DEMAND RESPONSE IN THE FUTURE SWEDISH ELECTRICITY MARKET

A TYPOLOGY BASED ON COST, VOLUME AND FEASIBILITY

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A master thesis in the field of Strategy and Management control at the Department of Industrial Engineering and Management, Division of Economic Information Systems, Linköping Institute of Technology

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ABSTRACT

The power balance of an electrical power system is crucial to the quality of the delivered electricity as well as the security of supply. In a scenario where Swedish nuclear power plants are being phased out and replaced by renewable energy sources new constraints are added to the power balance equation since the production of many renewable energy sources, such as wind and solar power, are intermittent by nature. This leads to a situation where the currently available regulating power might have difficulties to manage the increasing frequency fluctuations in the power grid. One possible solution to the problem is to build gas turbines for the purpose of peak power generation capacity. An alternative option would be to increase customer flexibility; that is Demand Response.

This master thesis investigates how the market for Demand Response can be designed and which potential Demand Response volumes different policy programs might release. This is done through a mixed approach. Firstly, a scientific review of previously documented Demand Response experiences compares and categorizes different Demand Response programs in a typology based on the parameters cost, volume and feasibility. Subsequently an interview series with different market agents, predominantly through interviews with the Swedish energy intensive industry, identifies the existing Demand Response potential in Sweden and offers the paradigm needed to transfer the results to a future hypothetical situation. The typology of Demand Response programs and estimation of the future industrial Demand Response potential in Sweden are the main new knowledge contributions of this master thesis. The scope however is limited to the Swedish market geographically and focuses on the time horizon 2020-2050. It is also assumed that only existing technologies are likely to be implemented on a large scale over the given time horizon.

The results of this master thesis suggest that a Real Time Pricing model would realize the largest potential of Demand Response and to a relatively low cost. This solution however requires actions and further development of both the pricing model and in technology. Firstly, all market agents must have free access to real time price information, something that is lacking today. Secondly, a smart grid with hourly meters is required. If policymakers consider security of supply to be more important than a low system cost, Direct Control or a continuation of the Strategic Reserve is to be preferred according to the conclusions of this report.

Previous studies have placed the existing potential for industrial Demand Response in Sweden between 600 and 900 MW. This report suggests that the available volume is in the upper region of the mentioned interval already today and has potential to rise significantly in the future as industries become more aware of the concept and the transmission grid is becoming more flexible. Another driving force for increased Demand Response volumes are the increased price fluctuations which are expected as a consequence of a greater share of renewable energy sources. For the future Demand Response potential, a cost perspective is introduced and a distinction between different response durations is made. More specifically the results indicate that the potential industrial Demand Response volume will be about 1,500 MW in 2030, given a response duration time of 4 h and a spot price on 2,000 SEK/MWh.

If 1,500 MW of peak generation capacity could be avoided through active Demand Side Management, it would reduce the system cost with about 350 Million SEK annually. Consequently, there is a business case for Demand Response and the issue is likely to be subject to further investigation and discussion in the future. On the long term however industrial Demand Response must be compared with other flexibility options, e.g. as import/export or energy storages but also residential Demand Response, and is in such case likely to be outcompeted due to its relatively high variable cost of providing capacity.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AS</td>
<td>Ancillary Services</td>
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<tr>
<td>CM</td>
<td>Capacity Market</td>
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<td>DC</td>
<td>Direct Control</td>
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<td>DR</td>
<td>Demand Response</td>
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<td>DSM</td>
<td>Demand Side Management</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>QAS</td>
<td>Quality assessment score</td>
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<tr>
<td>RES</td>
<td>Renewable energy sources</td>
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<td>RTP</td>
<td>Real Time Pricing</td>
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<tr>
<td>SEA</td>
<td>Swedish Energy Agency (Sv. SEA)</td>
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<tr>
<td>SoS</td>
<td>Security of Supply</td>
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<td>SR</td>
<td>Strategic Reserve</td>
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<td>SvK</td>
<td>Swedish National Grid (Sv. Svenska Kraftnät))</td>
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<tr>
<td>ToU</td>
<td>Time of Use</td>
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<tr>
<td>TSO</td>
<td>Transmission system operator</td>
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1 INTRODUCTION

In this opening chapter, the reader is being introduced to the topic of this master thesis. A description of the background gives a context to Demand Response. The purpose of the thesis is also presented, followed by a framing of research questions that together with the delimitations specifies the purpose further. In addition a target audience is defined and given a thesis outline.

1.1 BACKGROUND

This section introduces the reader to the global energy situation as well as the Swedish power system. It gives an overview about the current state of affairs and identifies future challenges and possibilities related to Demand Response.

Energy policy is a topic which over the last few decades has caused great public debate and now has risen to the very top of the political agenda (IEA, 2013). The increased interest in the issue is logical considering the heavy energy dependency of our society; from cooking and heating to transportation and production, we use energy in different forms, and there is little that indicates any drastic changes in the foreseeable future (SEA, 2013). Another reason for energy policy having a central role in the public debate is its many intersections with other major issues; global warming, national security and economic growth are all, in different ways, closely linked to the development in the energy sector (Bergaentzle et al, 2014).

Primal energy, the original source of the recovered energy, can be either chemically bound as in fossil fuels or be kinetic energy as is the case of the blowing wind or the flowing water. This primal energy normally needs conversion to be stored or consumed conveniently. The form in which the energy is transported is called energy carrier. Electricity is one significant energy carrier, constituting up to 35% of Sweden's primal energy use (SEA, 2013), that offers many advantages including flexibility and transferability. Consequently, the importance of electricity as an energy carrier is predicted to rise over the coming decades as processes like transportation and heating become increasingly electrified (Schröppel, 2013).

Despite the many advantages of electricity as an energy carrier, the disadvantages of a system based on electricity must also be regarded. Storing, or more correctly the lack of storage options, is one of the principal disadvantages of electrical power. Electricity cannot be stored other than through conversion to other forms of energy, e.g. to potential energy in pump-power station or chemical energy in e.g. power to gas processes (Dabur et al, 2012). In each conversion there are large energy losses which make the storage inefficient and hence relatively costly. The mix of energy resources within the power system is another problematic issue (IEA, 2013). Today, much of the power is generated by thermal plants using coal or gas and therefore contributes significantly to the emission of CO₂. Nuclear power, another major source of energy, is experiencing severe public criticism that in some countries has already led to the decision of its long term decommissioning. The nuclear meltdown in Fukushima, Japan, has e.g. triggered a huge debate in Germany recently ant thereby paved the way for a completely new energy policy. Those options of renewable energy sources (RES) that remain in the mid-term future, predominantly solar- and wind power, are facing profitability challenges and, more seriously, lack the basic characteristics of being the reliable base load of the system due to its by nature intermittent power generation (IHS CERA, 2014). With intermittent generation is understood that the production volume is weather dependent and hence volatile. Another more practical, disadvantage of electricity is the need for transportation. Technically, electricity is easily transmitted with acceptable losses but the grid needs to meet several requirements out of which the power balance in the system is the most critical (SvK, 2007).
Since a large-scale, economically profitable technology for storing electricity has yet to be developed, the requirement of power balance in the electricity grid implies that generated power must match the demand at each given point in time (Bergaentzle et al, 2014). Even if the energy balance could be maintained without nuclear power through the build out of RES, the power balance also needs to be satisfied in order to keep the lights on. In practice that means that e.g. wind power can be built in a scale that corresponds to the yearly electricity generation from nuclear plants, but the system would still suffer from power shortages when there is no wind if the balancing power resources are insufficient. The Swedish Power Grid (SvK), a state owned transmission system operator (TSO), has the main responsibility for keeping the power balance in the system but many agents, i.e. utilities and major electricity consumers, also have a statutory balance obligation. Due to this obligation, all major agents on the electricity market have to forecast and report their planned consumption/production in advance to enable SvK to keep the balance in the grid (SvK, 2007) and are charged for deviations.

Historically, Sweden and most of the western European countries have committed themselves to a supply oriented approach, meaning that the demand has defined the volume which has been met by a sufficient utilization of existing generation capacity (Albadi & El-Saadany, 2008). From a balance perspective however, there is no difference between added capacity on the supply side and a reduced demand (IHS Energy, 2014). The concept of Demand Side Management (DSM) includes general energy efficiency as well as Demand Response (DR) that targets large users to reduce their demand during critical peak situations (Chuang & Gellings, 2008). A technical problem at a base load power plant could be one example on such a peak situation, e.g. would a disconnection of a 1,000 MW nuclear reactor correspond to an outright loss of 5 % of the operating generation capacity on average. Extreme weather could also cause stress in the system, as more electricity is needed on cold winter days and less electricity is produced when there is no wind. A combination of these incidents occurring simultaneously would cause an extreme peak situation. In case of power shortage, technical equipment can get damaged due to frequency oscillations, and severe power shortage could lead to power failures in some regions.

The concept of DSM in general, and DR in particular, is predicted to play a role of growing importance in the future power system (Gils, 2014). This because of mainly two reasons. Firstly there have been too small investments in production capacity during the last years to ensure long term security of supply (SoS). Secondly, prices are predicted to fluctuate more as intermittent RES come to constitute an increased proportion of the energy mix. Already today, part of Sweden’s power reserve consists of DR-resources and in the future it is possible that DR will be of growing importance (SvK, 2014).

1.2 PROBLEM SPECIFICATION

This section narrows down the broad introduction to a specific problem; the power balance in a future, post-nuclear, Swedish power system. The purpose of the master thesis is connected to this identified problem.

The energy mix in Europe is gradually changing in composition and although individual countries are taking slightly different paths, such as Germany dismantling their nuclear plants whereas new reactors are planned and build in France (European Commission, 2012), there is a general trend favouring RES. E.g. RES, as proportion of the total energy production in the EU, have increased from 7 % in 1990 to 18 % in 2009 and has continued to grow since (Market observatory for Europe, 2011). In the example above hydro power, which production rate has remained fairly stable during the time period, is included; technologies such as biomass, solar- and wind power are progressing even more rapidly. There are good reasons to believe that this trend will continue as investments are steering into renewables, owing to a combination of
subsidiaries for RES and low electricity prices which make thermal plants unprofitable (IEA, 2013). Also, there is a strong public support for the development of RES. Put into a Swedish political context, the green party is advocating a 100% CO$_2$-free electricity production in Sweden as soon as 2030 (Miljöpartiet De Gröna, 2014). Also the European Union has long term targets to reduce CO$_2$ emissions with 20% by 2020 and 80 – 95% by 2050 (European Commission, 2010).

From a Swedish perspective, the potential of increased utilization of hydro power is considered to be limited as the accessible rivers are fully exploited and the remaining are under environmental protection (SEA, 2013). This implies that the lion’s share of new investments in RES would go into wind power because solar power and other options are yet struggling with profitability on a larger scale.

Wind power is a resource that produces electricity with low CO$_2$ emissions but offers no SoS due to the intermittent nature of the wind speed (IEA, 2012). Price fluctuations and challenges in the power balance are two direct implications of intermittent power production (SvK, 2007). Since the energy system needs to be in balance at each given moment in time, ways to keep the equilibrium of the equation when the demand exceeds supply must be examined. The opposite, a situation of oversupply, is normally easier to handle technically but remains nonetheless a problem as prices are dumped, resources wasted and that could affect the system cost negatively on the long term. Hence, also general energy efficiency can be used to better handle the problems relating to the power balance in the case of a nuclear phase-out.

Given a scenario where nuclear power is decommissioned and RES amount to a significant share of Swedish power production capacity, these fluctuations in power generation, and hence price levels, are predicted to occur more frequently and with increased amplitude in the future (IEA, 2012). To handle the gap between demand and supply there is, from a system perspective, three principal areas of solutions. These are illustrated in Figure 1 below.

![Figure 1 - Principle System Balancing Options](source: SEDC 2012)
One option would be to focus on the supply side; to expand the capacity base, and thereby having over capacity in the system, or increase the flexibility and manoeuvrability of the supply sources and the distribution grid (IHS CERA, 2014). One concrete option e.g. is for SvK to secure backup power generation capacity by contracting mothballed gas turbines with short response time to compensate for the intermittent production of RES (Alterbeck, 2014). This kind of over capacity is expensive however and an increased system cost might affect the whole society negatively in terms of competitiveness and efficiency (IHS CERA, 2014).

The second category of conceptual solutions would be the option of storing electricity which includes everything from pump-storage power plants and power to gas technologies to small scale storing in electrical cars or other batteries (IEA, 2012). Doubtlessly, this area has huge potential but a technical breakthrough has yet to occur. For the time being, there is no cost-efficient way of large scale transformation of electricity in the time dimension (Ma et al, 2014).

Finally, there is an option to work with the DSM (McKinsey, 2010). One subset of DSM is general energy efficiency, another is DR which includes load management. DR, and especially industrial DR is the very focus of this thesis. Technically there are two basic types of DR; load shifting and load shedding. Load shifting means transferring load in the time dimension, e.g. producing less today but more tomorrow. Load shedding implies a complete, or partial, non-recoverable reduction in the use of electrical power (Dabur et al, 2012). DR is already in active operation in different parts of the world (SEDC, 2014) and has the potential of assuming a greater role in the future (Badawy et al, 2013). To determine whether it is a good option however, certain aspects must be taken into consideration; how much power demand can be shifted (transferred in time) or shedded (cancelled)? What market design (DR-program) could facilitate a realization of the potential? Also, to determine whether DR would be an economically justifiable alternative to other flexibility options the system cost has to be estimated (Garg et al, 2011).

The power balance of a future power system, containing a high share of RES as described above, is a most practical contemporary problem which has yet to be solved (European Commission, 2012). This is why many market agents, such as governments and utilities, are working with DR programs. However, the issue is also interesting from an academic point of view since there are large knowledge gaps in the area which complicates decision making (Kiani & Annaswamy, 2014) and research areas which have yet to be penetrated (Söder, 2014). More specifically, Söder recently published a report based on simulations of a future electricity system with a high share of intermittent energy sources. His conclusions resulted in an urge for further research in the area, pointing out fields of special interests.

"There is a need for an analysis of the electricity market and its pricing model in a scenario with more RES. It is a big challenge as the contemporary pricing model is based on marginal costs and such a model faces huge challenges if there is a large proportion of intermittent RES, with low variable cost, operating within the system" (Söder, 2014)

After giving suggestions on more technical issues which need to be examined further, such as simulations of different types of weather scenarios and investigations in the agility of the future international transmission grid, Söder continues:

"The most cost-efficient way to obtain secure peak-capacity needs also to be studied further, especially if this is to be done by renewables alone. It is possible to include Demand Response and gas turbines which run on natural gas in this discussion." (Söder, 2014)

The electricity market is very complex and all fields of research in the area are strongly interconnected. For example two of the theoretical problems Professor Söder mentioned in his recommendations for further investigation, market design and peak capacity, are mutually
dependent as the availability of the peak capacity ultimately depends on the possibility for the capacity owner to recover the investments. Consequently, the academic problem, of which the society yet lack sufficient knowledge to make appropriate decisions and take action, reads: How can an electricity market be designed so that it secures available and affordable peak capacity in a system with a high share of intermittent production in terms of RES?

1.3 PURPOSE

In this section the purpose of the master thesis is presented along with accompanying research questions. Moreover, the expected results are defined.

The purpose of this report has been formulated together with the different stakeholders of the master thesis, including Vattenfall AB and Linköping University. The purpose of the master thesis is to:

Contribute to the understanding of industrial DR in the future Swedish electricity market and thereby provide a knowledgebase for decision makers and investors by estimating the future potential of industrial DR in Sweden.

A framing of questions has been conducted with the intention that adequate answers to each research question would sum up to satisfy the purpose. In the case of a phase out of existing nuclear power plants...

- ... which future market design for industrial DR is most feasible?
- ... what would the estimated potential of industrial DR-volume be?
- ... to what cost approximately could the potential DR-volume be realised under such market conditions?

The order of the research questions are logical in the sense that the DR-volume depends on the market design and therefore must the feasibility of different DR-programs be investigated and a base case scenario assumed before the future DR-volume can be estimated.

The research of the master thesis is to result in two models:

- A typology of existing DR-programs based on the parameters cost, volume and feasibility, given the base case scenario where nuclear power is phased out and replaced by RES. In the typology of DR-programs, the parameter of cost corresponds to the total system of a specific DR-program including investment cost, subsidies, variable costs etc. Volume means how much DR-potential that is released by a specific DR-program. Feasibility means, in this case, how well a specific DR-program fits to the future Swedish electricity market and thereby how plausible a successful implementation would be. The feasibility depends in turn on factors such as technical viability, economical justifiability and legislative limitations.

- A demand side Merit-Order graph of future industrial DR-potential, illustrating price levels and volumes for different response durations. The graph is to answer the question: given the assumed base case scenario and the most feasible DR-program, how much industrial DR-volume will be available as a function of price level and response duration times.

The construction of the models for presenting the results and the definition of the underlying parameters are more closely described in the chapter 5, methodology.
1.4 DELIMITATIONS

The ambition of this section is to clarify what research areas which are included in the scope of this master thesis and, perhaps equally important, to determine what is not.

The delimitations below are divided into different categories such as geographical, technical or practical delimitations. The boundaries are not absolute in nature but rather highlight the focus areas.

The geographical focus is on the Swedish electricity market. However, since the Swedish electricity market is strongly interconnected with the other Nordic countries, these will also be examined when needed. Although the results target Sweden, data will be collected globally to serve as a theoretical frame of reference.

The studied time horizon is 2025 – 2050. The actual focus of the thesis is a hypothetical situation, that of a need for DSM, rather than a period in time. However, if the existing nuclear power plants are being phased out without replacement, this situation is likely to occur sometime after 2025 and be a permanently present phenomena until 2050, after which the number and scale of uncertainties makes predictions even more uncertain.

From a technical perspective, only technologies which are currently in operation or under construction are being considered. New concepts for generating, storing or managing electricity is assessed to emerge during the given time horizon but such development has not been taken into account because of the high uncertainties and the difficulties in scenario analysis that such an approach would imply.

In this master thesis, DR-programs are referring to the financial concepts, i.e. payment models and contract forms that are included in the study. DR-programs on different levels and markets are described and evaluated. The technical aspects of the DR are on the contrary, although briefly presented, not the centre of attention in this master thesis. The focus is on DR as a subset of DSM. General energy efficiency is a natural by-product of several DR-programs but is not part of this thesis on own merits.

DR can operate on many different market levels and customer segments. Industrial DR is the focus segment of this master thesis, including industrial and commercial electricity users with a peak power demand over 5 MW. This delimitation is in line with the current limitation of customers obliged to participate in SvKs capacity reserve programs. Exceptions are made for residential or private customers who are part of consolidations of which the aggregated demand reaches 5 MW. Although the results are only presenting industrial DR-potentials, residential DR-potential is studied to complete the total picture of future DR prospects.

The results of this master thesis is based on a reference scenario (called the base case scenario) in which the European electricity market remains fragmented, even though the slow increase of international integration is expected to continue. In Sweden, the nuclear power is phased out and gradually replaced by RES. There are several alternative scenarios for the development of the Swedish and European markets; these however will only be examined more briefly.

1.5 TARGET AUDIENCE

This section defines the target group of the report and gives aimed reading recommendations.

