines to the UK as well as to Germany (SvK, 2015a). This will affect the Nordic system, and thereby Sweden, negatively as the Norwegian resources, that are used to a large extent today to level out imbalances in the Nordic system, will instead be transmitted to other markets (SvK, 2015a). This is thus a factor that will increase the demand for frequency control for Sweden.

A fourth factor on regime level is the limited transmission possibilities to the south of Sweden as there is a lack of regulating resources there. The regulating resources can be transmitted through the entire system, meaning that it can be from different countries as well as from different parts of Sweden (SvK, 2015c). The transmission capacity is however limited, both overseas and domestically. Most of the regulating resources in Sweden are located in the north (in SE1 and SE2) meaning that the southern parts of Sweden (SE3 and SE4) are, to a large extent, dependent on transmission possibilities (SvK, 2015c). At times when the maximum transmission capacity is reached, bottlenecks are created and balancing resources from the north can no longer be used to balance supply and demand. In cases of this
regional power deficit, gas turbines have been forced to be used to restock the automatically activated balancing resources in the primary and secondary control (SvK, 2015c).

6.1.3 Developments on Landscape-Level with Uncertain Impact

There are large ongoing developments in the entire energy sector today. This investigation has identified three developments located on the landscape level that has an uncertain impact on the frequency control. The developments are identified as the global trends of electrical vehicles, an increased popularity for private household consumers to produce their own electricity and the implementation of internet of things (IoT) in the energy sector. These developments are more uncertain regarding their impact as they, unlike the intermittent energy sources, have not been integrated to the electricity system in Sweden to a large extent yet. These factors are located on the landscape level since the development of these factors is beyond the control of single actors.

Today, it is largely debatable how and what impact a larger number of electric vehicles are going to have on the electricity grid. Research has shown that the development of electric vehicles could be, to a certain extent, something positive for the grid system as it can provide energy storage possibilities and offer frequency regulation to the grid (Devie and Dubarry, 2016). This could be done with vehicle-to-grid (V2G) technologies where the batteries of parked vehicles are connected to the grid and can supply electricity when there is a power deficit. The reverse is also possible called grid-to-vehicle (G2V) technologies where excess electricity available in the grid system is stored in the batteries (Devie and Dubarry, 2016). Uddin et al. (2018) argue that an advantage with this is that that electric vehicles can provide regulating services in areas where back-up supply and these kinds of resources today are unavailable. One obstacle with V2G and G2V technology is that there is a degradation of the batteries longevity if they are charged and discharged irregularly (Uddin et al., 2018). Uddin et al. (2018), however, argue that this effect can be minimized if a charging algorithm with an objective to maximize the longevity is applied.

There is also research that argues that electric vehicles will result in higher pressure on the grid system. Richardson (2013) argues that not restricted charging of vehicles will lead immense pressure on the electricity grid and large investment in generation and transmission capacity is needed. Furthermore, Richardson (2013) mentions that electric vehicles would also cause transmission bottlenecks and power quality concerns. This is a development that is likely to increase the demand for balancing resources. The uncertainty regarding the effects of electric vehicles is also confirmed by the power system analyst and the operations manager at SvK. They mentioned that electric vehicles either put pressure on the grid system, or it can provide services such as frequency control. There is thus no overall consensus of how electric vehicles will influence the grid system.

Another development is a trend in the world that individual private consumers of electricity are investing in smaller equipment to produce their own electricity. The most common thing
is to invest in solar panels that are put on the roof (SvK, 2015c). These people are in a somewhat unique situation since they act as both consumers and producers, called prosumers (SvK, 2015c). Like the development of electric vehicles, an increasing number of prosumers could have different kinds of impact on the electricity grid. A power systems analyst at SvK expressed that prosumers have to be handled in the future as they could disturb the balance in the system. One risk with prosumers is that they will supply large amounts of electricity to the grid during the summer, when the demand is low, and thus create imbalances. This could be hard to control as the production is decentralized and not part of the regular market (SvK, 2015c).

SvK (2015c) also states that there is a possibility that prosumers could be a good thing for the grid system as the demand for electricity from the grid will be lower, especially if they combine their production with some kind of energy storage. Energy storage is necessary since there is usually a mismatch between production and consumption for prosumers (Stelt et al., 2018). Most electricity from solar panels can be produced during the day and the demand is highest in the morning and evening (SvK, 2015c). Stelt et al. (2018) mention that another possible advantage for the grid system with prosumers could be that less electricity needs to be transmitted in the grid system and thereby take some pressure off the grid.

The third uncertain factor, located on the landscape level, is the development of internet of things (IoT) in the electricity sector. Kopetz (2011) argues that the IoT is not a completely new technology, it is just an extensive deployment of smart objects in the entire society and a smart object is an object which has an internet connection. In the electricity sector, the part of IoT that is usually discussed is smart grids which thereby are electricity grid systems that are integrated with smart object (Clastres, 2011).

Smart grids are a development that could lead to changes on both the supply side and the consumption side. A smart meter, that measures the power output or consumption in real-time, could be used by suppliers to control the supplied amounts as well as by consumers to control their consumption (Clastres, 2011). A power systems analyst at SvK argues that smart objects will have a large impact on the consumption patterns. If smart objects are connected to, for example washing machines and dishwashers, a consumer could choose to run the machines when there are low prices for electricity. The power system analyst at SvK argues that this is something that should make the load in the grids more even and remove some of the peak demands.

Smart objects have the potential to have a large impact on the entire energy sector, how they will affect the demand for frequency control is, however, still uncertain. Clastres (2011) argues that it has the possibility to make it easier to balance supply and demand in the system as more information will be collected both on the supply and the demand side. However, to get a widespread of smart grids, large investments would be required (Clastres, 2011). There are also risks with including IT-systems to such important societal function as the electricity system. Shichao et al (2013) argue that the electricity system would be vulnerable to cyberattacks that could shut down the entire system.
6.2 Possible Resources for Balancing Supply and Demand

This section will present and analyze the results from the second research question. The section investigates the possible resources that can be used in the regime for balancing supply and demand in the Swedish electricity system and is divided into energy sources, energy storage and consumers.

6.2.1 Energy Sources

The most common way to handle imbalances in the system is to use energy sources for electricity production and the possible sources that could be used for regulating purposes are discussed in this section.

**Hydropower**

Hydropower is a source that has good characteristics to be used as a frequency regulator and has particularly been developed and optimized for this purpose for a long time (SvK, 2015c). This is reflected in the regime for balancing supply and demand in Sweden as almost all of the automatic reserves in the primary and secondary control consists of hydropower. In addition to that, 95% of the bids on RKM in 2013 were regulating capacity from hydropower plants (SvK, 2015c). The advantage of using hydropower as a regulator is its ability to store water in large storage vessels, which entails that there is always power when needed. When the electricity demand is high, it is possible to use extra water stored in the vessel and when the demand is low, the flow in the river can be used to refill the vessel. This results in that hydropower quickly can change the production and thereby has a high regulation capacity which makes it possible to meet variations in electricity demand. Another advantage with this is that storing water is a sort of energy storage that can be carried out at a low cost (SvK, 2015c).

Vattenfall did an investigation which showed that the current capacity of hydropower in Sweden can regulate 13 000 MW wind power (SvK, 2015c). This further shows the ability of hydropower to regulate the frequency by compensating for sources that have a more unpredictable production. Hydropower is also a source of electricity that is considered to be renewable, which also is a factor that is positive for using hydropower as a regulator (Martínes-Lucas et al., 2015). One disadvantage with hydropower is that it is dependent on the water flow in the rivers which impacts the ability to regulate the frequency. Hydropower is thereby a source that is dependent on the weather conditions such as annual rainfalls, but hydropower is not affected to the same extent as solar and wind power. For a hydropower plant to stop working the entire river flow has to stop compared to wind power that does not work on a still day.
Combined Heat and Power
A source that is not part of the regime for balancing supply and demand and thus not used as a regulator today, but is technically possible to use, is biomass in CHP plants (Byman, 2017). According to SvK (2015c) bioenergy in CHP plants is, together with hydropower, the renewable source that has the largest potential to act as a regulator. Like hydropower, CHP has the characteristic of flexibility, which could enable it to participate in several regulating activities, such as in the primary control (SvK, 2015c). In a CHP plant, the electricity is produced by heat and the advantage with CHP’s is that it can produce heat in several ways, such as through boilers and heat pumps. Furthermore, due to the inertia in the heating system, it is not exclusively dependent on the heat consumption for electricity production. There is flexibility in a CHP plant since there is always a choice to produce electricity or not as it is possible to only produce heat. It is also possible to use electricity to produce heat and thereby consume electricity (SvK, 2015c). This flexible character makes CHP plants a good alternative to use for regulating purposes. One considerable reason that CHP plants are not used in the regime for balancing supply and demand is that the operators of these plants have not been informed about their possibilities to engage in such activities or at least not show any interest for that (SvK, 2015c).

A case study performed by Lund et al. (2012) shows that a small CHP plant in Denmark called Skagen CHP would be a good alternative for Denmark to balance some parts of its intermittent power. It is argued by Lund et al. (2012) that this CHP plant could provide both production bids and reduction bid on RKM as well as to be part of the primary control. It is furthered argued that the investment costs, as well as the operating costs, for this CHP plant to be able to provide regulating services is low. The investment cost for being able to provide plus/minus 1.4 MW was 27 000 euro (Lund et al., 2012). It is thus argued by Lund et al. (2012) that CHP plants could prove a cost-effective, renewable energy source that could participate in regulating activities.

There are, however, some constraints with using CHP plants for frequency regulation. NEPP (2016) argues that during the summer the usage of CHP plants is limited since several plants do not operate at all since there is not a large need for heat during the summer. A possible scenario in the near future is that the wind and solar power are producing a lot of electricity and the consumption is low during the summer, which will cause imbalances and at those times the CHP plans will not be able to regulate the balance (NEPP, 2016).

Wind power
Wind power is one of the reasons for an increased demand for frequency regulation in Sweden but it could possibly also be an option to use in the regime for certain frequency regulating activities. Modern wind power plants have control systems with a rapid response time which means that they could provide regulating services (SvK, 2015c). The regulating service that wind power plants can participate with is to leave a reduction bid, where they decrease their production in times when the production exceeds the demand. However, SvK (2015c) argues that it will take a long time before wind power will be used as an established regulator in the Swedish regime for balancing supply and demand. The main obstacles are
that wind power is highly dependent on weather conditions and cannot store any energy. This entails that the systems must always be in operation and it entirely depends on windy conditions to be able to participate in regulating activities. Furthermore, due to the lack of storage capacity, wind power would be financially disadvantageous compared to hydropower when it comes to decreasing its production at times when the production exceeds the demand (SvK, 2015c). The economic disadvantage and that it is weather dependent is thus two complicating factors that will make it hard for wind power to establish itself as a regulator in the Swedish regime.