Each author has a target group in mind while writing the text. This being a master thesis, the target groups are three; electricity market participants, fellow academic researchers and the broader public.
The primary target audience of this master thesis are decision makers within organizations which operate on the electricity market. The main motivation is that the result of the thesis can be of use for different agents on the electricity market, such as utilities, policy makers and large electricity consumers, who are interested in the future characteristics of their business environment. As this audience are assigned a good understanding of the current situation and the terminology used, they might want to focus on the results of the scientific review and the interview series (chapter 8) and the conclusions in chapter 9.

Another ambition is that future scholars in the same, or related, fields of research shall be able to find help and support in this thesis for their theoretical framework and empirical background. For this reason definitions are stated clearly, data presented structured and the methods used are academically recognized and accepted.

Finally, this master thesis intent to become an element in the public debate about the future Swedish electricity market. The extensive chapter on the Swedish electricity market, the outline of previous work and the appendix describing the electricity market in detail are included in the report for the convenience of readers who may lack previous understanding of the electricity market.

1.6 THESIS OUTLINE

The outline of the master thesis in this section is presented to help the reader to easily navigate in the report. The main content of each chapter is described shortly.

CHAPTER TWO – THE SWEDISH ELECTRICITY MARKET

This chapter contains a description of the Swedish electricity market in general as well as a more detailed mapping of the power balancing mechanisms. The information below is regarded as necessary background for the discussions later in the report. The reader who desires a more basic explanation of the electricity market is referred to appendix 1.

CHAPTER THREE – BASE CASE SCENARIO

This chapter serves as a context for all further discussion. The base case scenario is one possible future scenario for the electricity market that includes information about demand production and market regulations. In the end of the chapter, a short review of previous work on the future electricity market is given alongside some alternative scenarios.

CHAPTER FOUR – DEMAND RESPONSE

In this chapter, the concept of Demand Response is introduced and explained as are the different Demand Response programs which are included in this study. Thereafter some previous work on Demand Response are reviewed and discussed in order to give the reader a broader perspective on the issue. Finally some knowledge gaps, which this master thesis with regard to its purpose can help to close, are identified.

CHAPTER FIVE – METHODOLOGY

The basic purpose of this chapter is to describe what has been done, how it was done and why. Alternative solutions and their possible implications on the results are also discussed. The chapter focuses on the process for collecting data and the models for presenting the results.
CHAPTER SIX – THE CASE STUDY

In his chapter, the results from case study are summarized. The case study was performed through a systematic review, for further information see chapter five. First in this chapter, each source included in the review is given a quality assessment score. Thereafter, the extracted data are presented in a Table.

CHAPTER SEVEN – PERSPECTIVES ON DEMAND RESPONSE

The chapter gives a record for the interview series conducted with respondents from different stakeholders in the electricity market. The interview series were complemented with literature research and data from e.g. annual reports from the companies included in the study. The results are divided by industry and are to be regarded as an industry perspective rather than the opinion of any specific company.

CHAPTER EIGHT – ANALYSIS

In the first section of this chapter, the results from the case study and the interview series are analysed separately. Subsequently, the results are merged through a synthesis and put into the context of the base case scenario, which is resulting in a typology for DR-options as well as a demand side Merit-Order curve for future DR potential. In the final section, a summary of results is given.

CHAPTER NINE – CONCLUDING DISCUSSION

This final chapter includes a short discussion section giving some perspectives on the previously presented results before presenting the conclusions of this master thesis. The focus of the chapter is to answer positively on the purpose of the thesis and thereby address the knowledge gaps of previous works.
2 THE SWEDISH ELECTRICITY MARKET

This chapter contains a description of the Swedish electricity market in general as well as a more detailed mapping of the power balancing mechanisms. The information below is regarded as necessary background for the discussions later in the report. The reader who desires a more basic explanation of the electricity market is referred to appendix 1.

2.1 ELECTRICITY MARKET FUNCTION

This section provides information about the current situation in the Swedish electricity market in terms of electricity producing resources, demand characteristics and the divided transmission grid.

The Swedish electricity market is part of the Nordic electricity market Nord Pool. With regard to the delimitations of this master thesis however, the section will have a national focus while describing the production, transmission and consumption of electricity and the different market levels associated with the power system.

ELECTRICITY PRODUCTION

The total electricity production in Sweden amounted to 162 TWh in 2012 (SCB, 2013). In Figure 2 below, a graphical representation of the historical electricity production is presented as well as the proportion of each major energy source in the energy mix.

As illustrated by Figure 2 above, the base production in Sweden consists of nuclear power and hydro power. Together these two energy sources constitute over 85 % of the total electricity generation, forming the back bone of the system. Wind power has experienced massive investments throughout the last decade. Despite producing only 5-10 % of total electricity, the about 50 % of the investments in new capacity are connected to RES (IEA, 2013). However despite the increase in installed wind power capacity, wind power only contributed with 4 % of the total electricity generation in Sweden 2012 due to the low availability factor. The remaining power was generated by condensing power plants; categorized by fuel, bio-power and fossil fuels contributed with 7 % respectively 3 % of the total electricity generation. (SEA, 2013)

The Swedish electricity production is thereby rather environmentally friendly from an environmental point of view; only 3 % of the generation contribute significantly to CO₂.
emissions. Moreover, the current composition of different energy sources, which can be observed in Figure 3 below, offers low prices as well as a high SoS. Sweden has in total 37,000 MW of installed capacity (SEA, 2013). This can be related to the defined maximum power need of a 10-year winter, which is the coldest winter expected over a 10-years period, being 28,000 MW (SvK, 2014).

The electricity producing technologies could be divided into different categories depending on their time-variable generation characteristics (IEA, 2008). The nuclear plants, and to some extent the hydro power, are so called base loads. That implies that the production level is normally very stable, without any regard to price levels or sudden changes in demand. On top of that, wind, solar and other RES are forming a group of what is called intermittent production. That means they always produce at a maximum, depending on the conditions e.g. weather, regardless of external factors such as price or demand. Sometimes the RES contribute largely to the system, at other occasions the intermittent production is close to zero. To handle the fluctuations that arise, both due to cyclical changes in demand and intermittent production, the remaining part of the production capacity is called regulating load or balancing power (SvK, 2007). This includes thermal plants which offer certain flexibility as they can be switched on and off easily. However, the lion’s share of the balancing power in the Nordic countries is hydro based. Hydro power is well suited for the frequency regulating task as the production easily can be adjusted by controlling the water flow through the turbines. A final possibility to meet the demand is to use the connections of the international transmission grid, importing or exporting power according to need. This possibility is limited not only by the capacity of the transmission cables, but also by current situation in the neighbouring countries (SvK, 2014).

**ELECTRICITY USE**

The total electricity use 2012, including transmission losses, was 142 TWh (SCB, 2013). In relation, the total electricity production for the same period was 162 TWh meaning Sweden has had a significant power surplus which have kept electricity prices down and allowed exports during the last few years. The consumption is commonly divided between the industry-, commercial- and residential sectors. Figure 4 below is making the historical demand visible.
The industry sector was the largest electricity consumer in year 2012, using over 52 TWh. In Sweden a few industries dominate the industrial electricity demand, those being paper & pulp, metal working and chemical industries. Together they used 36 TWh 2012. The Second largest consumer segment was the residential sector that consumed about 43 TWh in 2012. The demand of this sector is divided by a great number of private end-users who typically are less sensitive to the price of electricity. The commercial sector is, as the transportation sector, becoming increasingly electrified and both sectors are likely to represent a greater share of the total demand in the future Swedish electricity market.

TRANSMISSION

The electricity needs to be transported from the power producers to the end-consumers. The Swedish power system is characterized by a geographical obstacle. Due to the location of the rivers and the varying density of population, Sweden has extensive production capacity in the northern parts of the country but a greater demand in the south. The national transmission grid enables transportation of electricity from the hydro power plants in the north to the households and industries in the south. However, this causes transmission losses and the government wishes to create incentives for relocating production sites and large power consumers. Consequently, Sweden is divided into 4 price zones between which prices can differ as demand and supply is matched separately in each electricity zone. This is nothing unique since the entire Nord Pool market is divided into price zones between which spot prices may vary. The geographical price zones are intended to match physical bottlenecks in the transmission grid. The division of the Swedish electricity market into SE1, SE2, SE3 and SE4 are to be examined in Figure 5 below.
As mentioned, the intention behind the price areas is to model the actual limitations in the Swedish transmission grid; the border between two zones reflects a physical bottleneck in the cable network. If the needed transmission between the different zones, national or international, is less than the maximum transmission capacity the price level will be constant throughout the system. If the required transmission exceed the capacity the prices will begin to differ, which they typically do. The price level is defined by the highest accepted production bid in the local price area. This is called marginal pricing. The long term ambition of SvK is that the local price differences will be smoothen by increased capacity investments in areas with high demand and high electricity prices. (Nord Pool, 2014)

2.2 ELECTRICITY MARKET PARTICIPANTS

This section maps the different market participants; government agencies, utilities, large consumers, retailers etc. and gives an account for each role.

In order to better understand the dynamics of the electricity market and the motivations of different market participants, the major agents in the market are presented and described below. The market agents are sorted after system level of operation, with organisations which have total system responsibilities first and individual end users last.

THE SWEDISH ENERGY AGENCY

The mission of the Swedish Energy Agency (SEA) is to promote and develop Sweden's electricity system in an economically and environmentally sustainable way. This means designing a system that lets its participants produce cost-efficient electricity while taking environmental care. The SEA is working with national energy policy issues and is one out of two Swedish government authorities with responsibility for the electricity market (SEA, 2013). The other one being the Swedish Energy Markets Inspectorate, which is monitoring the competitiveness and regulating legislation of the electricity market (Energimarknadsinspektionen, 2014).

In practice, SEA works with forecasting the future market in order to adjust the market design. The base case scenario in this report is largely based on forecasts made by SEA. Moreover SEA is working with education and information on electricity issues and organizes new projects in cooperation with different market agents such as SvK or utilities. SEA has also an investment fund that are used to promote new solutions that otherwise wouldn't make it to the market. One example is Smart Grid Gotland, a pilot project in which a modern, smart meter based, electricity grid is being build. A smart meter is an electronic device that records and controls electricity in intervals shorter that one hour and is able to communicate this information to a superior system. If all components in a system satisfy the mentioned criteria's a smart grid is formed (Sammordningsrådet för smarta elnät, 2012). Another example is Norra Djurgårdsstaden, where an energy efficient city is being built partially financed by SEA.

POWER GRID OWNERS

To deliver the electricity from the electricity production sites to the industries and residential customers, a power transmission grid is needed for distribution. The Swedish power transmission grid is divided into three different levels, technical as well as operational. Those being the national transmission grid, the regional grids and the local grids. The national transmission grid is of high voltage and is used to transport the electricity over long distances and to connect the different regional and local networks. This backbone grid is fully owned and operated by SvK who charge both producers and downstream network owners a fee for being connected to and provided by the system.
The regional networks are mainly a connection between the national transmission grid and the local grids which ultimately deliver the electricity to households and industries. The regional and local nets are commonly owned by power grid operators, companies specialized in transmitting electricity. These power grid operators are responsible for the maintenance of the grid and are adding their expenses on the end customer’s electricity bill. The rate is reported and controlled by the Swedish Energy Markets Inspectate. It is not allowed for an organization to both own the network and to trade electricity through it, according to the law on competition. All flow of electricity is measured and reported, this to facilitate settlement and billings as well as for authorities to keep statistics. (SvK, 2007)

**TRANSMISSION SYSTEM OPERATOR**

SvK (The Swedish National Grid) is a state-controlled company that owns the backbone of the domestic power grid and whose main function is to transmit the electricity from the major power plants to the regional grids. Their work is dictated by the government and paid for by electricity producer and electricity users through grid fees. Apart from maintaining and improving the infrastructure, SvK has major responsibilities such as emergency preparedness in case of disturbances and maintaining the power balance of the system. (SvK, 2007)

SvK is a monopolist TSO on the Swedish electricity market and does as such carry the full responsibility for the functionality of the electricity system. Beside their responsibility for maintaining the standard and capacity of the national transmission grid, this task includes an ultimate responsibility for the power balance. That implies that the sum of all production and import must at each given point in time equal the sum of consumption and export. In practice, this is done by the market but SvK needs constantly to adjust the balance in the grid through different operations which are yet to be described. In short, SvK regulates the frequency during the hours of operation, manages the national balance settlements and are acquiring long term reserve capacity to deal with disturbances in the system to guarantee SoS. (SvK, 2007)

**ELECTRICITY PRODUCERS**

Electricity producers (utilities) are companies who generate electricity and, through entry points, feed the grid with power. In Sweden, a few electricity producers dominate the market. Vattenfall AB, EON and Fortum together have a market share on 84 % (SCB, 2013), leaving 16 % to local producers and Norwegian owned Statkraft. Figure 6 below illustrates this relation.

![Figure 6 - Market Shares of Largest Electricity Producers in Sweden](source: SCB (2013))
It is possible for the electricity producers to have direct contract with the end user, and to some extent this is the case in e.g. the power contracts with large industrial customers. However, a vast majority of the produced electricity is sold to electricity retailers who in turn contract the individual customers. To enable SvK to maintain the power balance, all energy producers and end-customers need to be, or be represented by, a balance provider. (Vattenfall, 2014)

**BALANCE PROVIDERS**

It is of vital importance that there is balance between production and consumption and that the frequency in the system remains between 49.9–50.1 Hz. The guarantee for the maintained balance in the power system are the contracts between balance provider and SvK. Large electricity consumers, e.g. large industries, are balance providers themselves but electricity retailer carries the balance responsibility for the lion’s share of electricity demand going to private or commercial end consumption. Market agents with balancing responsibility commit themselves in advance to a certain outtake from, or input to, the system. To meet the commitment, the balance provider can plan or forecast the electricity use closely, adjust their own demand or production during operational hours, or through trading electricity on the Nord Pool market in order to compensate for the deviations. Finally, SvK has the responsibility to take measures to compensate for any remaining imbalances. Through the settlement, a balance provider will be charged for any deviations between its commitment and the actual outcome. The size of the fee depends on the measures taken by SvK as well as the amplitude of the error. The balance provider can also be active on the balancing power market, a secondary market that SvK has created to better be able to deal with fluctuations in the system (SvK, 2007). This market and the other market levels will be described in section 2.3 below.

**ELECTRICITY RETAILERS**

An electricity retailer is a collective term for all agents who trade with electricity on the Nordic electricity market. These agents can be aggregators with balancing responsibility, but it could also be electricity producing companies. These two groups of agents have different reason for being on the market; the electricity producers are trying to sell their production whereas the balance providing aggregators are buying electricity to satisfy the demand of the customers in their portfolio. Every electricity user or producer must have a balance provider who carries the legal and financial responsibility if obligations are not met. This can either be solved internally or through contracts with a third party balance provider. (Nilsson & Hammarstedt, 2014)

**AGGREGATORS**

The role of the aggregator is relatively new on the Swedish electricity market. The aggregator collects different capacity resources, e.g. peak power generators or DR-resources in a portfolio to sell products that are custom made for the Swedish balancing power market. The market for reserve capacity has a bid limit for volumes at 10 MW (5 MW in SE4) which excluded many customers. The entry of aggregators on the balance market enables the realization of new, large, flexibility potentials within the residential sector, services and small industries. The aggregator contracts the demand flexibility of individual consumers, repackages the smaller loads into price coherent block bids which can be offered at the balancing power market. The aggregator has the responsibility to coordinate its resources from a control station. (Eriksson & Sandwall, 2014)

**ELECTRICITY USERS**

The end user of electricity is either a company, government agent or a private person. The individual consumer needs a contract with an electricity retailer, to get the physical delivery of electricity, and contract with the local power grid operator to get access to a connection point.
Through the electricity network charge the customer gets access to all of SvK and its international connection within the common Nordic electricity market and can therefor choose any electricity retailer on the market (SvK, 2007). Some energy intensive industries have high voltage connection points directly into the regional grids which makes them independent of a local network operator. Still, they need to pay a network fee to SvK and to contract an electricity retailer. (Nord Pool, 2014)

2.3 ELECTRICITY MARKET LEVELS

This section explains how the electricity wholesale market is designed. The underlying principle is presented as well as the different market levels that exist within the Nord Pool market region.

As previously mentioned, the Swedish electricity market is not a national issue but part of a common Nordic electricity market; the Nord Pool Spot. Roughly 70 % of the electricity sold and used within the Nordic system boundaries passes through the trading floor of Nord Pool. The remaining electricity is traded through bilateral agreements between producers and consumers (Nord Pool, 2014). Through these agreements, the market agents commit themselves to trade specified volumes for long period of time, which enables a fixed price rate on a mid-long horizon.

Because the market is divided into different price areas, the trade is taking place on several markets at different locations. There is also a time dimension with regard to the trade of electricity, resulting in additional markets. For the concept of DR, the distinction between different points in time is of vital importance (Alterbeck, 2014). Figure 7 below illustrates the different market levels and how they relate to the time dimension. The market levels which are part of Nord Pool, that excludes the financial market, will be discussed below.

![Figure 7 - Different Market Levels for Electricity in the Time Dimension](image)

**SPOT MARKET**

The lion’s share of the electricity is traded on the spot market, also called the Nord Pool spot or day ahead market internationally. On the spot market, buyers and sellers submit bids regarding the forthcoming day and when there is a match in bids, the different market agents are entering agreements and signing contracts. The traded volumes are based on forecasts from both producers and customers, since it’s difficult to know exactly what the final quantities will be. The bids are often price dependent; the demanded or offered volumes are functions of the price. A supplier typically would be able to generate more electricity given a higher price level whereas an electricity retailer would normally by larger volumes at lower price levels. (Nord Pool, 2014)

The spot market closes at 12:00 one day before delivery, at which point all the bids are listed and matched. During this process, a price cross arises where the separate supply and demand curves intersect. The corresponding price level of the intersection defines the system price level for each hour for the following day. As mentioned in the section before, it is possible for the price
levels to differ between the price areas, nationally as well as internationally, if the need for transmission in order to level the system prices exceeds the available cable capacity. Figure 8 below illustrates this through giving a theoretical representation of the market. (SvK, 2007)

![Figure 8 - Principle Market Pricing Mechanism; The Supply and Demand Curve Intersection](image)

**Figure 8 - Principle Market Pricing Mechanism; The Supply and Demand Curve Intersection**

A distinction can be made between price dependent and price independent customers. A price independent customer buys a specified volume regardless of the spot price. For example, it could be a private household customer with small consumption for whom fluctuations in electricity prices are having but a minor economic consequence. It also includes electricity users who are so dependent on electricity that they have little or no option but buy the required amount of electricity. These customers, typically energy intensive industries, have secured themselves against risk, caused by price fluctuations in the electricity market, by long-term hedges on the financial market. In opposite the price dependent customers, e.g. companies with low profit margins which have not contracted a fix electricity price, submit price variable bids and are able to adjust their consumption to the current price level. These customers are offering flexibility to the market and are highly interesting from a DSM perspective. (Nilsson & Hammarstedt, 2014)

**INTRA-DAY MARKET**

Despite the existence of the day ahead spot market, unexpected events do occur; a power plant can go down for a period, a factory can suffer sudden shut downs or a change in the weather conditions can drastically impact the amount of produced electricity from wind power or increase the need for electrical heating. This being the case, another market called intra-day market, or Elbas, begins at 14:00, two hours after the closure of the day ahead market. The main objective of the intraday market is to give market agents a better possibility to keep their balance commitment by continue trading, letting the customer or producer adjust their volumes until 45 minutes before delivery hour. In practice, the market never closes because trading is going on continuously. Having reached the time of 45 minutes before deliverance though, all bids turn economically binding and any deviations will cost in terms of charges. (SvK, 2007)

**POWER BALANCING MARKET**

During the delivery hour, SvK is taking over the responsibility for balancing the system and for maintaining a stable frequency in the grid. In doing so, SvK is inviting market agents to participate on a balancing power-, or *intra-hour*, market where suppliers and consumers can sell
flexibility services in terms of capacity. SvK thereby has the option to call off bids, either to adjust the production or to reduce the demand. Every agent participating on the balancing power market needs a balance provider. Another limitation is the required bid size on 10 MW (5 MW in SE4) (SvK, 2014). There is no formal requirement on the response time, but normally an adjustment must be possible to carry out within 15 minutes. To facilitate the settlement, the participating market agents have installed smart meters which can measure and communicate power demand in real time (Sammordningsrådet för smarta elnät, 2012).