**Solar power**

There are some studies that show that solar power has potential to be used as a frequency regulator (Dreidy et al., 2017). Watson and Kimball (2011) have conducted research and experiments that shows that it is possible to regulate the frequency in a micro grid using solar power. The work from Watson and Kimball (2011) was, however, at a small scale and they conclude that more research is needed in order to determine the true potential of using solar power as a regulator in a large system. Using solar power as a regulator could, in terms of the theoretical approach, be seen as a niche development that is in an early stage. Since it has not been used, to a large extent, in a large system yet it is hard to argue that it could be part of the regime and provide regulating services today. Another factor that will make it hard for solar power to reach the regime and establish itself as a regulator is, as for wind power, that it is weather dependent.

**Nuclear power**

Nuclear power is a source that is not included in the regime for balancing supply and demand and thus not used as a regulator today even though it is technically possible. During the 80s and 90s nuclear was used as a regulator in Sweden and is still used internationally in countries such as France (SvK, 2015c). Some reports conclude that it is possible to use nuclear power plants today without making any large changes in the current production facilities (SvK, 2015c). However, nuclear plants are complex and include more security compared to, for example hydropower, which makes it more complicated to use as a regulator (SvK, 2015c). As described in section 3.1, there are also plans to decommission a large part of the nuclear capacity in Sweden. Thus, it is not likely that nuclear power plants will be able to establish itself in the regime for regulating activities again.

**6.2.2 Energy Storage**

Energy storage solutions are often used to store energy when the electricity prices are low and then use that energy when prices are high. It is also possible to use energy storage solutions to take advantage of electricity surpluses, instead of wasting it. Energy storage techniques could thus be a good resource to control the frequency in the grid apart from the regular energy sources. SvK (2015c) argues that there are three main storage techniques that can be used for frequency regulating purposes, which are discussed below.
**Pumped Hydroelectric Energy Storage**
Pumped hydroelectric energy storage (PHES) is a largely adopted technique for electricity storage worldwide and has been believed to have a good balancing potential (Kougias and Szabo, 2017). PHES is a hydropower plant with a pump device installed, which makes it possible to pump water back up to the power plant. The PHES would then be used to control the frequency just like a regular hydropower plant, the only difference between them is the ability to pump water back up to the power plant (Kougias and Szabo, 2017). The constraints with PHES are that it requires certain geographical conditions (e.g. water and elevation), and to be profitable it requires a high price volatility in the electricity price (SvK, 2015c).

**Compressed Air Energy Storage**
Another way to store energy is to use compressed air energy storage (CAES). CAES is today, except PHES, the main storage technique that is used commercially (SvK, 2015c). With CAES, air is compressed when the electricity prices are low and thereafter released to generate electricity when the prices and demand increase (Lund and Salgi, 2009). The air is stored either underground or in vessels above ground. One disadvantage with using CAES technologies is that it takes at least 15 minutes to reach 100 percent of the capacity, which thus can make it harder to use as a frequency regulator (SvK, 2015c). In order to make CAES profitable it requires, as with PHES, a high price volatility (SvK, 2015c).

**Batteries**
Batteries are another technique to store energy and can be seen as an alternative to achieve a more stable grid system (May et al., 2018). This technique is so far not very outspread but it is beginning to get recognition. It is particularly lithium-ion batteries that are under development and the production of these is increasing. The main barrier for these lithium-ion batteries to get a real breakthrough is the very high costs, which results in that other alternatives are considered (SvK, 2015c). However, there is a lot of work and research to make it cheaper to manufacture lithium-ion batteries and it is expected to take market shares in the future. In the short term, it is the households that are expected to use batteries to a greater extent. A combination of solar cells and batteries is something that is becoming more common, especially in Germany (SvK, 2015c). But it is in the car industry batteries are expected to dominate in the coming decade, and it is largely the private investors that will direct the development of the batteries (SvK, 2015c). As mentioned in section 6.1.3, there are possibilities to use batteries from electric vehicles for frequency regulating purposes with V2G and G2V technologies.

These three energy storage solutions could be seen as niches that are technically possible to use as regulators but are not used for that purpose today. The main issue with all of these three storage techniques is that they are expensive and requires a high price volatility to be profitable. The price differences that occur on the market today are not enough for these storage solutions to be profitable and it is thereby hard to argue that they are an implementable solution in today's market (SvK, 2015c). It will, thus, be hard for these three niches to be able to reach the regime if a more volatile electricity price does not occur.
6.2.3 Consumers

There is a possibility to use the consumers as part of the regime for balancing supply and demand in the system. The consumers can adjust their demand to facilitate a better balance. As discussed in section 3.4, there are five main sectors that consume electricity. Distribution losses are just losses in the system and cannot be used as a balancing resource. The transport and district heating sectors are quite small but there is a lot of potential in the two large sectors which are industry and households (Fritz, 2013).

Industry

Several studies have shown that the industrial companies can reduce their consumption of electricity, during shorter periods of time, without affecting their business to a large extent (Fritz, 2013). SvK (2015c) has concluded that the industry has a large potential to contribute more in the frequency control, and the combined potential is evaluated to be between 2000 and 4000 MW. There are, on the other hand, limits with these kinds of collaborations as the industry cannot decrease its electricity consumption for long periods of time. How much an industrial company can contribute and for how long varies with, for example, size of the industrial company and how dependent its core business is on electricity. SvK (2015c) presents a general pattern for this which says that the industry can decrease its consumption for three hours before its operation gets too affected. After a three hour decrease, they have to wait about eight hours before they can decrease the consumption for a second time.

Disturbing the consumption of electricity will always include a risk for industrial companies. They will thereby need an economic compensation to participate in a collaboration where they decrease their consumption (Fritz, 2013). These kinds of collaborations already exist today in the regime but mostly as part of “effektreserven”, to handle situations when the demand is unusually high (SvK, 2015c). There are also some industries that advertise reduction bids on RKM where they offer to decrease their consumption during a specific period of time for economic compensation, but this is not done to a large extent today. The reason that reduction bids from the industry are rare on RKM, and not used more frequently in the regime, is that they cannot compete economically with the reduction bids from hydropower (SvK, 2015c). The reduction bids from the industry are thus almost exclusively used when the maximum transmission capacity in the grid is reached. In those situations, balancing resources from hydropower plants in the north cannot be used to balance supply and demand (SvK, 2015c). SvK (2015c) has concluded that posing reduction bids from the industry on RKM could be one part of a solution for supplying the south of Sweden with balancing resources when the maximum transmission capacity in the grid is reached.

Households

Another reduction resource that is not established in the regime, to a large extent, is the households. There is potential in using the consumption patterns of households to facilitate a balance in the system. This can be done by moving the consumption of households from high demand periods to low demand periods. SvK (2015c) presents a number where the potential for this is at least 2000 MW.
In Sweden, there are about 1.2 million “stand-alone houses” that are heated with electricity (Fritz, 2013). Several field studies have concluded that it is possible to move the electricity consumption (from high demand hours to low demand hours) used for heating in these houses without affecting the overall comfort for those living in the house (Fritz, 2013). The field studies conclude that the movable effect is 2 kW per house. Fritz (2013) also mentions possibilities in using products used within the household that consume a lot of electricity, like white goods or water heaters. That would work just like the heating of houses where the usage of washing machines and dishwashers are moved to hours where the demand is lower and by that facilitate the balance in the system. A power systems analyst at SvK argues that smart meters and smart grids (discussed in section 6.1.3) would facilitate this change of consumption for households. The analyst argues that if, for example, the washing machine and the dishwasher are connected to the internet these household appliances would be able to assess electricity prices and operate when the prices are low and thereby when the demand is low.

There are, however, several concerns for establishing household consumers as a reduction resource in the regime for frequency regulating purposes. One issue is that they do not have large economic incentives for moving their consumption to save money by using more electricity during low demand periods. The power system analyst at SvK argues that there can be rather large price variations but since, for example the dishwasher, does not require that much power, the saved amount expressed in SEK will be very low. What could be done instead is that the households advertise a reduction bid on RKM. This would work in the same way as the industries, which are offering to reduce their consumption for a certain period of time for economic compensation. The power system analyst at SvK, however, argues those bids, like the bids from the industry, would be hard to compete economically with the bids from hydropower. The power system analyst expresses that to convince households to move their consumption other types of incentives would be needed. One example is to advertise to the households that it is more environmentally friendly to consume electricity during low demand periods. This is visualized in Figure 8 in section 3.3, that during low demand periods there are mostly wind power and hydropower used to produce the electricity and energy sources with more emissions are used during high demand periods. The power system analyst from SvK argues that if the amount of CO2 emission were presented for low demand and high demand periods, it might be possible to convince household consumers to move their consumption.

Another issue with using the consumption of households is that to leave a bid on RKM, there needs to be a bid of at least 5 MW in SE4 and 10 MW in the rest of Sweden as described in section 3.5.3. A senior power system analyst at SvK argues that it is hard to reach the power needed. The senior power system analyst explains that even if you have, for example 100 water heaters, there are still not enough power to have any real impacts on the frequency in the system. An additional issue with leaving a reduction bid on RKM, expressed by the senior power system analyst at SvK, is that if one has promised to regulate a certain volume, then the promised volume must be kept. In some way, it must be guaranteed that the reduction in
consumption can be carried out. This could be hard to do in a household since when the reduction bid is activated, the household might not use the dishwasher or the washing machine and thus the power for regulation is not available. The senior power system analyst at SvK argues thus that reduction bids on RKM are more suited for industrial consumers as they have more even and predictable consumption patterns even if it is technically possible to use households.

6.3 Balancing Efforts on a Local Level

This section will present and analyze the third research question involving possible efforts that could be carried out on a local level to facilitate a better balance in the system. The previous section (6.2) presented the possible resources that could be used. This section will build on that and investigate how those kinds of resources could be utilized on a local level. In terms of the theoretical approach, the focus will be on presenting niche developments and analyze their possibilities to reach the regime to mitigate the issues regarding the increasing imbalances and bottlenecks in the system.

The investigation has identified four possible efforts and none of them are used in any large scale today. The first effort is to utilize smaller local balancing resources and advertise these on RKM. The second effort is to increase the collaborations on a local level between balance providing companies. The third effort is to utilize balancing resources to avoid overload in the local grids. The fourth and last effort is to utilize local resources for stand-alone operation mode during extreme conditions such as when large parts of the national grid are out.

6.3.1 Advertising Local Resources on RKM

A former manager at SvK and a senior advisor at Fortum both argue that the largest effort that can be done on a local level, to facilitate a better balance in the system, is to advertise local balancing resources on RKM. This would result in that SvK would have more resources available to be part of the tertiary control and thereby more resources to manually handle imbalances in the system. Another advantage is that more capacity from the larger hydropower plants would be available since these would not have to be used to the same extent as today. This is beneficial for the entire system as it opens up opportunities to have more spare capacity available to handle larger unexpected imbalances.

The prerequisites for acting on RKM are described in section 3.5.3. The largest obstacle for a smaller actor to be part of RKM is that there is relatively high power outputs required to participate, 5 MW in SE4 and 10 MW in the rest of Sweden. A smaller actor, for example an owner of a small-scale hydropower plant, thereby needs to be able to produce that amount of power to be part of the market. This is, according to the former manager at SvK, one of the reasons that most of the available bids on RKM at the moment consist of power from larger power plants.
The former manager at SvK and senior advisor at Fortum argue that this problem can be solved by aggregating the power from several production facilities to reach the required power output to be able to act on RKM. This could, for example, be that several small scale hydropower plants are aggregated and act as one unit. It is possible to synchronize several production facilities and make them perform the same actions at the same time. It is also possible to aggregate resources on the consumption side. Two examples could be to aggregate a large fleet of electric vehicles or to aggregate several water heaters from households. The aggregated power could be used to submit either a production bid with synchronized production facilities or a reduction bid where consumers synchronized reduce their consumption.