The bids on the balancing power market need to include the following information (SvK, 2014):

- Power capacity
- Costs (activation cost and variable costs)
- Time (activation and duration time)
- Price area
- Type of response (production or flexible consumption)

The bids are subsequently processed by the Nordic TSO:s into an aggregated bid staircase based on price and capacity. If a need for balancing power arises, SvK start calling off the bids starting with the most cost efficient option. This is a form of manual regulation and, although automatic regulation does occur, the trigger is commonly phone calls to the balance provider of the market agent whose bid has been called off (SvK, 2014). Figure 9 below illustrates the bid staircase of the balancing power market.

![Bid Staircase on the Regulating Power Market](image)

After each delivery hour, a settlement is made. First, SvK calculates how big the deviations have been and notifies the balance providers that have failed to meet their commitments. The cost of regulation is thereafter divided between the defaulting parties who have created the need for regulation. The charge is based on two parameters; the scale of the deviation and the direction of the default. The direction is important because even if the system needed to be balanced upwards, and an individual producer actually produced more than expected. As such a deviation is less harmful than a generation deficit would have been, it is charged differently. (SvK, 2007)

This market design, together with the stable energy mix in the Swedish system, has proven successful and Sweden has not suffered from any major power shortages the last 20 years. Still, a certain risk remains due to the uncertainty that comes with a free market in which no actions or responses are guaranteed. Because of this reason SvK has, supported by the law of the power reserve (2003:436) formed a capacity reserve for the winter periods (November – March). There is also an active reserve for the case of system disturbance. These programs are described in the following sections. (SvK, 2007)
2.4 RESERVES AND SYSTEM SECURITY

This section describes the different reserves which exist to guarantee the operational durability of the system as well as the security of supply.

THE POWER RESERVE

The power reserve is, as the name suggest, a collection of capacity which is to guarantee the power balance of the electricity system in case of demand peaks during the winter period. The reserve is procured yearly and consists of reserve production capacity as well as consumption reductions from large electricity consumers. To be part of the power reserve, an agent needs a balance provider and to meet the bid size requirement on 10 MW (5 MW for SE4). The participants are offered a fixed payment per MW for taking part in the program and agree with SvK on predefined variable payments. The most cost efficient options, which meet the SoS requirements, are included in the power reserve. To give an example, for the winter 2012–2013 the average fixed payment per MW was 68,000 SEK/MW. Having signed the contract, SvK has full disposal right over the resources given the predefined financial remuneration. (SvK, 2014)

The Swedish government has declared that the power reserve is to be dissolved by 2020. The intention is for a market solution, based on demand side flexibility, to replace the regulated power reserve. The phase-out is to be a gradual process. Firstly, the power reserve is to be phased out by a stepwise reduction of its volume from year to year. 2013 the power reserve amounted to 2,000 MW and the set target for 2019–2020 is for it to be only 750 MW. Secondly, the intention is to increase the proportion of consumption reduction from todays 25 % to constituting 100 % of the remaining power reserve in 2019–2020. Table 1 below shows the plan for the remaining years of power reserve. (SvK, 2014)

<table>
<thead>
<tr>
<th>Year</th>
<th>Power Reserve (MW)</th>
<th>Demand reduction (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011–2013</td>
<td>1,750</td>
<td>450</td>
</tr>
<tr>
<td>2013–2015</td>
<td>1,500</td>
<td>750</td>
</tr>
<tr>
<td>2015–2017</td>
<td>1,000</td>
<td>750</td>
</tr>
<tr>
<td>2017–2020</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>2020–</td>
<td>0</td>
<td>&gt;750</td>
</tr>
</tbody>
</table>

As a consequence of this policy, more demand reduction bids will be searched for and subsidized, resulting in a bigger balancing power market in the future. When the power reserve is finally phased out in March 2020, the intention is that those industries and aggregators who had previously been part of the power reserve will now be agents on the balancing power market. (Nilsson & Hammarstedt, 2014)

ADDITIONAL CAPACITY RESERVES

Apart from the power reserve described above, which in international vocabulary would be a tertiary balancing mechanism, SvK also has a primary reserve (FCR) and a secondary reserve (FRR) in order to maintain a stable frequency about 50 Hz in the power grid. The principal difference between the different capacity reserves is the activation time, while also the size and composition of the reserves differ. FCR is almost instantaneous whereas FRR requires a longer activation time (SvK, 2014). A detailed description of the FCR and the FRR is given in appendix V.
3 THE BASE CASE SCENARIO

This chapter serves as a context for all further discussion. The base case scenario is one possible future scenario for the electricity market that includes information about demand production and market regulations. In the end of the chapter, a short review of previous work on the future electricity market is given alongside some alternative scenarios.

The base case scenario presented below is based on scenario 2 from the report *Roadmap 2050* (SEA, 2012), corresponding scenario 2 describes by NEPP (2014) complemented with the delimitations of this master thesis.

3.1 MARKET ASSUMPTIONS

This section states the basic assumptions upon which the entire base case scenario builds.

The base case scenario is based on some major assumptions made by SEA in their *Roadmap 2050* and *Long term market outlook 2012*. The major assumptions made are presented below:

- Carbon emission reduced to “close to 0” by year 2050. The approach assumes higher environmental ambitions than today and a non-binding EU target on 75 % RES by 2050.

Sweden operates in line with to the European plan to reduce carbon emission (European Commission, 2010). By 2050, the net emission of CO₂ is expected to be close to zero. To reach this target, subsidies encourage an increased share of RES combined and in parallel incentives for carbon capturing technologies are being implemented for the remaining share of fossil fuelled power generation. As a part of this major technology conversion, prices on CO₂ could rise from current levels, causing higher prices on electricity and thereby triggering new investments in RES. When the new technologies are installed, around 2030, and the need for carbon emission decreases, the price on CO₂ might begin to fall again (NEPP, 2014). Figure 10 below shows a forecast on the CO₂ price connected to the scenario.

![Figure 10 - Projected CO₂ Prices](source: NEPP (2014))

- There will be no homogenously integrated European electricity system by 2050

A fragmented world is assumed (SEA, 2012). This implies that the energy systems remain regional and that international transmission limited in scale. The ultimate implication however is that energy policies will continue to differ between European countries. E.g. Figure 11 below shows the different DSM programs and capacity mechanisms in Europe today. Although some
integration is expected, there are little or no signs of any drastic change towards a more internationally convergent energy policy according to the base scenario. (NEPP, 2014)

**The electricity system is slow changing**

The infrastructure that compose the electricity system in terms of production sites, distribution networks etc. are heavy investments that are only possible to replace gradually over time. Most of the existing infrastructure has an expected lifetime on 30–50 years. This implies that regardless of energy policy and technological development, it is unlikely that there will be a major short term transformation of the system. However, on a longer time horizon, e.g. by 2050, the changes in the system could be of significant magnitude. (NEPP, 2014)

**The interconnections will be extended and import/export will increase**

The Swedish interconnections are already today being heavily invested in. For example a cable has been built between SE4 and Lithuania (SvK, 2014). Figure 12 below shows the expected extension of the Nordic interconnections.
It is not only the cable capacity that is important for import/export, but also the availability factor. This factor comes from the fact that balancing power is not always instantly available in neighbouring regions either. For example, if Sweden a windy and sunny day needs to export electricity to balance the system, it might well be windy and sunny condition in Denmark and northern Germany as well which would prevent such a solution as they too experience oversupply. Consequently, this availability factor depends on the energy mix in our neighbouring countries. Figure 13 below shows the projection of the base case scenario regarding the expected import and export based upon capacity as well as need and availability.

- The nuclear power in Sweden is phased out and replaced by

The base scenario is characterised by three macro-trends in the changing energy mix according to the Long term energy market outlook (SEA, 2012). Firstly a gradual phase out of the existing nuclear power plants. Nuclear power generation goes down from present day 40 % to 25 % by 2030 and is close to 0 % of the total energy mix by 2050. Secondly, the use of fossil fuels needs to be reduced in order to reach European climate targets. Thirdly, a rapid expansion of RES as proportion of the total energy mix is expected. RES, predominantly wind, is expected to account for 18 % of the total power generation by 2030 and over 45 % by 2050 due to further expansion of both wind and solar power.

Figure 14 below shows the energy mix projected by the base scenario for 2030 and 2050.
3.2 MARKET PRICE AND DEMAND CHARACTERISTIC

This section projects the price and demand assumptions for the base case scenario on the time horizon 2014 to 2050.

The base scenario is characterised by two important trends with regard to market price and demand characteristics (NEPP, 2014). These are:

- The aggregated demand remains relatively stable

The total electricity demand in Sweden has been fairly flat over the last decade (SCB, 2013). This development is expected to continue throughout the studied time horizon. If the demand structure is analysed, two sub trends become evident (SEA, 2013).

Firstly, a slow but steady decrease in industrial electricity demand is expected. Energy intensive industries are continuously succeeding in reducing their energy consumption. Moreover, the trend is that domestic energy intensive industries are closing down or moving abroad which contributes to a long-term decline in industrial electricity demand.

Secondly, and in opposite to the previous trend, electrification leads to increased electricity usage. Ever more processes, which previously were driven by fossil fuels or performed manually, are being electrified. The biggest sector which will experience a rapid electrification, according to the base scenario, is the transportation sector, e.g. private electric cars.

- The price of electricity will increase

Regardless of what policy or currently available technology is used to replace existing capacity, the price of electricity is predicted to rise for several reasons. A higher CO₂ price has a large influence as well as the price on natural resources. However, the most important factor is the capital cost for new investments. As most of today’s power plants are depreciated due to age, they can operate at only variable costs which lead to a low marginal price.

If the electricity prices were to reflect the true cost in future, they need to be higher. In the base scenario, where the realisation of political and environmental goals is prioritised over a low system cost, the price increase will be even more significant than in alternative scenarios. Figure 15 below shows the forecast of the electricity price from the base case scenario. The prices are all in real terms.

![FIGURE 15 - ELECTRICITY PRICES EX. TAXES, BASE SCENARIO PROJECTION. SOURCE (NEPP, 2014)](image-url)
3.3 IMPLICATIONS FOR THE POWER BALANCE

This section discusses the implications of the base case scenario for the power balance generally and how that relates to Demand Response more specifically.

There is no coherent or generally accepted theory among academic researchers about what implications a high share of RES will have on a future energy system (Larsson, 2014). One perspective is that of Professor Söder at the department of Electrical Energy Systems, KTH. Söder has simulated a future electricity system similar to the base case scenario. In an interview Söder explains the results from his research and state following opinions:

Sweden is not an isolated system but must be regarded as part of a larger, European electricity system. What will happen in Sweden depends much on the EU. However, a high share of RES implies a certain electricity surplus on a yearly basis. To export this surplus electricity would be one option but it is not given that import/export is always an option since the availability depends on the situation in the neighbouring countries. Sweden has a 10,000 MW import/export capacity today. This capacity is likely to increase in the future and has potential to reduce the fluctuations in both electricity price and frequency, despite the low availability factor. DR can help reduce the peak demand, but DR also includes the possibility to increase power consumption. With a high share of RES there might also be about a 1,000 h per year of very cheap electricity based on marginal pricing. In such a situation it is important to use the surplus in a productive way. Positive DR, that means load increase, is one option. Power storing, e.g. technologies such as power to gas, heat storage or batteries, is another alternative. Söder (2014) also states that it is possible to implement a high share of RES, corresponding to 40 TWh/y of produced wind power, without destabilizing the grid. Based on simulations of a future power system without nuclear power, net demand exceeds the available balancing hydro power during about 700 hours per year. This gap can be closed through the installation of 5,000 MW of gas turbines. The Marginal cost of power generation in gas turbines is approximately 1,000 SEK/MWh. To be competitive, DR-options must match that cost and the cost of other flexibility options. However, DR has a strong advantage in low capital cost since no investments in capacity or in the transmission grid are needed to realize the DR-potential. In the case of DR, the time dimension of the response duration also has to be regarded. In a high-RES system, similar to the base case scenario, the need for peak capacity typically lasts between 1 and 4 hours.

Söder’s argumentation will be further elaborated on below with support of his simulations of a high-RES system. Net-demand can be defined as demand minus the production from intermittent RES on an hourly basis (Managan, 2014). The demand and net-demand of electricity per hour were simulated by Söder (2013) and plotted in a duration chart. Figure 16 below illustrates the difference between 2011 (to the left) and the base case scenario (to the right).

FIGURE 16 - DEMAND AND NET DEMAND FOR 2014 AND BASE CASE SCENARIO
Noticeable is that the net-demand has become more steep whereas the consumption curve remains stable. The underlying reason for the drastic change net demand structure is the irregular production from the RES, which now constitute a larger proportion of the total energy mix in the system (Söder, 2013). It can also be observed that, in the future power system, there might be power shortages for the hours where the net-demand is negative. Now, the power balance will be analysed with the hours sorted chronologically rather than in a duration curve.

Figure 17 below plots how the different components of the power balance vary over time. The hatched areas mark periods with negative net-demand which implies need for extra balancing power. It is to observe that these occasions do occur predominantly in winter, when heating is needed. The situation becomes extra critical when a low utilization of wind power coincides with daytime-periods when commerce and industry are operating at a high level (Söder, 2013).

If the net demand is examined under the assumptions of the base case scenario, it appears that the system is experiencing a power shortage during some 700 h per year. The most extreme peak situation corresponds to a power shortage of about 5,000 MW (Söder, 2014). Figure 18 below illustrates the net demand curve over a year.

It is important to acknowledge the fact that the system is experiencing even more days of significant power surplus which enables increased export as well as periods of low electricity prices which could benefit Swedish industry. However, since the focus of this master thesis is on
DR from a power balance perspective, only the hours of power shortage will be discussed further. Readers who wish to read more about increased electricity use and positive DR are referred to Söder (2014) and Gils (2014).

Finally, the potential for DR depends much on the duration of the response period. Typically, a reduction in consumption for half an hour is possible whereas a standstill that lasts days would be disastrous for many industries. Consequently the duration of the periods of power shortage, in average but also the extremes, are important parameters. The simulation of the base case scenario does not take this aspect into consideration but there is historical data that suggests demand peaks to endure between 0.5 h and 4 h. The longest demand peak lasted 7 h (Söder, 2013). Figure 19 below shows the profile of the 10 highest demand peaks during 2011.

With regard to the base case scenario, the majority of the demand peaks are estimated to remain in the interval between 1 h and 4 h. However, extreme situations with up to 12 consecutive hours of pervading power shortage must be regarded as a possible risk that must be handled. Consequently, the DR-potential will be investigated for the different respond times 1, 4 and 12 h.

3.4 DR POTENTIAL IN THE BASE CASE SCENARIO

In this section, the base case scenario is viewed from a Demand Response perspective.

The DR-potential is not stated by SEA in either the Long-term market outlook (2012) or in the Road Map 2050 (2012). Neither is the topic examined in detail by the external analysis performed by North European Power Perspective (NEPP), which aimed to enlarge the in-depth quantitative analysis of the different scenarios.

Instead, following assumptions are about the future role of DSM/DR are made:

- The role of DSM will increase. (SEA, 2012)
- System changes that enable a more responsive management of flexible consumption will be the focus of the technical development. (NEPP, 2014)
- Market regulations which encourage flexible load management are important in a scenario with less base load power generation. (Profu, 2010)

It is evident that there will be a role for DSM in the base case scenario and that DR has a potential to be part of a patchwork of solutions to maintain system stability. However, the extent of the potential is not estimated by the base case scenario, nor is it discussed how the potential could be realised. These questions, with regard to the purpose of this thesis, remain to be answered by the review of previous work on DR in chapter 4 and by the results of this report.
3.5 PREVIOUS WORK ON THE FUTURE ELECTRICITY MARKET

This section accounts for different reports on the future of the European electricity market to give a perspective on, and alternatives to, the base case scenario.

The analysis and conclusions of this master thesis presupposes the base case scenario described in the previous sections. However, in order to give a broader perspective on the future electricity market, a selection of previous work and alternative scenarios are given below.

Several reports have been published on the future of the European electricity market over the last years. This summary only covers work conducted since 2010, as the market changes quickly and older outlooks are more likely to be outdated. Most of the originators are government agencies or international industry organisations. However, there are also consultant reports and academic publisher among the collected works below. The works presented below are a selection of papers read during the literature review stage which were considered relevant with regard to the purpose of this study.

From a Swedish perspective, the *Long Term Outlook* (2012) and *Road Map 2050* (2012), published by SEA, are most relevant works. Every second year, SEA publishes a long term outlook for the energy sector in which the development is projected with regard to present situation and possible future policies. The report includes a reference scenario as well as two sensitivity analyses. The reference scenario assumes 25 TWh produced from RES by 2020. Moreover, the scenario assumes an increased number of international connections as well as continued low prices on fossil fuels and CO\(_2\) (SEA, 2012). The key assumptions connected to the reference scenario are:

- The existing fleet of Swedish nuclear power plants are phased out to 2050
- The electricity production will increase with 30 TWh per year, mainly due to a 10 TWh increase in wind power production and a 6 TWh increase in combined heat-power plants
- Increased international export/import capacity.
- The industry increases its electricity use with 8 TWh due to higher production volumes
- The energy intensity is reduced with 15 % in comparison to 2008 levels.

The *Road Map 2050* is rather a vision than a projection. The report is addressing the zero-emission target for 2050 which has been set by the Swedish government. Different scenarios, which all reach the zero-emission target, are presented (SEA, 2012). A closer description of the different scenarios is to be found in Appendix II, whereas Table 2 below gives a summarised version of the same.