Aggregating power is, however, not something that is occurring much in the regime today even if it is technically possible. A senior advisor from Fortum argues that even if it is unusual there is nothing that prevents a producing company to aggregate its own smaller production facilities and use these to pose a bid on RKM already today.

Since aggregating power is not used in the regime, to any large extent, is can be seen as a niche in the multi-level perspective. The former manager from SvK argues that the main reason that aggregating bids are not breaking out of the niche-level and into the regime, in a large scale, is that it is unclear which actor that should aggregate the power. One example is that the balance providing company, for the area where the power is located, could undertake that role and aggregate the capacity and submit the bid on RKM. Another option is that a new independent company creates a new role in the energy market called “aggregator”. The purpose of this company would be to aggregate available power within the local area and then make a contract with the balance provider to submit a bid on RKM. A contract with a balance provider would be necessary since it is only balance providing companies that are allowed to submit bids on RKM. The former manager at SvK concludes this by expressing that it will be important to use these resources and it is already technically possible but how they are going to reach the market in large scale is still unknown.

6.3.2 Local Collaborations

A senior analyst at SvK argues that increased collaborations on a local level between balance providers are another niche development that could facilitate a more stable frequency. If there is two or more balance providers close by, it might be possible to collaborate to keep the balance. For example, if one actor has produced or purchased a higher amount than the demand and the other has produced or purchased a lower amount than the demand, they could benefit from each other. Instead of that the one that has produced or purchased too much has to shut down the production and the one that has not produced enough must produce or purchase more, they could collaborate by benefiting from each other’s imbalances.
The senior analyst at SvK explains that the prerequisites needed for a collaboration of that kind to work are to build an infrastructure where the momentary imbalances for each balance provider are measured individually. Individual measurements of that kind would make it possible to summarize the imbalances from several balance providers and then they could act together to correct what is left of the summarized imbalance.

If an infrastructure was built and they would have knowledge about the imbalances of each balance provider, it is not obvious how these would be handled. For example, if there is not enough production in one area, that could be handled by producing a higher amount locally. It would also be possible to handle it by purchasing more production from a distant area with cheaper prices. If there exist balancing resources within the local area that are cheap, for example if you could use the batteries from electric vehicles to charge more or less or possibly hydropower, it would be a good solution to handle imbalances with local resources. If it, on the other hand, is more expensive to handle imbalance with local resources it would not be a good solution from an economic point of view to let every local area handle its imbalances on its own. The senior analyst at SvK argues that it should thereby be judged from case to case what the most appropriate action is to handle the leftover imbalance from such collaboration.

This solution is not something that is part of the regime today. The senior analyst at SvK argues that there is nothing preventing such a solution but to make it work an infrastructure that does not exist today would have to be built. Building an infrastructure would require both investments and dedication from the balance providers and this is a complicating factor for this niche of local collaborations to be able to reach the regime. Building a strong social network around this niche is, thus, one factor that could be vital to make it reach the regime.

6.3.3 Overload in the Local Grids

The operations manager and power systems analyst at SvK express that something that would be interesting to do on a local level is to work with balancing resources to avoid overload in the local grids. An operations manager at SvK argues that this is something that a local grid owner would have incentives to do. If they manage to avoid overload in their grids they can postpone investments in the future or perhaps even avoid them entirely. A senior analyst at SvK argues that avoiding overload in the local grids could be highly important in the future with the development of electric vehicles. As this is something that could increase the load substantially in the local grids and force local actors to make large investments.

The operations manager at SvK further argues that avoiding overload on a local level is also something that could be good for the entire system and thereby also, to a certain extent, facilitate a more stable frequency. When there is a high load on a local level it is likely that there is a high load in the entire system. Decreasing that load on a local level would thus have good impacts on the frequency in the grid. That might not always be the case but it is likely that the load on a local level and the load in the entire grid correlates at certain times.
The senior analyst from SvK expresses that it is not very likely that a local grid that suffers from overload would have access to production. The senior analyst at SvK argues that a more likely solution to handle the overload would be to collaborate with consumers to reduce their consumption when there is an overload in the local grid. It is not necessary to aggregate the same amount of power to make an impact on overload in a local grid as it is for having an effect on the frequency in the system. Being able to control the load in the grid like this could, thus, be a good alternative instead of making large investments to be able to take a higher load. This niche for avoiding overload by controlling the load in the grid is thus fairly straightforward to carry out. It is, to a large extent, the local grid owners that have to decide if this is a solution that they are interested in or not.

The operations manager at SvK mentioned another method for working with overload, that is believed to be fairly controversial, and that is to work with something called brownout. This is applied in a few countries in Europe, such as France and the UK, and it is when there is an intentional reduction of the voltage in the electricity system. In those countries, the TSO reduces the voltage in the system to reduce the load. This is mostly used in emergency situations when there is a risk for a blackout, i.e. when there is a risk for a power outage. A brownout is not as dramatic as a blackout since the customers still have electricity available.

A brownout is used on national level, i.e. the larger grids, in other countries in Europe. Even so, the operations manager argues that it might be possible to use a brownout on a local level, in the regional or the local grids, to reduce the load in the grid. It would also be possible to increase the voltage in a local grid if they wanted to have a higher load, even if that is not as likely. The senior analyst at SvK argues that it might be hard to use a brownout on a local level as there is a limited area in which the voltage is allowed to be within. It is agreed by both the operations manager and the senior analyst that it would be interesting to do a more extensive investigation if it would be possible to use a brownout in Sweden. A brownout is thereby a niche development that possibly could be carried out on a local level to avoid overload but it would take more extensive research to determine the possibilities for this niche with a higher certainty.