<table>
<thead>
<tr>
<th>Table 2 - Scenarios Presented in Road Map 2050 (SEA 2012)</th>
<th>Low electricity consumption</th>
<th>High electricity consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragmented world</td>
<td>Scenario 1</td>
<td>Scenario 2 (Base case scenario)</td>
</tr>
<tr>
<td></td>
<td>- High electricity prices</td>
<td>- Less Fossil Fuels</td>
</tr>
<tr>
<td></td>
<td>- Wind power investments</td>
<td>- Very high electricity prices</td>
</tr>
<tr>
<td></td>
<td>- High price on CO(_2)</td>
<td>- Increased capacity</td>
</tr>
<tr>
<td></td>
<td>- Less district heating</td>
<td>- Heavy investment in RES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Import instead of export</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Need for DSM</td>
</tr>
<tr>
<td>Globalized world</td>
<td>Scenario 3</td>
<td>Scenario 4</td>
</tr>
<tr>
<td></td>
<td>- Low prices on Fossil fuels</td>
<td>- Low electricity price</td>
</tr>
<tr>
<td></td>
<td>- Low electricity price</td>
<td>- Small capacity investments</td>
</tr>
<tr>
<td></td>
<td>- No capacity investments</td>
<td>- Some wind power</td>
</tr>
<tr>
<td></td>
<td>- Import is needed</td>
<td>- Gas (CCS) technology</td>
</tr>
<tr>
<td></td>
<td>- Potential need for DSM</td>
<td></td>
</tr>
</tbody>
</table>
The base case scenario in this thesis is based on scenario two in the table above. The scenario analysis made by SEA is quite general and avoids specifics. However, the Swedish Energy branch organisation elaborated on the numbers connected to the scenarios above in a consultant report from Profu AB in 2010. The perhaps most powerful statement made by Profu says:

“Swedish electricity production is close to the zero-emission target already today. The Nordic electricity system will reach the target in 2020 and the whole European system will be carbon neutral about 2050.”

- Page 3, Profu (2010)

With regard to the delimitation in this thesis, in specific the phase out of nuclear power plants, Profu makes the analysis that Sweden will experience a national power shortage in 2050. Instead of replacing the Swedish nuclear power plants with RES in Sweden, it is argued that it might be economically beneficial to invest in more efficient sources abroad and increase the capacity of international connection cables instead. Thereby Profu implies that a decision regarding nuclear power also is a question about national energy dependency. Figure 20 below illustrates the energy mix today (to the left) and without nuclear (to the right). Observe that the share of RES here is significantly lower than in the base case scenario.

![Figure 20 - Energy Mix, with and without Nuclear Power. Source: Profu (2010)](image)

Apart from the Swedish reports, which have been mentioned above, there are many reports published on a European level. The European Commission has published two influential reports on the future of the European electricity market:

* **A new energy strategy for 2050 (2010)** is a report on general energy strategy, including targets on energy efficiency and reductions of carbon emissions as well as targets for specific energy sources and countries. It also regards the prospect of a common European electricity market. The strategy is not legally binding for individual nations but it has a great influence. The Swedish *Road map to 2050* is based upon the targets below which are parts of the energy strategy by the European Commission (2010):

  - Reduction in CO₂ emissions: 24 % by 2020, 32 % by 2030 and more than 80 % by 2050
  - Energy efficiency improved with: 20 % by 2020 and 30 % by 2030
  - RES as proportion of total electricity production: 20 % (2020) and 27 % (2030)
  - Investments: 52 Billion SEK in connecting European grids, 210 Billion SEK in structural funds to support RES and 54 Billion SEK in R&D.

* **A common electricity market regulation (2011)** is a more concrete directive that regulates the European electricity market. It is based on the principle of free movement of goods and capital (European Commission, 2011). For example, it is not allowed for countries or national TSO to cut
off their connection cables to other countries in order to optimize the national grid (European Commission, 2010). This has very positive implications for the base case scenario of this report since Sweden might have a need for increased imports in the case of a nuclear phase-out.

Moreover, the European Commission has strong regulation on different pricing models for electricity. The principal accepted pricing model is marginal pricing which implies that the electricity costs as much as the highest variable production cost among the activated resources at a given point in time. For DR, this implies that some DR-programs might need legal exemptions to be implemented (Saele & Grande, 2011).

From an academic perspective, the visions are more progressive. Dr. W. Schröppel e.g., professor at the University of Karlsruhe, published his paper An electrical power vision for Europe 2040 in year 2013. The study is based on simulation as well as qualitative analysis and data from the European Commission (Schröppel, 2013). Before analysing the power balance, Schröppel simulates the future demand structure. On a European level, the demand is predicted to increase from 3,000 TWh in 2008 to about 4,000 TWh in year 2040. Figure 21 below illustrates the development in demand divided by the different consumer sectors.

![Figure 21 - European Electricity Demand in GW. Source Schröppel (2014)](image)

An important observation, with regard to DR, is that the industrial sector decreases whereas the residential sector increases. Especially, transportation is experiencing rapid growth in electricity consumption. Schröppel assumes that 30% of all private vehicles will be electro-cars by 2050, increasing power demand but also the available DR-resources.

On the supply side, the trend indicates an increased share of RES which affects the relation between installed power and generated electricity due to the lower availability factor of e.g. wind power (Schröppel, 2014). Figure 22 below illustrates this relation.

![Figure 22 - Installed Capacity 2050. Source Schröppel (2013)](image)
As evident in Figure 22 above, the relation between installed capacity and generated energy can vary greatly depending on technologies used in the energy mix. In 2008, with the current energy mix, the Peak Load was 500 GW and the installed capacity 600 GW. In year 2040, the peak load is predicted to be 900 GW. To reach a corresponding level of SoS by only adding RES, Schröppel’s research indicates that another 600 GW of RES is needed. If also the nuclear is to be phased out, the total installed capacity in the system needs to be above 3,000 GW.

Schröppel argues that it is possible to meet the targets set by the European Commission, but doing so will be extremely expensive. The high-RES scenario, which is comparable to the base case scenario of this master thesis, is estimated to require about 54,000 Billion SEK in capacity investments to 2050, nearly doubling the cost of the trend scenario which cost is estimated to 29,000 Billion SEK. To reduce the cost, Schröppel suggests that the most cost-efficient solution would be to extend the international transmission grid with high capacity cables. Such a development is already being partly implemented (SvK, 2014; European Commission, 2012).
In this chapter, the concept of Demand Response is introduced and explained as are the different Demand Response programs which are included in this study. Thereafter some previous work on Demand Response are reviewed and discussed in order to give the reader a broader perspective on the issue. Finally some knowledge gaps, which this master thesis with regard to its purpose can help to close, are identified.

Demand Response (DR) is a subset of programs and activities within the broader of the more well-known concept of DSM (Dabur, et al., 2012). DSM addresses all actions taken by authorities or utilities to change the consumption pattern of the end-user. This includes general energy conservation as well as load management; programs with the objective of changing the load-shape by e.g. reducing demand peaks or shifting load over time. The terminology load management is gradually being replaced by DR or Demand Side Response, especially in Europe (Chuang & Gellings, 2008).

Technically, a distinction is made between load shifting and load shedding. Load shifting implies that the power consumption is transferred from one point in time to another, e.g. a factory runs a certain process a few hours later than initially planned. Load shedding means that the power consumption is irrevocably reduced, which for the industry means lost production (Dabur, et al., 2012). Figure 23 below illustrates the two different technical principles of DR.

DR as terminology is used within a wide range of applications and there are several definitions available. For example, the US Department of Energy (2006) writes:

“Demand Response can be defined as the changes in electricity usage by end-use customers from their normal consumption pattern in response to changes in price. Further, DR can be also defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.”

The International Energy Agency (2008) offers a somewhat broader definition of DR:

“Demand Response is programs and activities designed to encourage consumers to change their electricity usage patterns, including timing and level of electricity demand, covering all load shape and customer objectives. Demand Response includes Time of Use and dynamic rates or pricing, reliability programs such as direct load control of devices and instantaneous interruptible load, and other market options for demand changes, such as demand side bidding.”

In this master thesis, research and conclusions will consequently be based on the latter definition due to its wider scope which allows more options to be considered. Also, since US DoE is a national American agency whereas IEA is a global organization, it is reasonable to choose the definition of the latter with regard to the scope of this master thesis.
4.1 CLASSIFYING DR-PROGRAMS

This section explains how, and according to which parameters, the DR-programs are classified in this master thesis.

This chapter will in section 4.2 discuss different DR-programs in order to create the typology of DR-programs which is one of the targets of this master thesis. Before introducing the specific DR-programs however, the underlying categorization will be discussed in order to define them.

Since the definition of DR is wide, numerous ways of categorizing different DR options are available. The actual technical function of the response, i.e. load shifting or peak clipping can be examined, or the classification could be based on the financial incentives that enables customers to participate (Dabur, et al, 2012). A third possibility would be to distinguish between the market levels on which the DR-program operates (IHS Energy, 2014). The classification of DR-programs below will, in consequence of the strategic cost focus of this thesis, be based on the financial incentives and contract forms.

A first general distinction is made between monetary and non-monetary DR-programs. The driving motivation for participation in a monetary based program is potential economic benefits, in terms of reduced energy bills or revenues through subsidies, for the end-user whereas the conceptually driving force behind participation in non-monetary programs could vary from legal obligations to ethical concern for increased corporate responsibility. (Dabur, et al., 2012).

The range of monetary programs can in turn be divided between price-based and incentive based DR-programs. All price based DR-programs includes prices that are vary over time and space and are based on the assumption that the aggregated demand is depending on the given price level. Consumers are prone to use more electricity at a lower price level but would look for other options at significantly higher spot price (Dabur, et al., 2012).

The form of these price- based programs varies greatly between different countries but also over time. Following the development of smart grid technology, i.e. large scale installations of smart meters, more precise methods for monitoring real time consumption and price levels are enabled together with new and more effective price based programs (Capgemini, VaasaEtt, Enerdata, 2006).

Among the Monetary based DR-programs, the incentive based programs are best described by their common characteristic of not being directly connected to the price of electricity. Indirectly, an imbalance between supply and demand will have impact on price and require a response from the system, but the price signal is neither the primary indicator nor the principal executor (Dabur, et al., 2012). Instead the programs are based on mid- or long term contracts where end users of electricity, typically large industries, make binding commitments to utilities or TSO:s for predefined compensation.

Finally, there are non-monetary initiatives to extend the participation in DR programs without adding financial incentives. The common idea that unites the non-monetary programs is the desire to change the behavioural pattern of individuals and organizations in order to reach environmental targets or reduce system costs (SEDC, 2012). This however can be done in numerous ways; through information, education, binding laws or even a mixture of them. For the energy intensive industry, security of supply might be an even more crucial factor than the price on electricity itself. Hence, some companies voluntarily participate in non-monetary programs to increase the stability of the grid (Torriti, et al., 2009).

Figure 24 below introduces the different DR options and their relation to one another. The model, Figure 24, takes it starting point in the classification of the program as either price-based,
incentive-based or non-monetary. Thereafter, each of the demand programs included in the study will be described in detail. DR-programs belonging to the same group are presented together in the order that best explains the underlying principle.

Another underlying parameter to distinguish between different classes of DR-program is the decision making process. In other words, who has the authority to execute and control the DR? It could be the individual electricity consumer, it could be the utility, an aggregator, the TSO or even a government agency. Typically, more centralized decision making processes are difficult to organise and find a working business model for but can potentially offer large DR-potentials with short response times. DR-programs that let the execution right remain at the individual customer are normally easier to implement. Because of these principal and practical differences, the aspect of the decision making process is taken into consideration.

Apart from the underlying market principle and the DR-execution process, the time dimension is of vital importance when distinguishing between different DR-programs. As previously mentioned in chapter 2, electricity is traded on different markets levels depending on the point in time. Technically, that market is where the contracts are being signed in relation to the hour of delivery (SvK, 2007). Likewise, different DR-options are designed to match one or a few of these time dimensions. Figure 25 below shows this separation in the time dimension for the six DR-programs included in the master thesis. The figure is relative and its main purpose is to
compare different DR-Programs with each other from a time dimension perspective. E.g. both DC and AS have response times counted in seconds, however since AS can offer even quicker responses than DC, the DC-bar in the figure below ends before the AS-bar on the time line.

It is evident that different DR-Programs operates on different market levels and hence are designed for different purposes. E.g. Ancillary Services and Direct Control programs can initiate a response within seconds, Real-Time pricing works well on an hourly basis, a fixed Time-of-use model can help to steer and shape the demand structure month ahead whereas Strategic Reserves or Capacity Markets typically secures the power balance for years to come. These different characteristics make it possible to combine different DR-options which are operating at different levels in the time dimension (Albadi & El-Saadany, 2008). Because of the principal differences between DR-programs in this sense, and the practical implication of the differences, the parameter of operational market level is also considered in the classification below.

In short, there is a wide variety of DR-programs and sometimes the difference between them are small and occur more because of local variation in context and name rather than on principles. Hence, DR-programs are only included in the study performed in this master thesis if they:

- Are based on a unique principle mechanism in relation to other DR-programs.
- Have been implemented on a large scale that enables comparison.

The Tables 3-8 below that summarises the characteristics of the included DR-program gives following information in each case:

- DR-program – What is the name of the program?
- Classification – What mechanism is triggering the DR?
- Initiator – Based on the decision process; who is executing the DR?
- Market level – When in time is the DR taking place?

The included DR-programs are defined and discussed below. Thereafter, a brief overview of programs not included in the study is given.
4.2 INCLUDED DR-PROGRAMS

This section defines and exemplifies the different DR-programs included in this master thesis.

TIME OF USE (TOU)

Time of Use, the most basic form of price-based programs, includes normally only two predefined price levels; one peak time rate and another for off-peak time. This is a primitive incentive model with limited precision but it is easy to administrate to a low cost and has proven relatively well-functioning in levelling cyclic, non-extreme demand fluctuations (Dabur et al. 2012). Technically, more price levels could be included and hence give ToU increased flexibility and management options. However, with more price levels the complexity is rising and thereby the program loses its advantages which were the low costs and manageable administrative work (SEDC 2014). The characteristics of ToU are summarised in Table 3 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-of-Use</td>
<td>Price-based program</td>
<td>Consumer</td>
<td>Spot market</td>
</tr>
</tbody>
</table>

REAL TIME PRICING (RTP)

A Real-Time Pricing program is the ultimate form of a price based programs; the cost of electricity is ultimately tied to the ToU as the end-user pays market spot price (Dabur, et al. 2012). The aim is to level the demand curve by letting the price fluctuate freely and with a fully installed smart grid, with meters and automatic regulators integrated in household devices the potential is very large (Torriti, 2011). The theoretical support for the method is solid also for industrial applications. However in practice RTP depends on a few requirements that are not always fulfilled such as access to real time price information and an in-house responsible manager with authority to interfere in the regular activity due to price fluctuation in the electricity market (SEDC, 2014). The characteristics of RTP are summarised in Table 4 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-Time pricing</td>
<td>Price-based program</td>
<td>Consumer</td>
<td>Spot- / Intra-day market</td>
</tr>
</tbody>
</table>

CAPACITY MARKET (CM)

Capacity Market is an incentive based program. In a CM, agents on both the supply side and demand side are free to participate in a power market with a longer time horizon (Torriti, 2014). Normally the CM operates until a day ahead of actual use, but theoretically the contracts could be fixed far earlier, up to years in advance. The capacity contracts are typically sold through auctions to the provider with the lowest bid. The Market agents commit themselves to provide a pre-specified capacity, be it actual supply or load reduction, when contingencies arise in the system (SEDC, 2014). Participating agents typically receive yearly capacity payments. As in other markets, participants profit from high market prices but will have to pay fees if a commitment cannot be realized. The characteristics of CM are summarised in Table 5 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Market</td>
<td>Incentive-based program</td>
<td>TSO</td>
<td>Financial market</td>
</tr>
</tbody>
</table>
STRATEGIC RESERVE (SR)

A Strategic Reserve is an incentive-based program which dual payments. Firstly, the participants of the SR receive a yearly capacity payment that depends on the DR-volume and the time horizon of the contract (SEDC, 2014). Typically, a government agency or a balancing responsible TSO procure the SR on a yearly basis. This means the DR is not triggered by a market price signal or an automated frequency regulation, but through a manual intervention or request. Participation is typically voluntary but is only intended for a small proportion of the total demand volume since it is a reserve. The form of the capacity payment for participating industries varies; it could either be a bill credit or a discount rate on electricity (Torriti, 2014). The characteristics of SR are summarised in Table 6 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic Reserve</td>
<td>Incentive-based program</td>
<td>TSO</td>
<td>Financial market / Spot market</td>
</tr>
</tbody>
</table>

DIRECT CONTROL (DC)

Direct Control is an incentive based program but distinguishes itself in terms of technical execution. In so called DC- programs, utilities or the TSO have the possibility to remotely control parts of the customers equipment and hence the ability to shut down certain processes on short notice when necessary. Normally supporting processes such as heating or air-conditioning would be the first to suffer restrictions but theoretically entire productions sites can participate. The financial benefit for the participant is mainly based on a fixed payment but participation could also result in lower average power costs (Dabur et al. 2012). The characteristics of DC are summarised in Table 7 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Control</td>
<td>Incentive-based program</td>
<td>TSO / Utility / Aggregator</td>
<td>Intra-day / Balancing power market</td>
</tr>
</tbody>
</table>

ANCILLARY SERVICES (AS)

Ancillary Services operate on the power balance market instead of the spot- or intra-day market, hence the time horizon is very short (Dabur et al. 2012). AS are non-monetary in the sense that the individual customer has no opportunity to react but has to pay the fee for any AS that the TSO finds necessary. Normally, the TSO has access to its own back up capacity, or has predefined deals with utilities and large consumers for them to adjust their load during the operational hour if needed. However, it is possible for demand resources to participate (Capgemini, 2006). Being a balance provider is a prerequisite for participation. Typically the volumes are small, but the response can have significant impact of the frequency in the grid and hence on the power quality. Some utilities and demand resources are legally obliged to participate in AS. The characteristics of AC are summarised in Table 8 below:

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>Classification</th>
<th>Initiator</th>
<th>Market level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ancillary Services</td>
<td>Non-monetary program</td>
<td>TSO</td>
<td>Balancing power market</td>
</tr>
</tbody>
</table>
4.3 DR-PROGRAMS NOT INCLUDED IN THE STUDY

Apart from the six principal DR-programs described above there are several further options. Some have also been implemented and tested in pilot studies somewhere, others are mere conceptual solutions. The reasons for excluding these are either due to lack of exclusivity, which is they are too similar to included programs, or because they have not been substantially implemented which makes evaluation impossible or unjust.

An example is Critical Peak Pricing. It is a price-based, monetary program which basic principle is similar to Time of Use. The main difference is that the program is temporary initiated in case of electricity shortage or any other emergency. Still the price signal is judged to be sufficient to trigger large scale DR (Dabur et al. 2012).

A closely related program to Critical Peak Pricing is the Emergency DR. Emergency DR is also only initiated when shortage of supply arises, however it’s an incentive-based program and the response is binding and not voluntary. End users are typically prepaid to participate but are not receiving as high variable payments when the response is activated (Dabur et al. 2012).

There are also several non-monetary DR-programs. One such is free and instant information. Theoretically, a market with is served by perfect information will find a cost efficient and stable equilibrium at the intersection of available supply and aggregated demand. Since a spot market already exists, customers themselves could adjust their consumption depending on the current market price if they had access to real-time and binding price information (Torriti, et al, 2009).

Other non-monetary programs that have been tested are education and marketing initiatives. Through putting resources on raising the awareness of the issue, authorities expect to influence the behavioural pattern of electricity consumers. In a best case scenario the global benefits, such as environmental care and system balance, can be presented in conjunction to financial benefits for the individual end user. This has proven to reduce the general energy consumption and it is plausible that it might also have a positive impact on the level of participation in DR-programs (Capgemini, 2006).

4.4 PREVIOUS WORK ON DEMAND RESPONSE

The ambition of this section is to shortly summarize some of what has been written about DR previously and where to find it. This section accounts for various studies and articles that specify the practical implications of Demand Response from a system perspective.