6.3.4 Stand-Alone Operation

A former manager at Växjö Energi argues that one highly important utilization of local balancing resources is under extreme conditions for the grid system. An example of such condition is when extreme weather events have caused severe damages to the national grid. These kinds of conditions are rarely occurring for the grid system but, when they occur, they have devastating consequences as a large part of the population will lack access to electricity. The former manager at Växjö Energi argues that handling these kinds of situations is a matter of national security. The former manager at Växjö Energi further argues that, to his knowledge, there are no other ways of handling these situations than to use smaller local production facilities and run them in something called “stand-alone” mode.
The former manager from Växjö Energi explains that running a production facility in stand-alone mode implies that the power from the local power plant is distributed directly to the local grid without any assistance from the national grid. This can be a complicated process since, during stand-alone mode, the local production facility has to be able to control the frequency in the grid on its own. To be able to run a production facility in stand-alone mode it is thereby necessary that the production facility is equipped with devices that automatically can control the frequency. Balancing supply and demand and keeping a stable frequency is, thus, not only important during normal operating conditions for the electricity system. Local production resources that can be runned in stand-alone mode are thus an important resource for the entire community and in the long run, as mentioned, even for national security.

Stand-alone operation should not be seen as a niche that is possible to use during normal operation. This should be seen as effort that could be used in the regime but only during extreme situations and that is the application for stand-alone operation. The former manager at Växjö Energi gives one example when this has been applied in the Swedish regime already and that is during the storm Gudrun. The storm Gudrun occurred in Sweden during the 7th of January 2005 and caused severe damage to the entire landscape. The national grid was damaged and at most there were 415 000 households that lacked electricity (SMHI, 2017). The former manager at Växjö Energi explains that during this time, small-scale hydropower plants were used to generate electricity to some parts of the community, one example is the city of Ljungby. This was accomplished by running the small-scale hydropower plants in stand-alone mode and distribute the electricity directly in the local grid so that it could reach the consumers.
7 Discussion

This chapter will discuss the main findings and takeaways from this study. The development for frequency control in the Swedish electricity system is discussed as well as the possibilities to engage in balancing activities on a local level.

7.1 The Development for Frequency Control in Sweden

The introduction of intermittent energy sources is the factor that is usually highlighted in these kinds of studies as one of the main reasons that the balance in the system has gotten worse. This is a factor located on the landscape level and is thus a development that is hard to control for single actors. This investigation has shown that there are several other factors, than the intermittent energy sources, that have a large effect on the balance. Another substantial factor is the current market design as SvK has concluded that almost half of all the frequency deviations in the system are occurring during hour shifts and this is connected to how electricity is traded. This is, however, a factor that is located on the regime level and thus a factor that is not as difficult to control and adjust. As mentioned in the result and analysis chapter, there are ongoing discussions to change the market design and introduce a market where electricity is traded every 15 minutes instead of hourly. Since almost half of the deviations are connected to the market design, this is a development that may have a large impact on the demand for frequency control. This shows that there are factors on regime level that is possible to adjust to facilitate a better balance in the system and not only landscape factors that is hard to control like the intermittent sources.

Looking at the regime for balancing supply and demand, which includes using hydropower as the main balancing resource, it can be concluded that it historically has been stable. The regime has been stable for a long time since the capacity from large-scale hydropower plants has been enough to handle the deviations in the system and the balance has thus not been a large issue for the electricity system. Today there are, however, destabilizing factors that are putting pressure on the regime such as the introduction of intermittent energy sources, decommissioning of nuclear power, overseas transmission capacity and the market design. This leads to that more of the capacity from the hydropower plants is being used.

One of the reasons that change still has not occurred, and other resources than hydropower is not used to a large extent, is that it is hard for any other balancing resource to compete economically with hydropower. Another part is that hydropower has been used for this purpose for a long time and has specifically been developed for these kinds of activities, which no other resource has. This is two stabilizing factors and it is therefore likely that hydropower is going to continue to be the main source for frequency regulation for as long as there is capacity available. Using other resources is relevant in particular situations, for example, when the maximum transmission capacity is reached and the hydropower is trapped by bottlenecks in the system and cannot be used to balance supply and demand.
The capacity of hydropower is, on the other hand, not unlimited. It is thereby the availability of hydropower capacity that, to a large extent, dictates the development of what resources that are used for frequency control in Sweden. One resource that possibly could be used more already in today's market conditions is CHP power plants. There is a large potential in using CHP plants and they could serve as an important complement to hydropower if the operators could be convinced to participate in regulating activities. For the other resources, it will require some developments if they were to be used more frequently. Resources such as reduction bids from households and industries, or even wind power, might be economically relevant to use more frequently if the balancing capacity from hydropower were to be fully utilized or trapped by bottlenecks in the transmission system.

It should also be said that there are large developments occurring in the Swedish electricity system that has the potential to change the entire market. It is possible that the electrical vehicles develop as a cost-effective alternative in the future and will be used as the main balancing resource with V2G and G2V technologies. It is also possible that the deployment of IoT in the energy sector will have a large impact on the balance in the system and radically change how the frequency is handled. The future is thus hard to predict and it is important to be aware of and monitor how these kinds of factors develop.