Having defined DR, and introduced the DR-programs included in this master thesis, it is of interest to investigate what previous work has written about DSM and DR in order to get a better understanding of the concept.

In the United States there is a long history of working with DSM and a comprehensive summary of the benefits that come with DSM is given by the US DoE in their report Benefits of Demand Response in Electricity Markets and Recommendations for Achieving them, which was published in 2006. Table 9 below summarizes the key points from the report.

<table>
<thead>
<tr>
<th>Actor</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer</td>
<td>Reduced peak-load generation</td>
</tr>
<tr>
<td></td>
<td>Less need for peak units</td>
</tr>
<tr>
<td></td>
<td>Less need for capacity reserves</td>
</tr>
<tr>
<td></td>
<td>Higher share of RES possible</td>
</tr>
</tbody>
</table>
| TSO           | - Lower congestions  
|              | - Less outages  
|              | - Lower losses due to a flattened load  
|              | - Lower investments in grid  
| Market       | - Lower price volatility  
| Government   | - Higher security of supply  
| Retailers    | - Lower exposure to high price/high demand situations  
| Consumers    | - Increased awareness and participation  
|              | - Possibility to have a control on the electricity bill  
| Environment  | - Increased integration of RES  
|              | - Reduced emissions through less use of fossil fuels  

The table above focuses on the benefits that come with a successfully implemented DR-program. No corresponding list of disadvantages was found during the literature review, possibly since the reports often are written by organisations or individual advocating DSM. Regarding the implementation however, the US DoE states that the decision process for industrial customers to participate takes years; investments in infrastructure is needed, strategies must be developed, contacts taken and contracts signed. The best way in which the government can facilitate the process is to provide a stable regulatory environment that enables long term investment planning (US DoE, 2006).

Large firms and consultancy agencies are also taking interest in the potential of DR. In a report from 2010, called *The smart grid and the promise of Demand Side Management*, McKinsey & Co defines DSM as a set of interconnected and flexible programs which allow customers a greater role in shifting their own demand during peak periods and reducing their overall energy consumption. In a business case, the potential benefit from DR-programs in the US was translated to 360 Billion SEK between 2010 and 2020 (McKinsey, 2010). McKinsey research on existing DR-programs has shown:

- Successful DR-programs combines different tools such as variable price levels, incentives, information, and Direct Control.
- US peak demand could be reduced by 20 % within 10 years with a universally applied DR-program
- Industry accounts for about 40 % of the potential DR. The residential market possesses greater potential but is difficult to realise due to high fragmentation.
- Smart-grid technology provides the scalability and is a prerequisite to make implementation of DR-programs effective and convenient.

(McKinsey, 2010)

One of the most exhaustive classifications of existing DR-programs found during the research phase of this study is given by SEDC (2014) in their report *Mapping DR in Europe Today*. Initially, the current state of European DR is mapped. Figure 26 below show the spread of DR in Europe. Sweden is classified as having a partly operating DR-program since the Strategic Reserve includes demand resources to a limited extent.
With regard to this initial mapping of DR-programs in Europe, SEDC (2014) concludes that DR has been slow to emerge. SEDC finds that in the majority of European states, DR is either illegal or made by laws and regulations. To counter that obstacle, SEDEC (2014) formulates 4 criteria to facilitate future implementation:

1) Enable consumer to participate in DR-programs. In concrete, DR must be accepted as a capacity resource and get the same information and possibility to participate in the market as do supply resources.

2) The program description needs to be enlarged to serve a broader purpose. Traditionally, the DR-programs were designed to fit the needs of utilities and TSO.

3) The smart-grid infrastructure needs to be enhanced. Many European countries lack the technical devices measuring and regulating power consumption. In addition, regulation concerning measurement and verification needs to adapt to the technical environment.

4) Payments for DR must be fair. Today, DR resources are typically paid less per MW than in generation resources. However, penalties for non-performers are generally adequate. Standards of transparent and reasonable payments must be implemented.

IHS CERA (2014) argues that DR is only one aspect of an overarching question that regards capacity shortage. Bottom line is that an energy-only market prevents utilities to remunerate their capacity investments. This causes a gap, by IHS CERA called "missing money". This being the case, investments levels are going down which is causing concern for the long term security of supply. To deal with the potential risk of power shortage IHS CERA, in their report Keeping Europe's lights on, introduce the possibility of capacity payments. It is suggested that a mechanism is needed which targets power capacity rather than energy generation and that such a mechanism also could comprise DR resources in terms of "Negawats". "Negawats" is the concept of a Megawatt never used. In particular, IHS CERA findings state that:

- Capacity Markets provide a way to reduce risk and incentivize investments in DSM. By receiving pre-payments, risk-averse companies will be able to participate.
- The potential for DR in Europe could be increased with up to 10 GW at a price level between 130,000 – 700,000 SEK/MW\(\text{y}\) if a Capacity Market is implemented.
- An energy-only market based on voluntary demand-side participation is insufficient to ensure security of supply.

(IHS CERA, 2014)

Apart from being a solution to imbalances in a fluctuating power grid, several authors indicate the synergies between DR and reaching the environmental policy targets. Among others, Bergaentzle et al. (2014) argue in their journal article *DSM and European environmental goals* that DR helps reaching the environmental targets in several ways. Firstly, the general consumption is reduced which cuts emissions directly. Secondly, if DR could help neutralize the need of peak-capacity, which is typically fossil-based in terms of gas turbines, the general energy mix also becomes more environmentally friendly. Thirdly, the implementation of DR-programs highlights the energy situation and involves companies in the broader discussion on efficiency and responsibility which on a longer term can affect their patterns of action (Bergaentzle, et al, 2014).

Being on the same track, Garg et al. (2011) conducted a more detailed study on different DR-resources in India. It was found that implementing DR-programs can, over a 10-year period in this case, lead to a 25 % reduction in energy consumption and a 50 % reduced power shortage during periods of peak loads. Translated into CO\(\text{2}\), this equals a reduction of greenhouse gases with over 25 % which is well ahead of the current targets (Garg et al., 2011).

The perhaps most encouraging research findings regarding the connection between DR and environmental goals is that it could even lead to reduced system cost (Arif, et al, 2014). Arif et al. (2014) conclude that their evaluations show that implementing DR-programs can efficiently reduce operating cost of power grids and create value for both suppliers and consumers. In a system with a high share of RES, similar to the base case scenario of this thesis, Arif et al (2014) argue that operating cost could be lowered by 5 % with DR and setup costs in terms of grid- and capacity investments could be cut by up to 30%.

4.5 DR POTENTIAL IN SWEDEN

*This section summarises previous work that gives estimation on the future DR potential.*

Knowing what DR is and in what context it is relevant, it is also of relevance to study what previous studies have found out about the DR-potential in Sweden. Today, DR is part of the SvK’s power reserve in Sweden and would contribute with about 500 MW in terms of consumption reduction in case of disturbance or power shortage (SEDC, 2014). How large the actual potential is today, and what the potential will be in the future, is a topic which many researchers have been investigating the last few years. The distinct interest in the question relates well to the purpose of this thesis, which was to estimate the future potential of industrial DR in Sweden. The review of previous work serves both as a benchmark to validate the results from this master thesis, but also to give the reader an option to get an even wider range of sources. This relates directly to the purpose of this thesis to provide a foundation for future decision makers and investors by outlining the expected future business environment.

One weakness among previous works are that they typically do not define the duration of the response, nor the price level at which the DR-potential is available. In short however, the current DR-potential is estimated within the interval between 500 and 1,000 MW, whereas the long term potential for industrial DR reaches between 1,500 and 2,500 MW. Even greater potential, up to 5,000 MW, is reached in studies which investigate future potential and includes other sectors. The primary additional DR-potential is found in the residential sector. Figure 27 below
summarises some previous works on the DR-potential in Sweden. The Y-axis represents flexible load in MW. The different studies are categorized after two parameters, the scope of the study and when the results were published. The colour indicates the sectors included in the study and the time horizon. Within each category the studies are sorted in chronological order.

Unfortunately, the different studies vary in scope, limitations and methodology so it is hard to compare the results without certain back ground information. Hence some additional information on each source is presented in Table 10 below. According to the author of this master thesis, following factors are important to keep in mind while interpreting Figure 39:

- **Originator**
  The author of studies has potentially a great impact on the result. E.g. organizations with responsibility for the realization of the potential typically underestimate the numbers with a safety margin.

- **Scope**
  Scope suggests which sectors are included in the study. Also, the definition of potential could differ between economic, technical or other approaches. Economic potential is normally greater than technical potential.

- **Method**
  There are two main methodologies used; interviews or analytical methods. The latter methods tends to generalize more which gives higher numbers whereas interview based studies that only includes confirmed potentials might underestimate the potential.

- **Price**
  Since the demand depends on the price level in a market based system, it is essential to give a price level for an estimated potential when comparing results from different studies.
- **Time horizon**

Researchers who study the existing potential typically reach lower volumes than studies which estimates future potential since technology and knowledge are assumed to develop further.

To give the reader a possibility to compare the results more accurately, the necessary background is presented for each included study in Table 10 below.

**TABLE 10 - INFORMATION ON SOURCES USED FOR COMPARING DEMAND RESPONSE POTENTIAL**

<table>
<thead>
<tr>
<th>Source</th>
<th>Originator</th>
<th>Scope</th>
<th>Method</th>
<th>Price</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alterbeck, (2014)</td>
<td>Student thesis</td>
<td>Industry in SE3 and SE4, technical potential</td>
<td>Investigating available resources</td>
<td>(500/850) MW at (1,500/7,000) SEK/MWh</td>
<td>2014</td>
</tr>
<tr>
<td>Bartusch et al, (2011)</td>
<td>Academic research</td>
<td>All sectors, Theoretical potential</td>
<td>Analytical method, Simulation</td>
<td>N/A</td>
<td>2030</td>
</tr>
<tr>
<td>Capgemini, (2008)</td>
<td>Consultant report</td>
<td>All sectors, economic potential</td>
<td>Exploring existing resources and calculating future potential</td>
<td>N/A</td>
<td>2020</td>
</tr>
<tr>
<td>Elforsk, (2013)</td>
<td>Utility branch organization publication</td>
<td>All sectors, theoretical potential</td>
<td>Simulation of system based on smart meters</td>
<td>80,000–350,000 SEK/MW, y</td>
<td>2012</td>
</tr>
<tr>
<td>Eriksson &amp; Sandwall, (2014)</td>
<td>Student Thesis</td>
<td>All sectors, theoretical potential assuming aggregation</td>
<td>Interviews with market agents such as TSO and demand resources</td>
<td>N/A</td>
<td>2030</td>
</tr>
<tr>
<td>Fritz, (2006)</td>
<td>Utility branch organization publication</td>
<td>All sectors, existing potential</td>
<td>Analysing different business models to realise the potential</td>
<td>3,000–10,000 SEK/MWh</td>
<td>2010</td>
</tr>
<tr>
<td>Gils, (2013)</td>
<td>Academic researcher</td>
<td>All Sectors, Theoretical potential</td>
<td>Defining and identifying characteristic load profiles</td>
<td>N/A</td>
<td>2013</td>
</tr>
<tr>
<td>Nilsson &amp; Hammarste dt, (2014)</td>
<td>Utility branch organization publication</td>
<td>Industrial sectors, technical potential</td>
<td>Literature review and interviews with market participants</td>
<td>1,800–2,500 SEK/MWh</td>
<td>2014</td>
</tr>
</tbody>
</table>
4.6 KNOWLEDGE GAPS

This last section on Demand Response identifies knowledge gaps in the previous works and connects this need for further research to the purpose of this thesis.

Since it is the purpose of this thesis to contribute to the general understanding of DR on the future Swedish electricity market, it is important to know where knowledge is lacking today. Consequently some knowledge gaps are identified and explained below. It is intended for the discussion in subsequent chapters to reconnect to this section.

Now, as the field of research deals with prospects for the future, there are numerous uncertainties and knowledge gaps. Still, much work has been published on the topic and some aspects and conclusions seem to be generally accepted. One example is the share of RES, which is predicted to increase drastically to 2050 (Schröppel, 2013; IEA, 2013; SEA, 2012). Further examples on well accepted implications of such a system is a more volatile production and consequently greater fluctuations in electricity prices (Söder, 2014; Kiani & Annaswamy, 2014) as well as a probable shortage in capacity investments (IHS CERA, 2014; SEDC, 2012).

A vast majority of the sources mentioned above devotes a chapter or a section to recommend directions for further investigations in which knowledge gaps are identified. With regard to the scope of this master thesis, some closely related areas of research which have yet to be examined more closely are presented below:

- Which market design and business models for DR will be used?

The present structure of legislations and business models exclude large parts of the total consumption. To include small business, residential customer and facilitate for large industrial consumers, new business models for load aggregation and electricity trading must be further investigated (Cui, 2011; Wallén & Walsh, 2013). More specifically, Cui states following about future research on DR in his master thesis The Future of DR in Europe:

“In conclusion, Demand Response is on the way. The uncertainty lays in which business models will be used and what standards will come with them”

- p. 49 Xiangmei Cui (2011)

This master thesis addresses the question indirectly when categorizing DR-programs in the typology. Especially the feasibility parameter targets the knowledge gap by giving an indication on what market designs are plausible on the future Swedish electricity market.
What parameters drive customer flexibility?

To estimate future DR-potential, it is essential to understand what drives customer flexibility and equally important, what obstacles is counteracting the potential (Ei, 2014). Although the expectations on future DR are high, the general understanding of the underlying forces which determines the potential of DR is limited (IEA, 2008).

During the interview series conducted in this master thesis, this knowledge gap is addressed directly by asking industry representatives specifically about the parameters that drive further DR and the obstacles which counteracts it. The answer is of course not representative for all DR-resources but it clearly helps in understanding the perspective of a DR-participant better.

What are the advantages and disadvantages of DR as a capacity mechanism?

Since there are many, often overlapping DR-programs available in the toolbox, governments and market agents are confused about the characteristics of the different options (Torriti, et al. 2009). In their report *Flexibility in European electricity markets*, IEA writes:

“The resulting conclusions and insights from this study lay the groundwork for further analyses of how the necessary changes in power systems can be achieved. In particular, further consideration should be given to the challenge of system adequacy in an environment which possibly does not trigger investments into secured capacity due to potentially missing revenues. The advantages and disadvantages of compensation mechanisms for Demand Response in a situation where an energy-only market may not provide sufficient revenues for peak capacities have to be discussed.”

- p.82 IEA (2013)

This knowledge gap is targeted by the very purpose of this thesis. In order to contribute to the general understanding of DR-programs in the future electricity market, a typology of DR-programs has been initiated. In this typology, the parameters cost, volume and feasibility is evaluated and analysed. Moreover, by examining previously implemented mechanisms in the case study, the policy impacts and key findings in chapter 7 are giving concrete examples on advantages and disadvantages of each DR-mechanism.

What potential economic savings can be achieved through DR?

The economical aspect is very important for DR since the concept is partly triggered in order to lower system costs. However, the present day understanding of how much money can be saved through increased DR-participation is limited (Torriti, 2014). Capgemini (2006) argues that the potential for DR in Europe is massive, but market agents fail to esteem it and thereby also falls short in realizing the existing potential.

To assist in filling this knowledge gap, the base case scenario was included and elaborated on in this master thesis. By estimating the system costs without DR, and in parallel giving indications on the economic implications of industrial DR in Sweden, it is possible to calculate the economic savings achieved through DR. This gives a sound indication on the relations of numbers on the Swedish and European markets which also is the scope of this thesis.

What is the future potential of Demand Response?

Many market agents are interested in the actual potential of future DR. This is an area which has been investigated previously by several researchers (se section 6.3), but the potential cannot be determined with precision since the question involves the future. Hence the demand side Merit-Order graph constructed in this report aims to contribute to this knowledge gap and thereby by support policy makers and investors in their decision making process.
5 METHODOLOGY

The basic purpose of this chapter is to describe what has been done, how it was done and why. Alternative solutions and their possible implications on the results are also discussed. The chapter focuses on the process for collecting data and the models for presenting the results.

5.1 RESEARCH STRATEGY

This section outlines the overall research strategy that has been designed for the purpose of this study. The section also gives a brief account of the scientific approach of the author and discusses possible alternative approaches.

The purpose of this master thesis was to contribute to our understanding about DR in the future Swedish electricity market and provide a knowledge base for decision makers and investors. Concrete, the study is to result in:

- A typology of DR-options based on the parameters cost, volume and, feasibility.

In order to satisfy the purpose, data have been collected and new knowledge generated. There are many different ways to acquire new knowledge and interpreting old knowledge. For a method to be classified as scientific it must be transparent, repeatable and its result based on observations. The methodology of this master thesis was designed to meet the criteria’s above and has fulfilled the following requirements:

- Only academically accepted methods for data collection and interviews were applied.
- The result was based on observations, empirical data and previous research.
- The report has been officially published for other to review and criticize.

The purpose of the thesis was also, as mentioned above, to serve as a base for decision makers and investors. This ambition added complexity to the methodology since it became important to identify and handle the risks of subjectivism and bias, which always needs to be regarded in scientific studies. All researchers have a personal perception that influences the science performed. These glasses, through which individuals or societies interpret their surrounding world, is called paradigm by Thomas Kuhn. (Faria et al, 2011). Being unavoidable, strong paradigms also can constitute a threat to good science as the researcher tries to confirm a statement rather than testing a hypothesis (Mössner, 2011). With regard to the concerns of Mössner (2011), several measures have been undertaken in this master thesis to reduce personal influence in the research and on the results. The influence of personal prejudice has been limited by closely citing from other researcher and the tendency towards scope expansion was controlled by a strict dedication towards the methods defined in this chapter. Specifically, the report was to result in a typology of DR-options as well as a quantification of the future DR-potential in Sweden. In order to classify the different DR-options in a typology based on the parameters cost, volume and feasibility, a review of previous work was conducted to give context and definitions. Moreover, a case study was conducted in order to enable evaluation of the different DR-options. To estimate the future DR-potential in Sweden, the results from an interview series were used to project the currently available potential on the future Swedish electricity market.

The overall research strategy was to define the purpose and research questions together with the different stakeholders of the master thesis initially and thereafter design a methodology with regard to the specific characteristics of the purpose.
The research strategy is illustrated in Figure 28 below. The different stages of the process are subsequently described individually. Important to notice is the iterative process which includes theory, research and analysis. Eisenhardt & Graebner (2007) argues that a research process is not intended to be linear, but rather iterative in terms of a continuous reciprocation between theory and empirical data. This because the theory is emergent in the sense that it is situated in and developed by recognizing patterns of relationships among constructs within and across cases and their underlying logic.

In accordance to the above framework the steps 3-6 were initiated simultaneously and worked on in parallel to add flexibility to the process and enhance the coherence of the report. Smaller adjustments were also made in step 1 & 2 as is became evident what was relevant and not after the first literature reviews and interviews. However, the difference in approach was that the redefinition of step 1 & 2 were logical consequences of an increased understanding of the research area whereas step 3-6 are intentionally iterated and performed in parallel in order to achieve the best possible result.

In the first step, the purpose was defined and research questions formulated. This was a process involving both Vattenfall AB and Linköping University to secure the practical as well as the academic relevance of the master thesis.
The purpose and the limitations were reformulated several times. For example did Vattenfall AB as a contractor stress the importance of the parameters price and volume, and consequently these parameters were in the typology. Moreover, after deliberation with representatives from Linköping University, the choice was made to investigate what people thought about the future development rather than to predict the future development in order to get results which can be validated.

The limitations which were set in this step have a direct impact on the results. Some are deliberate simplifications of the real world. For example, the geographical limitation to only study Sweden as a market has no natural counterpart in the physical world since the smallest system boundary are the Nordic market. Doppelt (2012) argues that all scientific models need to simplify the reality to generalize the findings. However, it is also stated that it is important to be aware of the limitations, simplifications and generalizations made and regard these as conclusions are drawn. In this report, this was done through an explicit outlining of the limitations in the first chapter as well as a sensitivity analysis in chapter 8.

The second step, including the choice and motivation of research strategies and methodology, is described in this chapter (5). The overall research strategy was to use a methodology that combined the advantages of both a qualitative field study and a quantitative desk study. Specifically, the methodology included a quantitative case study of previous DR-program as well as an interview series with respondents from the energy intensive industry. Moreover, a review of previous work in related areas is conducted. The method used for each sub-study will be regarded in step 3, 4 and 5 respectively in the subsequent sections. Before introducing the individual steps however, this section continuous to outline and discuss the overall research strategy and the choice of a mixed approach.

To evaluate the DR-potential in an unknown and distant future, a qualitative analysis was needed to interpret and transfer the results from the current situation. However, to classify different DR-options after the parameters cost, volume and feasibility, it was advantageous to take historically collected data into consideration. Therefor a mixed strategy was developed for the purpose of this study.

This mixed strategy allowed the use of parallel studies needed in order to deliver the expected results of this master thesis. In specific, the data based approach used for the literature review which led to the typology of DR-options has strength is its positivistic procedure and hence offers good result validation (Yilmaz, 2013). However, its predictions are limited by the context from which the data originally was collected. The interview series added strength to the transformation of existing industrial DR-potential to the base case scenario, as understanding the motives behind individual agents can produce a more agile and flexible result (Baily, 2014).

One alternative approach would have been to focus on a quantitative approach and thereby possibly extend the data range included. Since Yilmaz (2013) states that a quantitative study often requires a large amount of data to for its result to be statistically validated, such an approach might have led to better supported results. This would especially affect the validity of the case stud since a quantitative method was used for the purpose.

The interview series, based on interviews, the correlation between number of respondents and the validity of results probably is weaker. E.g. the largest electricity consumers were included in the interview series to reduce the impact of industry extrapolation. That implies that the marginal use of each respondent added would diminish. However, also in qualitative approaches, a wide range of perspectives is beneficial. The reason for choosing a mixed approach was the synergies between qualitative and quantitative research strategies which have
been described previously; a case study based on historical data would have made a poor forecast for future development without a qualitative input.

Another thinkable methodology would have been to focus on just one of the aspects included in the report, either the typology of DR-options or the future DR-potential. To narrow down the focus would certainly have given a less sprawling report. The reason for maintaining a dual focus was the interdependence of the two aspects; to evaluate the future DR-potential it was necessary to analyse the context in terms of feasible market designs. Moreover, the contractor emphasized on including the parameters of cost and volume in the typology. Admittedly, a larger study had been to prefer. That includes more cases reviewed and additional respondents from further branches interviewed. Time was the limiting factor for the scope of scale of the study.

This description of step 1 and step 2, with regard to Figure 28 on Page 45, concludes the general research strategy. The steps 3, 4, 5, 6 and 7 will be discussed in the subsequent sections 5.2‒5.6 below. Focus remains on what has been done and why.

5.2 STEP 3 - REVIEWING PREVIOUS WORK

This section discusses how previous work was searched for, selected, examined and included in the study. It is also discussed how this collected experience from previous work is used in the analysis process and how the selection of previous work can affects the results.

Sir Isaac Newton is attributed to famously have written I have seen further by standing on the shoulder of giants. The success of science can partly be attributed to the process in which individual researchers bases their work on previous publications and simultaneously contributes to the collective knowledge themselves (Doppelt, 2013). This master thesis was no exception. To be able to answer the research questions, an extensive literature review was conducted within the following fields:

- The future European electricity market
- Demand Side Management and Demand Response
- DR potential in Sweden

Firstly, the review of previous work on the future European electricity market was performed in order to create the base case scenario and to be able to transfer the results from the case study to the same. Secondly, the study of previous work about DSM and DR was included to enable and facilitate the construction of the DR typology. Thirdly, previous estimations of the DR potential in Sweden were collected to be used as benchmarks and hence help to secure the validity of the results from the interview series.

Together, the reviews of previous work form a comprehensive and exhaustive frame of reference but identified however a few knowledge gaps. These were also mentioned and analysed in section 4.6. Since part of the literature review was conducted before the final formulation of the purpose, the research questions of this report was redesigned to contribute to the general knowledge base by filling these academic knowledge gaps.

For all three fields studied in the literature review, works representing different sources of information were included. Academic publications were included as well as reports from utilities, consultant firms and government agencies. The reason for this was to get, and reproduce, a multifaceted picture of the different topics. Since the master thesis regards the future, a domain in which nothing is given for certain, it was assessed that all perspective must be regarded. Having performed the literature review, the next step was to initiate the case study and the interview series.
5.3 STEP 4 - THE CASE STUDY

This section describes how the case study was conducted using the method of scientific review. The original methodology is describes briefly as are the major changes which have been made to adjust the method to the purpose of examining Demand Response.

In order to satisfy the purpose of this master thesis, a typology of DR-programs was designed so that the parameters of the typology corresponded to the research questions defined in section 1.3. To evaluate the characteristics, in terms of the parameters cost, volume and feasibility, of the different DR-programs, a quantitative approach based on a case study principle was selected. With case study is, in this report, understood a systematic review of previously documented case studies as described by Warren (2014). The exact procedure will be outlined below. The general strategy was to collect previous global experience of DR and thereafter transfer the results in order to apply the key findings on the future Swedish electricity market.

There are many ways to gather and structure quantitative data. One option is to perform a systematic review which is an efficient method for collating the results from previous studies (Warren, 2014). In this master thesis a version of the method, developed by Peter Warren, has been used that applies scientific review to analyse DSM policies.

Systematic review is a method which has been used very seldom outside its original domain medical science. This lack of proven generalizability of the scientific review methodology is a disadvantage and opens for a debate about whether other methods would have been better applicable for this case study. However, the concept of systematic review is starting to spread to other research areas due to the quality of the produced results. For example, the method is placed on the very top of the hierarchy of evidence.

Figure 29 below shows the hierarchy of evidence according to Evans (2002). Based on the high validity of the results and the fact that Warren (2014) has developed a version of systematic review which specifically targets comparison between different DSM-programs, systematic review was chosen over alternative options as methodology for conducting the case study.

![Figure 29 - Hierarchy of Evidence in Science. Source Evans (2002)](image)

The scientific review method includes a broad review of literature, including journal articles and books but also "gray" literature such as unpublished material, consultant reports or policy documentation (Warren, 2014).
The case study was conducted according to the generic stages of the systematic review. These stages, originally formulated by Harden & Thomas (2005), and are presented in Table 11 below. Subsequently, the different stages are explained shortly with a focus on the modifications which have been done to adjust the method to fit the purpose of this master thesis.

TABLE 11 - STAGES OF A SCIENTIFIC REVIEW (WARREN, 2014)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The development of review questions and boundaries</td>
</tr>
<tr>
<td>2</td>
<td>The development of a review protocol</td>
</tr>
<tr>
<td>3</td>
<td>The comprehensive search</td>
</tr>
<tr>
<td>4</td>
<td>The application of inclusion and exclusion criteria</td>
</tr>
<tr>
<td>5</td>
<td>Quality assessment</td>
</tr>
<tr>
<td>6</td>
<td>Data extraction</td>
</tr>
<tr>
<td>7</td>
<td>Synthesis of findings</td>
</tr>
</tbody>
</table>

STAGE 1 – REVIEW QUESTIONS

In the first stage, it was foremost important to define the purpose of the study and the research questions as well as the delimitations. This was done in chapter one in this report, see 1.3 Purpose and 1.4 Delimitations.

STAGE 2 – REVIEW PROTOCOL

The second step included the development of a review protocol. The review protocol defined what data that was to be extracted from each paper. With support in Warren’s methodology, following protocol questions formed the review protocol of the case study:

1) What constitutes DR?

2) What DR policies have been implemented around the world?

3) According to documented evaluation of such policies, what where the results?

4) Key findings; how and why did the DR-programs succeed or fail?

The first question of the review defines the terminology used and limits the range of literature that is to be reviewed. The answer to the question what constitutes DR is answers exhaustively in chapter 4 and hence not regarded further in the systematic review.

Question 2 and 3 were formulated to extract the information needed to create the typology of DR-programs which is one of the targets of this report. To do so, the different programs available must be found and defined as well as analysed. In question 3, results refer to the parameters of cost and volume for the program under the given circumstances.

Also question 4 connects directly to the purpose of this master thesis; by extracting the key findings, how and why different programs have succeeded or failed, a contribution to the public understanding of the electricity market was given. Moreover, transferring best practice to the future Swedish electricity market provides decision makers and investors with relevant information to support their decisions.
STAGE 3 - SEARCH STRATEGY

In this stage was specified what databases and which search phrases were to be used when searching for documents and literature. It was on beforehand decided to include 10 different case studies in the review. This decision was a compromise between the two aspects, statistically validity of the results contra the review quality of each individual case. The former aspect requests a larger number of cases reviewed and the latter, since the time for the case study was limited to three weeks, benefited from a manageable amount of cases. Since the results of this report are averages of the results from the included cases, it is well possible that a review of 20 or 30 cases would significantly impact the percentages. However, the most important outcome was not the actual percentages but the relation between the different DR programs. Consequently the number of 10 cases was assessed to be reasonable with regard to the overall quality requirements and the time limitation of this master thesis.

As previously mentioned, Warren (2014) finds it positive for the review to cover a wide variety of documents types. Hence databases with different characteristics were identified and a mixture of different sources, such as academic journal articles, consultant reports or government program descriptions, was reviewed. In order to evaluate the different sources a quality assessment was implemented in the method. See stage 5 below for further details.

Following data bases and search engines were used in order to find studies to include:

- UniSearch, Linköping University Library, www.bibl.liu.se
- Google Scholar, www.scholar.google.se

UniSearch offered a good coverage of academicals journals, The Demand Response Directory had a wide collection of official case studies and reports and through google it was possible to find unofficial, but often cited, “gray” literature such as newspaper articles or consultant reports.

Following search phrases were used while searching on the above mentioned data basis:

- “Demand Response”
- “Demand Response Program”
- “Demand Response Case study”
- “Demand Response Review”
- “Demand Response Potential”
- “Demand Response Demand Side participation”

The initial intention was to choose only one or a few search phrases to facilitate the selection process. However, it was an early discovery that even small subtleties in the search phrase returned different but related results. Hence, to get a comprehensive and exhaustive set of study objects, the used search phrases were extended to the list above.

STAGE 4 - INCLUSION CRITERIA

The aim of this step was to select the most relevant and interesting documents from all the selected data collected in step 3. With regard to the delimitations of the report, the inclusion criteria focuses on the DR programs to exclude the many papers and case studies focusing on technological trials and modelling studies which also has been conducted.
The inclusion stage was needed since the amount of material published on the topic was quite extensive. For example, the search phrase “Demand Response” at UniSearch gives 24,500 hits and Google Scholar finds 2.100 hits on “Demand Response program”. Since a full examination of all possible case studies would have been impossible within the given time frame, an iterative approach was used that continuously included found documents which fulfilled all inclusion criteria’s to the list for the scientific review. As the inclusion criteria’s builds on the principle mutual exclusive and collectively exhaustive, it was easy to find the first cases and ever more difficult to match additional cases to the list. However, given the extensive search material, finding the cases to include in the study was relatively easy and when the predefined target of 10 relevant cases was met after two days the search was terminated after two days.

Following inclusion criteria’s were applied in this stage of the scientific review:

- Documents that discusses an implemented, or the implementation of a, DR programme and includes information about 1) cost of system, and 2) Extent of DSM
- DR- Programs in which industrial customers are taking part in
- An evaluation of the case and a discussion about the context should be included
- Documents which are accessible and downloadable from the internet
- Documents that are written in Swedish or English
- Case studies that complement the previously included documents so that each DR- programs included in the study (ToU, RTP, CM, SR, DC, AS) are represented at least twice.
- Case studies that supplement the previously included documents so that a wide variety of context emerges in terms of geographical, technical and economic aspects.

STAGE 5 - QUALITY ASSESSMENT

To enable further analysis and discussion, it was as important to evaluate the data as to extract it. Because the different documents vary in quality and reliability, the results of each have to be evaluated individually before contributing to a general conclusion (Warren, 2014). Therefore a quality assessment system (0–14), based on certain “yes/no” quality indicating parameters, is applied. The quality indicating questions included were based on a sample quality assessment suggested by Warren (2014). Although there might be other quality indicators, and possibly other ranking systems, a proven model was used in order to maintain focus on the main research questions of this master thesis. For each case included in the study, a quality assessment score was given in accordance to Table 12 below:

<table>
<thead>
<tr>
<th>“Yes/No” quality indicating question</th>
<th>Points received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Has the process for programme implementation been clearly explained?</td>
<td>4</td>
</tr>
<tr>
<td>Has the process for programme evaluation been clearly explained?</td>
<td>4</td>
</tr>
<tr>
<td>Has the document been peer reviewed or independently verified?</td>
<td>2</td>
</tr>
<tr>
<td>Are the statements of copyright, regulatory compliance and possible conflicts of interests presented?</td>
<td>2</td>
</tr>
</tbody>
</table>
Is the authority of the publishing organisation reliable and reputable?  

Where percentages are given, are the totals given?  

The first two questions were included because of their direct impact on the transferability of the results. To be able to generalize findings, it is essential to be aware of how big the difference is between the source and the situation to which the results are to be extrapolated (Lee & Baskerville, 2003). Consequently, explicit and exhaustive description of the implementation and evaluation of the DR-programs are essential for the quality, which also is indicated by the relatively high maximum points received if the criteria’s are satisfied.

The remaining four criteria’s are testing the credibility of the source by in two different ways. If the author is reliable and whether the document has been peer reviewed, check the formalities behind the document. However, to investigate the overall quality of the text, two control questions which are focusing on the actual work and not the formalities that surround it were included: are totals given after percentage and are possible conflicts of interest presented. To give the total after a percentage gives the reader a better possibility to compare the results and assess its quality. The score was given by the author of this report when reviewing the different documents. Admittedly, this can be regarded as a week evaluation method but the quality assessment was performed to give an indication of the reliability of each included case from a DR-perspective, not to give a general opinion of the different studies reviewed.

**STAGE 6 - DATA EXTRACTION**

After the evaluation of the included case studies came step number 6, data extraction. In this step the relevant data was extracted from the original documents and filled in a review comparison cheat. It is important to define what data is interesting and relevant with regard to the protocol questions (Warren, 2014). With regard to the purpose of this study, it was necessary to include parameters regarding policy choice and policy impact. To enable further analysis the background and the key findings were also extracted and collected for each case. After having defined the data extraction in Table 4 below, these different categories will be discussed and motivated further. If the requested data was not available, the corresponding field was to be left empty. In chapter 7, the data from the systematic review are presented in accordance to Table 13 below.

**TABLE 13 - MATRIX SPECIFYING DATA TO BE EXTRACTED FROM EACH CASE STUDY**

<table>
<thead>
<tr>
<th>Background</th>
<th>Policy context</th>
<th>DR-program</th>
<th>Impacts</th>
<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Document type</td>
<td>Electricity market</td>
<td>Policy choice</td>
<td>Energy savings</td>
<td>Conclusions</td>
</tr>
<tr>
<td>Review date</td>
<td>Electricity resources</td>
<td>Policy design</td>
<td>Peak load reduction</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Regulation</td>
<td>Policy coverage</td>
<td>System cost</td>
<td></td>
</tr>
<tr>
<td>Quality assessment score</td>
<td>Demand structure</td>
<td>Policy success</td>
<td>System benefits</td>
<td></td>
</tr>
<tr>
<td>Country (region)</td>
<td></td>
<td>Policy evaluation</td>
<td>DR-volume</td>
<td></td>
</tr>
<tr>
<td>Participants</td>
<td></td>
<td>Policy implementation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aim &amp; Method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The background classification data is for data management purposes and serves as points of reference in the synthesis discussion that follows the data extraction. The policy context is important for the possibility to transfer best practice from the reviewed cases to the future Swedish electricity market. The DR-programs are, together with the corresponding policy impact, the main focus of the study.

It is important to compare the context when generalizing and understand that depending on the circumstances results and best practice can be hard to transfer. Still, historical data do provide a good understanding of a problem and could give indications on future events. For example Lee & Baskerville (2003) argue that analysis of historical data may not completely solve a problem but it can provide an appropriate start for a solution.

STAGE 7 – SYNTHESIS OF FINDINGS

In writing the findings down systematically, patterns emerge from the results. According to Eisenhardt & Graebner (2007) one possibility is to link different data categories to each other. The basic idea is that conclusions can be drawn through observing patterns between context, measure and outcome. In this case, such a change of basis was performed through as transformation of the structure from source based to object based. That implied sorting out the different DR-programs included in the study and examines the results for each individually with regard to the context. In line with the above concept, Figure 30 illustrates the analysis model used for syntheses of the findings from the systematic review.

FIGURE 30 - ANALYSIS MODEL BASED ON CHANGE OF BASIS

The analysis of the relation between policy impact and the associated context helped e.g. to determine the cost and volume characteristics of each individual DR-program. Moreover, the analysis of policy mechanisms contributed to the understanding how and why policies succeeded or failed, as have been argued by Frels & Onwuegbuzie (2013). The key output from this process was the connection between DR-programs, context and policy impact which formed the basis for the latter analysis with regard to the purpose of the thesis.
The transferability of best practice to a specific context is made by comparing the background and context with documented impact (Baily, 2014) for each case with the corresponding elements of the base case scenario and thereby estimates the feasibility of each individual DR-program. This was done in this stage and the procedure is to find in chapter 8 in this report where key drivers for DR are identified for the different cases and related to the context of the base case scenario which was described in chapter 3. The power mix, demand structure and pricing model were also regarded for each DR-program when transferring best practice.

A final part of this stage was to publish the results. Publishing the results had two reasons. Firstly it enables reviewers and opponents to test and validate the results, secondly it is a possibility to spread the acquired knowledge (Doppelt, 2013). This being a master thesis, the result from the scientific review was presented through with the publication of the finished report as well as on the final presentations at Linköping University and Vattenfall AB respectively. In chapter 6, the collected data from the scientific review is summarised and the final typology, which was based on the previously mentioned data, is presented in chapter 8.

5.4 STEP 5 - CONDUCTING THE INTERVIEW SERIES

This section discusses the method used when conducting the interview series. It is discussed how the respondents were contacted, what questions were asked and how the results was interpreted.

Parallel to the case study, interview series was conducted. The aim of this complementary investigation was to understand the current state of mind among the energy intensive industry, the future trends in energy use within the industry sector and what drives the development related to the use of DR. Although the scale of the interview series was much smaller, and the selection more random, than the case study, interviews enable more in-depth knowledge (Frels & Onwuegbuzie, 2013) about the processes which are ultimately setting the boundaries for industrial DR. Moreover, by asking detailed questions about the DR-potential in dominating industries it’s possible to transfer the results from one context to another (Doody, O & Noonan, 2012) by taking the different regional, industrial and regulatory contexts into consideration. The interview series result in a demand side Merit-Order graph, described in section 5.5 below.