7.2 Possibilities on a Local Level

This report has identified four main possibilities to engage in balancing activities on a local level. The largest possibility that can be carried out at this moment without any major difficulties is to use local resources to pose a bid on RKM. The most suitable resource for this purpose is hydropower plants due to its economic benefits and unique flexibility that has been developed by storing water. Posing a bid can be done either by having enough power in one power plant or to aggregate several facilities. Other local resources such as reduction bids from industries or households are also something that is possible to pose on RKM but they would have to compete with the economically advantageous hydropower.

The other possibility that is fairly straightforward to engage in, already at this moment, is to avoid overload in the local grid. This possibility is not focusing on the balance in the system in first hand even if it can have those effects as explained in section 6.3.3. Overload would be handled mainly by controlling the load in the grid. The main benefit of controlling the load through collaborations with households and industries would be to avoid investments for the local grid owners. Since it would take more extensive research to find out if a brownout could be used that is not seen as a viable alternative at this moment.

The two other possibilities are to increase the collaboration between balance providers and to run production facilities in stand-alone mode. These two possibilities are dependent on investments and certain conditions and thus not considered to be as straightforward to engage in as the two firstly explained possibilities in this section. Collaboration between balance providers is not something that is occurring today. As described in section 6.3.2, a large
infrastructure would have to be built before this would be possible and it is thereby not
considered to be a solution that could be carried out at this moment. Running power plants in
stand-alone mode is a highly important resource for the community and even the national
security. This is, however, nothing that will be used during normal operation mode and thus
only used at rare moments.
8 Conclusions

The purpose of this report is to investigate the demand for frequency control in the Swedish electricity system and what could facilitate a better balance in the system. To operationalize the purpose, the following research questions have been answered.

Main RQ: What is affecting the demand for frequency control in the Swedish electricity system and what balancing resources and efforts could facilitate the balance?

RQ1: What are the underlying factors affecting the demand for frequency control?
RQ2: What resources could be used to control the frequency?
RQ3: What balancing efforts could be carried out on a local level?

These questions have been assessed in detail in the results and analysis chapter, and will in this chapter be presented in a more precise and concluding manner. The main research question encompasses the three sub questions, thus the combined answers to RQ1, RQ2 and RQ3 answers the main RQ.

8.1 RQ1: What are the Underlying Factors Affecting the Demand for Frequency Control?

The identified factors that affect the demand for frequency control in the Swedish electricity system have been divided into the landscape-level and the regime-level according to the theoretical framework, the multi-level perspective. On the landscape level, two main factors have been identified. Firstly it is the introduction of the intermittent energy sources. These sources have a volatile and unpredictable production. This, in turn, causes imbalances in the system and thus affects the frequency. The other factor is the decommissioning of nuclear power plants. This results in that the hydropower has to cover a larger amount of the base production which affects the capacity of the hydropower plants to regulate the frequency as their capacity instead must be used to produce electricity.

On the regime level, four factors have been identified. The first factor is the current market design for trading electricity. The trade occurs hour by hour and there is a risk that the production in the system heavily increases or decreases to meet the traded amount at the start of a new hour. The consumption increases or decreases more slowly and changes during the hour instead of during the hour shift, which will result in imbalances around the hour shifts. The second factor is the increased overseas grid connections. The overseas transmission possibilities have increased the complexity of the system and it does not take frequency into consideration when it transmits electricity over country borders. The third factor is that the Norwegian hydropower capacity is going to be traded at the Germany and UK market and will thereby not be available to the same extent in the Nordic market and thus in Sweden. The fourth factor is the limited transmission possibilities to the south of Sweden. Many regulating resources in Sweden are located in SE1 and SE2. This results in that when maximum
transmission capacity is reached, bottlenecks are created, and the hydropower in the north gets trapped and cannot be utilized to balance supply and demand in the system.

Apart from these factors with known effect on landscape and regime level, three additional developments on landscape level with uncertain impact have been identified. The first is the global development of electric vehicles. Electric vehicles are a development that may put pressure on the grid and cause transmission bottlenecks and power quality concerns, which will result in an increased demand for balancing resources. It is also argued the electric vehicles could be used for frequency regulating services, where the batteries are used to supply and store electricity from the grid when that is necessary. The second factor is an increasing number of prosumers. One risk with prosumers is that a lot of decentralized production that is not part of the regular market could reach the grid during the summer when the demand is low and thus create imbalances. It is also possible that prosumers could take some pressure off the grid system and decrease the need for transmission in the grid. The third and last identified development is the deployment of IoT in the energy sector. An increased usage of smart objects is something that may impact the frequency control. Researchers argue that it will be easier to balance supply and demand since smart objects can collect more information and suppliers and producers will have more information on how to act to facilitate a balance. The risk with having IT-systems connected to the electricity system is that it is vulnerable for cyber-attacks which would have devastating impacts on the entire system.

8.2 RQ2: What Resources Could Be Used to Control the Frequency?

Two renewable energy sources have been identified as good balancing resources. The source that is currently the most suitable, and also the most utilized, for frequency control is hydropower. The reason why hydropower is good is due to its ability to store water. This enables to have power when it is needed and also make it possible to rapidly change the production and thereby has a high regulation capacity. The other resource that has been identified which could be a good alternative to use as a frequency regulator is CHP plants. CHP plants have the flexible character needed to work as a regulator due to that the plant can choose to produce heat or electricity, or even use electricity to produce heat when there is an excess of electricity in the system. The main issue is that the operators of these plants are not informed about their possibilities or has not shown any interest to engage in regulating activities. Another issue is that several of the CHP plants are not operating during the summer.

Wind power would be difficult to use as a regulator since it is weather dependent. It could possibly be used to reduce the production, when there is an excess of electricity in the system, but that would require windy conditions. It would also be economically devastating to use wind power instead of hydropower for those purposes. Solar power has not been used as a
regulator but there are ongoing research projects that investigate that possibility, for now, solar is not an option. Nuclear power has previously been used as a regulator but due to safety concerns and that a large part of the nuclear capacity in Sweden is being decommissioned it is not an option for today.