The interview series was included in the research to get first-hand information from persons who are active on, and knowledgeable about, the electricity market. It was found necessary to complement the quantitative case study with this qualitative input to transfer the results from the latter to a Swedish context. In addition, the interview series provided the base for assessing the existing DR-potential in Sweden and gave an account for how the energy intensive industry in Sweden look upon the future prospects of DR. The use of the interview series, and the logic of the process with regard to the purpose of this thesis, is illustrated in Figure 31 below.

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**FIGURE 31 - INTERVIEWS WITH THE INDUSTRY GIVE INPUT TO FURTHER ANALYSIS**

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Before going into the interviews conducted as part of this master thesis, some general comments on the method is given. Interviews are typically used to collect data and gain knowledge from individuals (Doody, O & Noonan, 2012). In their paper *preparing and conducting interviews to collect data*, Doody & Noonan describes how to plan, conduct and process information from interviews. The ambition for the interview series conducted as a part of this master thesis was to follow the principles presented by the authors above. Especial care has been taken during the interview planning phase. Who to interview, and what questions to ask, are important choices which influence the result (Doody, O & Noonan, 2012).

During the interview process agents from different industries and with different positions were interviewed. With regard to the purpose of this thesis, a distinction between two different categories of interviews was conducted. Firstly, an interview series with the energy intensive Swedish industry was conducted in order to estimate the future DR potential in Sweden, and thereby provide decision makers and investors with a basis for discussion. Secondly, other agents such as utilities, researchers, TSO:s and government agencies were interviewed for two reasons; to receive background information and to get a holistic approach on the following analysis. To collect multiple perspectives relates to the purpose of this thesis by contributing to the general understanding of DR in the future Swedish electricity market.

**INTERVIEWS WITH THE ENERGY INTENSIVE INDUSTRY**

As industrial-DR was the scope of this thesis, the interviews were held with representatives from the energy intensive industry in Sweden. The end-user of electricity is the principal agent in DR. Hence it is important to understand their point of view. The interviews started off with a discussion on the current situation but focused on future possibilities and challenges. The aim was to estimate the future DR-potential and the key factors for realizing the potential based on the experience and anticipations of the respondents and the organisations they represented.

It is important for the possibility to extrapolate the results that the respondents represent the dominant industries in terms of electricity consumption. Hence, the interview respondents were chosen from a selection of companies after a sortation based on industry characteristics and electricity consumption. The four most energy intensive industries were identified to be Paper & pulp, metal working & mining, chemistry and manufacturing. Figure 32 below shows the electricity consumption per branch as share of the total industrial energy use 2013 (SCB, 2013).

![Figure 32 - Electricity Use per Industry in Sweden 2013. Source (SCB, 2013)](image)

Moreover, SEA (2013) points out two further branches with high potential of becoming increasingly electrified; transportation and retail industry (commercials). Since this study aims to estimate the future DR-potential, these two branches were also included.
The interviewed industries were:

- Paper & pulp
- Metal working and mining
- Chemical industry
- Manufacturing industry
- Transportation
- Commercials (shops, stores and boutiques)

Energy intensive industries

Industries with high potential

Having decided which industries to include in the interview series, the largest electricity consumers in each industry were contacted pre-e-mail. To increase the probability of a positive answer on the interview request, only persons who had participated in previous studies, typically energy managers at each firm, were contacted.

Table 14 below shows the interviewed respondents, their company and industry as well as the date when the interview took place. The Table sorts the respondents after industry and date of interview.

<table>
<thead>
<tr>
<th>Branch</th>
<th>Company</th>
<th>Position</th>
<th>Date of Interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper &amp; Pulp</td>
<td>Holmen</td>
<td>Production manager</td>
<td>20/10-2014</td>
</tr>
<tr>
<td>Metal &amp; Mining</td>
<td>Vargön Alloys</td>
<td>Financial manager</td>
<td>13/10-2014</td>
</tr>
<tr>
<td>Metal &amp; Mining</td>
<td>Sandvik</td>
<td>Senior engineer</td>
<td>30/10-2014</td>
</tr>
<tr>
<td>Chemistry</td>
<td>AGA</td>
<td>Energy manager</td>
<td>30/9-2014</td>
</tr>
<tr>
<td>Chemistry</td>
<td>INEOS AB</td>
<td>Energy manager</td>
<td>14/10-2014</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Preem</td>
<td>Senior engineer</td>
<td>3/11-2014</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Scania</td>
<td>Energy manager</td>
<td>29/10-2014</td>
</tr>
<tr>
<td>Transportation</td>
<td>Trafikverket</td>
<td>Energy manager</td>
<td>2/10-2014</td>
</tr>
<tr>
<td>Commercials</td>
<td>ICA</td>
<td>Energy manager</td>
<td>1/10-2014</td>
</tr>
</tbody>
</table>

The interview questions are fully recited in Appendix 3 – Interview template. According to the principles of Doody & Noonan, (2012), the general idea behind the choice of questions were to have a dynamic and interactive dialog rather than filling in a questionnaire. This was done in three steps:

1) Firstly, the current energy situation at the company was mapped through the initial questions. To reach a higher trust level and to put the interview person in his comfort zone, the first questions regarded the current energy situation at the company and the daily work of the respondent which could be related to energy questions.

2) Secondly, DR was discussed in general terms. Questions were asked about the attitude towards DSM and the knowledge about DR. This gave a good background to the answers on the more specific questions following in the third step. Different market design, their advantages and implications where also discussed.
3) Finally, the questions led into possible DR-measures which could be undertaken by the company in the future, regarding what will be technically possible, economically profitable etc. This third step included the filling of a table that describes the future DR potential depending on cost, volume and duration time of the flexible loads for three different points in time, see Table 15 below. These three parameters were focused on in order to generate a demand side Merit-Order curve which is based upon the parameters cost and volume. The duration of the response is important to regard from a system perspective since it relates to the availability of the potential response. During the interviews, the table below was used as a base for discussion. Relevant data, when available, were filled in the table for each company interviewed.

**Table 15 - Industrial Demand Response Potential Matrix**

<table>
<thead>
<tr>
<th></th>
<th>Load shifting</th>
<th>1h</th>
<th>1 day</th>
<th>1 week</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2014</strong></td>
<td>Example of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fix cost (SEK/MWyr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variable cost: (SEK/MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2025</strong></td>
<td>Example of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fix cost (SEK/MWyr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variable cost: (SEK/MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2050</strong></td>
<td>Example of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fix cost (SEK/MWyr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variable cost: (SEK/MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After the interviews, the results were linearly extrapolated for each branch. The interviewed companies’ consume together over 20 TWh per year which is about 13% of Sweden’s total electricity demand (SCB, 2013). More specifically, the branches they represent are aggregating to over 90% of the industrial electricity demand in Sweden, which is the scope of this study. To better extrapolate the results from the interviews, each energy manager was specifically asked how they assessed their situation in relation to other companies within the same branch.

**OTHER INTERVIEW OBJECTS**

Apart from the energy intensive industry, some other agents with interest in, and knowledge about, the electricity market were interviewed. These interviews were rather dialogs that aimed at two things. Firstly, filling in knowledge gaps in the background of the report and secondly to ask each agent their perspective on the future development.

The interviews of other persons and organisations than industrial electricity consumers were not an intentional part of the research strategy but rather a consequence of the questions that arose during the literature review. E.g. in some information on the Swedish electricity system was missing, SvK were interviewed. If a scenario analysis made by SEA was unclear, they were contacted. And in case a specific perspective on an academic report was needed, the author of the study was contacted, as were the cases with the professors Söder and Gills.
In opposite to the interviews with the power intensive industry, most of these interviews were held via telephone or even per e-mail. In some cases though, where the geographical situation allowed, the interview was conducted in person.

One major difference between the two interview series was the approach. Since these other interview respondents did not have any price information to conceal, the questions were asked more directly to the point. Also, since all respondents presented in the Table 16 below work with DR on a daily basis, much less introduction was needed.

Following categories of organizations were interviewed:

- **Utilities**
  
The electricity producers were included in the scope for mainly two reasons. Firstly, the utilities have a major impact on the future electricity market in terms of investments and lobbying power (IEA, 2013). Therefor the interviews were focusing much on different scenarios. Secondly, they have good knowledge about the behaviour of the customer and are thus able to give a second opinion about how DR is operating and developing.

- **Government agencies**
  
  Government agencies and authorities have regulative power and hence a good possibility to shape, or at least strongly influence, the future market designs (SEA, 2012). The base case scenario is almost exclusively based upon data collected from the Swedish electricity market inspectorate. Furthermore, SvK is responsible for the power balance in the grid which is the practical problem that is to be solved by DR.

- **Smart grid technology companies**
  
  To understand what is technically possible for industrial DR it was necessary to contact companies working with the development of the smart grid and its components. The interviews were focusing on their belief and visions for the future as well as their understanding of customer needs.

- **Researchers**
  
  To get an academic perspective, researchers who focus on the future electricity market in Sweden as well as on a European level were interviewed. The academic perspective is important for several reasons. First of all the researchers are probably less economically bias as opposed to other respondents such as utilities or electricity users. Moreover, they have often access to power full analytical tools such as simulation software and possess a deep knowledge at a system level.

Table 16 below shows the respondents, apart from the previously listed representatives from Swedish energy intensive industry, who have been contacted as part of the interview series.

**Table 16 - Non-Industrial Respondents**

<table>
<thead>
<tr>
<th>Branch</th>
<th>Organization</th>
<th>Position</th>
<th>Date of Interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility</td>
<td>Vattenfall AB</td>
<td>Senior analyst</td>
<td>1/9-2014</td>
</tr>
<tr>
<td>Utility</td>
<td>Holmen Energi</td>
<td>Manager</td>
<td>20/10-2014</td>
</tr>
<tr>
<td>Government agency</td>
<td>SEA</td>
<td>Market analyst</td>
<td>16/9-2014</td>
</tr>
</tbody>
</table>
In this section, the models for analysing and presenting the results are described. In parallel to explaining the analysis process, one objective of the section is to discuss the scientific validity and practical usability of the result.

These last steps involve analysis and are crucial for the process, as all the input data from previous work, the case study and the interview series need to be processed, analysed and transferred to the base case scenario. Faria et al. (2011) argues that the creation of knowledge constitutes an interaction between previous experience and new findings. Therefore, this step is not done at one occasion in the end of the process but rather continuously throughout the steps of literature review and data collection as described in the overall research strategy. The data was analysed in accordance to the method described below which is developed to fit the purpose of this thesis.

In order to serve the purpose, two models were developed to deliver results in accordance to what has previously been defined as a request:

- A typology for DR programs with according to the parameters cost, volume and feasibility.
- A Demand Side Merit-Order curve which estimates the future DR potential in Sweden.

Results can be presented in many different ways and the presentation actually has a big impact on how the results are interpreted and received (Aberson, 2002). Because of this, the models chosen are designed to be visually pleasant and logically viewable. For example, the three dimensions of the typology consists of a two dimensional plane and a colour code instead of a third axis. Likewise, when presenting future DR volumes a function was used rather than a number which also would have been an option. Most other reports actually put a number on the estimated potential and connect that potential to a specific system cost. However, since the cost of a good and the demanded volume of the very same good are interdependent according to basic economic theory, the function approach offers a more flexible presentation of the results. Since the purpose states that the result is to serve as basis for decision makers and investors, this flexibility increases the usability of the results.

**A TYPOLOGY OF DR-OPTIONS**

A typology of DR options based on the parameters price, volume and feasibility is, with regard to the purpose of the master thesis, one of the main objectives of this report. A model for such is given in Figure 33 below.

The Model below is three-dimensional. The Y-axis indicates the system cost, the X-axis the potential DR-volume and the feasibility is indicated by the colour of the field representing each DR-option. Green represents high feasibility, red means impossible and the shades in between are a gradual scale between the two extremes. The axes are intentionally ungraded, due to the
fact that the model is of comparative nature and thus visualizes relation between the different DR-programs rather than quantifying specific numbers.

![Typology of DR-programs](image)

**FIGURE 33 - TYPOLGY OF DR-PROGRAMS WITH EXAMPLE INPUT**

First and foremost, in order to better understand the construction of the typology, a definition of the parameter cost volume and feasibility is needed.

**COST**

In short the cost parameter indicates how expensive one DR-program is in relation to other DR-programs if all costs are taken into consideration. In this case, cost can be defined as "increase in system cost due to implementation of the specific DR-program". In the typology above, the Y-axis is labelled system cost-efficiency which is the relation between the system cost and the DR-volume triggered. This axis was chosen in order to get an intuitive model in which the upper right corner corresponds to a *best practice*. The system cost is supposed to take all cost into account; technical investments, higher electricity prices, subsidies, capacity payments etc. It is not important for this parameter whoever carries the cost; be it customer, utilities or government agencies. That aspect however is important and thus regarded in the feasibility parameter. In general, DR-programs with a low system cost are requested.

The US DoE has proposed a framework for how to evaluate the total economic cost of DR-programs. In Table 17 below, the most important factors according to the US DoE (2006) are listed, together with a translation to the terminology of this report:

<table>
<thead>
<tr>
<th><strong>TABLE 17 - COST DRIVING PARAMETERS FOR DEMAND RESPONSE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost according to US DOE</strong></td>
</tr>
<tr>
<td>Program Administrator Expenses</td>
</tr>
<tr>
<td>Financial Incentive to Participant</td>
</tr>
<tr>
<td>DR cost for administrator and participants</td>
</tr>
<tr>
<td>Participant Transaction Costs</td>
</tr>
<tr>
<td>Participant Value of Lost Service</td>
</tr>
<tr>
<td>Increased Energy price</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Lost Revenues to the Utility</td>
</tr>
<tr>
<td>Environmental Compliance Costs</td>
</tr>
</tbody>
</table>

A remark is that although the US DOE consider environmental compliance costs to be an important factor, it is not taken into account in this master thesis. This because of the difficulty of quantifying the parameter. Consequently, the mathematical definition of cost of DR-options for this report is:

\[ TC(DR_o) = AC_{DR_o} + I_{DR_o} + S_{DR_o} + VC_{DR_o} + LR_{DR_o} + \Delta EP_{DR_o} \]

Where, \( TC \sim \) the total system cost, \( DR_o \sim \) the specific DR-option, \( AC \sim \) Administrative costs, \( I \sim \) Investments required, \( S \sim \) Subsidies, \( VC \sim \) Variable costs, \( LR \sim \) Lost revenues and \( \Delta EP \sim \) the difference in average electricity wholesale price.

When quantifying, it is very difficult to put a number on what is a high or a low system cost. However, to give a few benchmarks, some examples follows. In an energy only market, only the price of electricity is regarded which facilitates comparisons.

- The average price of electricity in Sweden is about 400 SEK/MWh (Nord Pool, 2014). During the demand peaks in 2010 this variable cost rose up 12,000 SEK/MWh but only for a few hours (Nord Pool, 2014).
- A system with gas turbines as peak capacity could operate at a system cost of 1,000 SEK/MWh which could be regarded as a reasonable upper limit for DR-programs if the incentives are to be economical (Söder, 2014).
- In reality though the motives are often political. The British government e.g. announced this autumn that they guarantee a strike price, a lower price floor, on 1,080 SEK/MWh to the nuclear plant of Hinkley point in order to secure long term capacity targets. This could be compared to the current UK wholesale price which is about 570 SEK/MWh.

**VOLUME**

In short, how much power load is potentially flexible? Volume is in this case defined as the extra load that has become flexible as a consequence of a specific DR-option (SvK, 2014). The model does neither distinguish where in the system the flexibility arises, nor how long response time is needed. However, as the base case scenario highlighted the need of peak demand reductions between 1−4 h, the durability of the load flexibility must exceed 1 h to be considered. Moreover, as flexibility comes to a price and that price must be globally applied in the model to enable an objective comparison, the price level was assumed to follow the forecast of the base case scenario. Typically, DR-options which release large volumes of flexible load are desired.

The DR-potential, or volume of flexible load, is actually a ratio rather than an absolute value since it also depends on how large the program or market is. Hence, the mathematical definition of DR-volume was in this case:

\[ DRV(DR_o) = \frac{L_{DR_o}}{M_{DR_o}} \]

Where \( DVR \sim \) DR-Volume, \( DR_o \sim \) the specific DR-option, \( L \sim \) the flexible load in MW obtained and \( M \sim \) the market size in MWh
One example is the Swedish power reserve. SvK has procured a Strategic Reserve including about 630 MW of DR-resources for 2014/15 (SvK 2014). That equals L ~ flexible load in the equation above. M, ~ the market size, is in this case represented by the total industrial power demand which in Sweden is about 10,000 MW (SEA, 2013). Consequently, the volume DRV of the power reserve used in Sweden today is about 6%. In relation to other DR-programs that is a moderate number that can be used as a benchmark to validate results from other sources.

**FEASIBILITY**

In short, how likely is the DR-option to be implemented? Feasibility was in this case defined as the likelihood or plausibility of an implementation of a specific DR-option. This parameter is itself an aggregate between many different factors such as the principle mechanism, the cost, previous experiences, political will, technical availability etc. There is no commonly accepted formula for how to evaluate feasibility, nor is this an attempt to construct a universal methodology for it. Instead, feasibility is a subjective appraisal of the different aspects. The most important factors, and how they influence the parameter of feasibility, are summarized in Table 18 below. The factors presented below, which are used to support the feasibility parameter, are based on the article Prioritizing Demand Response programs by Aalami et al. (2010).

**TABLE 18 - MODEL FOR QUANTIFYING FEASIBILITY**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Principle effect on feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>A more complex system is a less feasible option. The more regulation is needed, the more difficult it would be to implement. In some cases the DR-programs would be unauthorized by current legislation and changing laws takes time.</td>
</tr>
<tr>
<td>Cost</td>
<td>A more expensive system is a less feasible option. In general the government, companies and private persons alike tries to save money and are hence reluctant to expensive programs. Also the cost structure matters; especially difficult is it if a system requires large early investments whereas a solution which distributes the cost over time might be more feasible.</td>
</tr>
<tr>
<td>Desire</td>
<td>A more desired DR-program is obviously a more feasible option. Political will and parliamentary work has a strong influence here. If the ruling parties want a solution, it is more likely to be implemented. The desire of other strong market agents such as utilities and large electricity consumers are also considered as part of this factor.</td>
</tr>
<tr>
<td>Neighbours</td>
<td>A policy that aligns with policies of neighbouring countries is a more feasible option. The European Union is still fragmented but is showing sign of convergence. In such a situation it might be difficult for one nation to differ greatly in its market regulation.</td>
</tr>
<tr>
<td>Technology</td>
<td>A system that is technically tested and available is a more feasible option. Hypothetically there can be designs which are preferred but are difficult to implement because of lacking or not verified technology.</td>
</tr>
</tbody>
</table>

Each of the five factors above is given a ranking number on the scale (0;5). A low number is negative for the feasibility. I.e. if a technology is not available, the costs are high or the
neighbouring countries propose other options. A high number means that the possibility to implement the program is high from the specific perspective of one influential factor. This could be e.g. that the government is having a desire for a certain DR-program or that the complexity of a DR-program being very low which facilitates a successful implementation. The total feasibility is determined by the aggregated score from the five parameters defined by the table above. An important remark is that a "0" score in any of the individual factors means highly improbable and will consequently give a total score of zero. Mathematically, this could be described as:

\[ FR(DRo) = \left( \sum_{f=1}^{5} (DRo_f) \right) \times \left( 0 \text{ if } \prod_{f=1}^{5} (DRo_f) = 0 , \text{ else } 1 \right) \]

Where, \( FR \) ~ Feasibility ranking, \( DRo \) is the DR-option for which the ranking is being calculated, \( DRo_f \) the score from each factor for the specific DR-program.