It is technically possible to use different energy storage solutions as regulators and the three most suitable storage techniques are PHES, CAES and batteries. The main concern for all these three is that they require a high price volatility on the electricity market to be profitable and the volatility that exists on today's market is not enough. It would thereby not be a profitable investment to use these solutions and for today's market, they are thereby not a viable solution to use as regulators.

It is also possible to use consumers to balance supply and demand. The two sectors that consume most electricity are industry and households and this is where the potential lies. Industries are used already today where they leave reduction bids in effektreserven or on RKM. The main reason that the industry is not used more on RKM is that the reduction bids from the industry cannot compete economically with the reduction bids from hydropower. These resources are thereby most suited during transmission bottlenecks when the capacity from hydropower is trapped by the bottlenecks. The consumption of households could also be used to leave a reduction bid. The main issues with this are that to reach the power needed and a lot of households would thereby have to be aggregated. It is also hard to guarantee that the power is there when it is needed since, for example, a dishwasher does not operate during the entire day like an industry usually does. It is thereby concluded that it is more suitable to use industries for reduction bids than households, even if it is technically possible.

8.3 RQ3: What Balancing Efforts Could Be Carried Out on a Local Level?

The thesis has identified four balancing efforts that could be carried out a local level to facilitate the balance in the system. The first possibility that has been identified is to advertise local balancing resources on RKM. This could both be local production facilities that contribute with production and consumers that change their consumption to leave a reduction bid. If the local resources cannot reach the power output needed to act on RKM, it is possible to aggregate several resources and thereby reach the required power output.

A second possibility is that balance providers collaborate on a local level. By benefiting from each other’s imbalances, they could collaborate and level the imbalances against each other. This is not something that is occurring today and one identified prerequisite to make this possible is that an infrastructure is built where the momentary imbalances for each balance provider is measured separately. Such an infrastructure does not exist today.

A third possibility is to work with balancing resources to avoid overload in the local grids. This is mainly beneficial for the local grids as they could avoid investments by controlling
the load in the grid. It could, however, also have a good impact on the frequency in the system as a high load on a local level and a high load in the system may correlate at certain times. Avoiding overload would be carried out by controlling the load in the grid through collaborations with industry or household consumers. Furthermore, handling overload could possibly be done by working with brownout in the local or regional grids. However, this method is somewhat controversial and more research is needed to determine if it could be used on a local level.

The fourth option is that a local actor engages in balancing activities in extreme situations. In a situation, where large parts of the national grid are out, electricity could be generated and supplied directly to the local grids by running smaller production facilities in stand-alone mode. In those situations, the smaller production facility needs to keep the frequency in the grid on its own without assistance from the national grid. Smaller production facilities that can control the frequency thus serve as an important resource for the community.

8.4 Implications for Utility Companies

This study has resulted in some implications for utility companies. The implications will be focused on how utility companies, like Mälarenergi, could utilize smaller balancing resources locally. Further, the implications are based on the current market conditions and viable possibilities for today's market. The first suggestion will be to advertise hydropower capacity on RKM. A suggestion for a working process for this could be:

1. Investigate the exact capacity of the current hydropower production facilities
2. Sort the power plants in two categories; the power plants that can produce the required capacity to act on RKM on its own and the power plants that cannot produce that amount. The required capacity is 5 MW in SE4 and 10 MW in the rest of Sweden.
3. Use the larger power plant that can produce 5 or 10 MW to pose a bid on RKM
4. Investigate which of the smaller power plants that can be aggregated
5. Pose a bid of the aggregated capacity

The second suggestion will be to inform the operators of the CHP plants of the possibilities to use their plants in regulating activities. There is a large potential in using CHP plants for regulation purposes and they could serve as an important complement to hydropower.

A third suggestion is to inform the grid operators about the possibility to collaborate with consumers to avoid overload. Instead of making large investments in their grid there is a possibility collaborate with the consumers and by that control the load in the grid.
8.5 Limitations and Suggestions for Further Work

This report has investigated the balance between supply and demand in the electricity system in Sweden. The electricity system is a large complex sector including several different actors and processes. One limitation of this study is, thus, that only a few stakeholders that have been considered relevant for this study have been interviewed. A second limitation is that most of the interviewees are connected to SvK. The other interviewees are single persons from other relevant organizations. This is a limiting factor since the material will, to a large extent, be influenced by the opinions connected to SvK. A third limitation is, as briefly mentioned in the methodology chapter, that it might be hard to generalize the findings for the electrical systems in other countries than in Sweden. One example could be that other countries may have a different grid infrastructure, not divided into national, regional and local grids as in Sweden, which could make the results hard to generalize.

This report has been delimited to identifying overall directions for what resources that could be used to control the frequency and what balancing efforts that could be carried out on a local level. The recommendations for further work are thereby focused to further investigate the identified directions. Firstly, it is suggested to conduct a more rigorous study on how CHP plants should be used in the most efficient way for regulating purposes. CHP plants have been identified as a resource that could serve as a complement to hydropower in regulating purposes and should thus be further investigated. Such a study could include which equipment that is the most cost-efficient to invest in and what type of regulating activities that CHP plants are most suited to be in. Secondly, it is suggested to further investigate the conditions for utilizing the concept of brownout on a local level in Sweden. It has been concluded in this study that avoiding overload in the local grids could mainly be handled by controlling the load in the grid through collaborations with households and industries. An interesting concept that has appeared in the study is that brownout could be a more simple way for the local grid owners to control the load. The prerequisites for utilizing a brownout should thus be further investigated.
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