The feasibility ranking varies in the interval \((0; 25)\) and is indicated by a colour scheme in the model through following distribution illustrated in Figure 34.

<table>
<thead>
<tr>
<th>FR:</th>
<th>0</th>
<th>1-5</th>
<th>6-10</th>
<th>11-15</th>
<th>16-20</th>
<th>21-25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 34 - COLOR CODE FOR THE PARAMETER OF FEASIBILITY IN THE DR-TYPOLGY**

**DEMAND SIDE MERIT-ORDER CURVE**

The Merit-Order curve is a model which sorts different energy sources depending on their marginal production costs. The Y-axis displays the price level and has the unit SEK/MWh. On the X-axis, with the unit MW, the model also illustrates the available capacity for each energy source given a specific electricity price level (IEA, 2008). Typically, it is uses to describe the sequence of activation of power plants and to determine market spot price. This works because the market spot price is defined by the highest variable cost of electricity production among the activated power plants. E.g. If a system demand so much power that expensive gas turbines must be activated to satisfy the aggregated demand, the relatively high marginal price of that energy source will define the spot price for the entire market volume. Figure 35 below shows a principle Merit-Order graph.
In this report, the concept of Merit-Order was transformed to be applied to the demand side; sorting the responses from different industries after activation price. The total DR-potential was also to be possible to infer from the graph. The method used was in line with that described by FFE (Forschungsgesellschaft für Energiewirtschaft) in a report by Gruber, et al. (2013).

The demand side Merit-Order curve is based on two cost-parameters: specific costs, i.e. costs for the activation that depends on the amounts of flexible loads, and opportunity costs which is quantified in SEK/MWh (Gruber, et al. 2013). The basic idea behind the model was to investigate at what market price level different industries begin to shift load and to calculate at what price level load is shedded. These investigations and calculations were made for each industry and the results are put into tables which ultimately constitute the base for generating the demand side Merit-Order curve (Gruber, et a., 2013).

Figure 36 below illustrates the generic steps to create the demand side Merit-Order curve.
The method clearly distinguishes between load shifting, that is to shift load in time through variable production rates, and load shedding which is defined as a complete shutdown of the production process due to the high electricity prices that shrink the profit margins.

To integrate the potential of load shifting in electricity intensive processes in the Merit-Order curve, the costs for load shifting in these branches need to be gathered. A first step is to conduct interviews with companies and investigate how they bid flexible loads to the market and, more importantly for this study, how they presume to do it in the future. All of the interviewed companies had energy intensive processes but not all of them were actively bidding flexibility today. The activation of the flexible loads was typically realized manually, having received a phone call from the TSO with the instruction to shift or shed load. Normally, on-site personnel are needed to restart the process, which obviously adds fixed costs for the DR. Moreover, costs in terms of inefficient production occur. In order to restart an electricity-intensive process an employee is required on-site. Additionally, costs occur due to a more inefficient production and reduced quality as the production then is optimized after other parameters than utilization. The variable cost of shifting load can be determined by taking the sum of specific costs into account.

Having collected the data needed from each company, that is information on flexible volumes and price structures, the input from the interview series was extrapolated for each industry. The price levels were assumed to remain constant for the entire industry and the volumes for available load shifting were generally linearly extrapolated in relation to the electricity consumption. Mathematically, this extrapolation can be described with the following equation:

$$L_{Shift_b} = L_{shift_c} \times \left( \frac{EC_b}{EC_c} \right)$$

Where $L_{Shift}$ ~ potential load shifting volumes, $EC$ ~ annual electricity consumption, $c$ ~ the interviewed company and $b$ ~ the entire industry. This process was repeated for each industry included in the study.
For load shedding, the methodology differed depending on the complexity of the potential. Theoretically, load shedding is more expensive. The basic principle behind load shedding is that production is cancelled if the variable cost, due to e.g. high electricity prices, is exceeding the profit margin and thereby makes production unprofitable. However, many other aspects can influence whether a company shed load on not; strategic production, order fulfilment, production targets etc. Hence the collection of accurate information and even more so generalisations in terms of extrapolation would have been very difficult (Gruber, et al. 2013).

Instead, for each industry the theoretical, economical potential is calculated. This model calculated at which spot price load is shedded depending on only the electricity intensity and profit margin. This a mathematical description of this concept follows. Figure 37 below shows the general structure of costs and earnings in companies.

$$SP = FC + VC_{M&P} + VC_{el} + M$$

Where SP ~ Sale Price, FC ~ fixed costs, VC ~ variable costs, M&P ~ Materials & personnel, El ~ electricity and M ~ profit margin.

The fixed costs do not depend on production, but the variable costs correlates with the production process. The formula below describes the different input resources in a process. Electricity is one of the significant resources for many Swedish industries; other important variable costs are materials and fossil fuels (SCB, 2013). The electricity price is in this case the total cost for the company, which includes spot price, taxes, grid charges etc. In this case, the energy dependency is of interest. According to SEA (2012), the electricity intensity can be defined as:

$$EI = \frac{VC_{el}}{TC}$$

Where el ~ the electricity intensity, $VC_{el}$ ~ the electricity costs and TC ~ the total costs

Companies with electricity intensive processes typically purchase their electricity directly from the spot market, e.g. the Nord Pool Spot. Some of them however buy electricity through long term contracts with electricity producers. Regardless of contract, load shedding at high electricity wholesale prices can be economically sound as purchased electricity can be sold back to the grid (Nord Pool, 2014).
Figure 38 below illustrates the cash flows in case of load shedding. The figure shows that the factory, in the case of DR through load shedding, neither consumes electricity nor produces any goods. Instead the contracted electricity is sold back to the grid operator and the company makes a profit contributing arbitrage on the difference between spot price and contracted price.

Load shedding leads per definition to a non-recoverable loss of production (Dabur, et al., 2012). To calculate the price levels from which load shedding becomes profitable a mathematical model of the problem is needed and consequently presented below.

In case of normal production, the profit contribution is the sales price minus the variable costs.

\[ PC_p = SP - VC \]

Where \( PC_p \) ~ profit contribution from production. \( SP \) ~ sales price and \( VC \) ~ total variable cost

In case of Load shedding, the profit contribution can be described by the equation

\[ PC_{L,shed} = \Delta EP \times EI \times TC \]

Where \( PC_{L,shed} \) ~ profit contribution from Load Shedding, \( \Delta EP \) ~ Difference in electricity price (arbitrage between contracted price level and spot price) and \( TC \) ~ total costs

With regard to the demand side Merit-Order curve, it was of interest at what increase in electricity price (\( \Delta EP \)) load is shedded. Theoretically that occurs when the profit contribution from load shedding exceeds that of production. In mathematical terms, load is shedded when

\[ PC_{L,shed} > PC_p, \Rightarrow \Delta EP > \frac{PC+M}{EI+TC} \]

Given the previous definition of opportunity costs, the calculation of opportunity cost for lost production depends ultimately on the proportion of different costs; the electricity intensity and the profit margin. (Gruber, et al., 2013)
The formula above indicates that if the profit margin and cost structure of a company is known, the opportunity cost for load shedding depends only on the wholesale electricity spot price. Hence, in order to create a demand side Merit-Order curve, it was of vital importance for the study to investigate the distribution of different cost and the profit margin in different branches. Consequently, the companies included in the interview series were asked about these parameters. In case of lacking data from the industries, that is if annual reports does not cover the questions, statistical sources such as SCB were be used. The information was filled in according to Table 19 below:

<table>
<thead>
<tr>
<th></th>
<th>Total costs</th>
<th>Electricity costs</th>
<th>Profit margin</th>
<th>Power demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company A.1</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>MW</td>
</tr>
<tr>
<td>Company A.2</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>MW</td>
</tr>
<tr>
<td>Industry A</td>
<td>Average %</td>
<td>Average %</td>
<td>Average %</td>
<td>Average MW</td>
</tr>
<tr>
<td>Company B.1</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>MW</td>
</tr>
<tr>
<td>...</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>MW</td>
</tr>
</tbody>
</table>

Table 19 - Sheet to Organize Data Necessary for Calculating Load Shedding Potential

Having calculated the opportunity costs of load shedding in electricity-intensive industry, the corresponding potentials needed also to be determined in order to create a demand side Merit-Order curve. The potential for load shedding is obviously larger than that of load shifting since the entire production process is shut down.

To quantify the potential of the flexible load for load shedding, the energy consumption by industry according to data from SEA was used as a basis. However, the input from the base case scenario, in terms of economic development, and the qualitative indications given by respondents in the interview series was also to be taken into account.

Basically the mean load of these electricity-intensive processes can be calculated by the division of energy consumption and mean operating hours (Gruber, et al., 2013). It is normal for industries to have a certain margin in their production so the actual potential is slightly higher than the mean value.

\[ P_{b,el} = \frac{E_{b,el}}{OH_b} \]

Where E ~ annual energy consumption, P ~ mean load, OH ~ mean operating hours per annum, b ~ branch and el ~ electricity.

An important remark is that the, by the above presented formula determined, magnitude of load shedding includes the potent load shifting. Consequently, the already quantified potential of load shifting was subtracted from the total potential before the actual load shedding potential could be observed.

Having investigated the current load shifting potential and calculated the present load shedding potential for each company and extrapolated the results to a branch level, the data was structured in accordance to Table 20 below.
TABLE 20 - DATA NECESSARY TO PLOT DEMAND SIDE MERIT-ORDER CURVE

<table>
<thead>
<tr>
<th></th>
<th>Paper &amp; Pulp</th>
<th>Metal &amp; Mining</th>
<th>Chemistry</th>
<th>Manufacturing</th>
<th>Retail</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{\text{shift}})</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
</tr>
<tr>
<td>(C_{\text{shift}})</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
</tr>
<tr>
<td>(L_{\text{shed}})</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
</tr>
<tr>
<td>(C_{\text{shedd}})</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
<td>(SEK/MW)</td>
</tr>
<tr>
<td>Total DR</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
<td>(MW)</td>
</tr>
</tbody>
</table>

Finally the costs and DR-potentials, for load shifting and load shedding respectively for each industry participating in the study, were plotted in a demand side Merit-Order curve. A principle result is given in Figure 39 below.

FIGURE 39 - PRINCIPLE DEMAND SIDE MERIT-ORDER CURVE

5.6 FURTHER REFLECTIONS ON THE METHODOLOGY USED

The following section discusses the quality of the research and the reliability of the results by a critical examination of the chosen methodology as well as giving suggestions on alternative course of actions.

The overall research strategy aimed to combine the advantages of a mixed approach by using both a quantitative and a qualitative method. This mixed method has many advantages. For example the use of data crossover analysis increases the rigor of the results from the qualitative open-ended interview (Frels & Onwuegbuzie, 2013). Also, the method used for each of the sub-approaches was both academically renowned and previously tested. In the case of the systematic review (Warren, 2014), the proposed methodology was closely followed when extracting data for the own-created DR-typology. Likewise, to support the creation of a demand side Merit-Order curve for future Swedish DR, inspiration was drawn from FFE and the methodology used by Gruber, et al, (2013). Still, the reliability of results from the study is admittedly weak for several reasons.
Firstly the scale of the study was rather limited. In total 10 cases were studied in the scientific review and 17 respondents participated in the interview series out of which 10 interviewees were representatives from the Swedish electricity intensive industry. A wider scale would offer more statistically valid results and probably give a more nuanced picture. Time was the limiting factor for this master thesis and hence the scale was narrowed down to a manageable size. To strengthen the argumentation and conclusions, a second iteration covering a significantly, that is times 10, larger proportion of both previous case studies and interview respondents would be to recommend.

Secondly, it could well be argued that the aim was too ambitious and the scope to wide. A more focused purpose is likely to have given a more qualitative and reliable result. The division between investigating different market mechanisms for DR as well as the future potential caused a split in focus and caused thereby some discontinuity in the work as well as in the report.

Thirdly, no simulation tool was used. Simulation is a powerful method when it the future is involved, especially stochastic optimization (Söder, 2014). Already today the future electricity market is simulated by many market agents such as electricity producers, total system operators, government agencies and university institutions. It would be beneficial if such powerful simulation tools could take DR-options into account and thereby support further studies. In this case the knowledge and resources to conduct a customized simulation was lacking. Vattenfall AB, the contractor of this report, could have provided tools to simulate the future electricity grid based on the assumptions made in the base case scenario regarding the energy mix and the demand characteristics. However, it was agreed on to continue the work based on Söder’s simulations since simulating energy systems are complex and time consuming and hence not a realistic option for this master thesis.

It could be questioned how relevant it was to, as part of the quantitative approach, study previously implemented DR-programs. These were often constructed for a very specific situation (a country, a policy, a point in time etc.) and, because of the many customized regulations and subsidies, may not be very representable for the underlying principle used. Also the scope of each case study varies; some are including households others only industrial DR, some cover million customers whereas others only allies to a few. All this makes a comparison difficult and a synthesis based on patterns in results less reliable. That said, the scientific review contributed largely to the results of this report with benchmarks on DR-volumes and, most importantly, the data on which the typology of DR-programs were based. In particular, the case study performed gave a broad overview of the available DR-programs and key findings which related directly to the purpose of the thesis.

In addition to the typology of DR-programs based on the case study, the interviews conducted with respondents of the energy intensive Swedish industry led to a projection of the future DR-potential in Sweden. The demand side Merit-Order curve can hence be regarded as a helpful and valid tool to be used in the decision making process by future decision makers and investors.
THE CASE STUDY

In his chapter, the results from case study are summarized. The case study was performed through a systematic review, for further information see chapter five. First in this chapter, each source included in the review is given a quality assessment score. Thereafter, the extracted data are presented in Table 23.

The scientific review has found that a wide variety of DSM-project and studies on DR have been conducted during the last decade. In Europe, DR has been slow to emerge but there are signs of increased activity, especially in north-western Europe (Torriti, et al, 2009). Some are still ongoing whereas others have been terminated after evaluation (Ming, et al, 2013). When evaluating, it is important to understand the context in which the DR-option was operating and the method used to investigate its effect (Warren, 2014).

Some studies are large in scale and scope, other more narrow. Some focused on the pricing mechanism, others on the technical solutions which enabled the DR-program. Moreover, the results are sometimes measured, at other occasions extrapolated from surveys and in yet other cases only simulated. To get a solid foundation for the further analysis, a mixture from cases with different context and method has been chosen. The different regions from which DR-programs have been studied are shortly presented below to highlight how much the context can vary and how that may impact the policy results.

In the United States, local state governments and TSO:s have been working with DSM since the late 70s (US DoE, 2006). The majority of the programs have been targeting large, industrial consumers to reduce peak demand during hot summer days when air-conditioning is operating on a large scale (Schwartz, 2012). The US market is not one, homogeny integrated system but consists of several local and/or regional power grids that all face different challenges depending on the environment and demand structure. Therefore there is a variety in policy also with regard to DSM and DR. The studied US-American pilots are PJM, the world’s largest power wholesale market situated in central US, the ISO New England that has many characteristics similar with northern Europe, the Salt River project in Phoenix which has taken a holistic approach and a Californian DR-pilot with a clear focus on industrial DR.

The Chinese context differs much from the US American. Firstly, the market is strictly regulated. Moreover, the country has experienced major power shortages for a long period of time. What they have in common is a long history of DSM. In china, this policy has been transformed from focusing on reducing peak demand until 2005 to target carbon emissions ever since.

In northern Europe, several different market designs for DR have been tested with varying success (Managan, 2014). There are technical pilots focusing on the promise of a smart grid (Cecati, et al., 2011) as well as pure policy mechanisms which aim to influence the behaviour of different market agents (Torriti, et al, 2009). The pilots included in this case study are performed in the UK, Germany, Norway, Denmark and Sweden. The UK form an own power market, Germany is part of the European grid EEX to which also parts of western Denmark belongs whereas eastern Denmark is part of the Nord Pool region together with i.e. Norway and Sweden. The regional differences in geographical circumstances influence both power mixture and import/export possibilities and thereby also the choice of DR measures (Capgemini, VaasaEtt, Enerdata, 2006).

An extra focus is given to European countries, especially neighbouring countries to Sweden, since the transferability of the results from a pilot correlates strongly with the similarities in context (Samarkoon, et al., 2013).
In this chapter the data is presented; the following analysis is to be found in chapter 8. However, before extracting data from the different case studies, each source was given a quality assessment score in accordance to the methodology described in chapter 5. Table 21 below is reminding the reader how the quality assessment score was defined and is repeated here to increase the understanding of Table 22 in which the different sources are evaluated.

**TABLE 21 - QAS DEFINITION ACCORDING TO STEP 5 SECTION 5.3**

<table>
<thead>
<tr>
<th>Question</th>
<th>“Yea/No” quality indicator</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>Has the process for programme implementation been clearly explained?</td>
<td>4</td>
</tr>
<tr>
<td>2)</td>
<td>Has the process for programme evaluation been clearly explained?</td>
<td>4</td>
</tr>
<tr>
<td>3)</td>
<td>Has the document been peer reviewed or independently verified?</td>
<td>2</td>
</tr>
<tr>
<td>4)</td>
<td>Are the statements of copyright, regulatory compliance and possible conflicts of interests presented?</td>
<td>2</td>
</tr>
<tr>
<td>5)</td>
<td>Is the authority of the publishing organisation reliable and reputable?</td>
<td>1</td>
</tr>
<tr>
<td>6)</td>
<td>Where percentages are given, are the totals given?</td>
<td>1</td>
</tr>
</tbody>
</table>

**TABLE 22 - RESULTS FROM QUALITY ASSESSMENT**

<table>
<thead>
<tr>
<th>Source</th>
<th>1)</th>
<th>2)</th>
<th>3)</th>
<th>4)</th>
<th>5)</th>
<th>6)</th>
<th>ΣQAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>California Energy Agency, 2005</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>Ming et al. 2013</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Andersen et al. 2006</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>0</td>
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<td>11</td>
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<tr>
<td>Yoshimura, Henri 20011</td>
<td>4</td>
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<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>12</td>
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<tr>
<td>Seale &amp; Grande, 2011</td>
<td>4</td>
<td>4</td>
<td>2</td>
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<td>1</td>
<td>1</td>
<td>14</td>
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<tr>
<td>Klobasa, 2010</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>10</td>
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<tr>
<td>Chappers et al. 2009</td>
<td>4</td>
<td>4</td>
<td>0</td>
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<td>1</td>
<td>9</td>
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<tr>
<td>Schwartz, 2012</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>8</td>
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<tr>
<td>Chatziioannou et al. 2013</td>
<td>4</td>
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<td>10</td>
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<tr>
<td>Warren, 2014</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<td>14</td>
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The case studies reviewed are, based on the quality assessment performed above, reliable sources. Thereafter, in accordance with the methodology scientific review described in chapter 5, data were extracted from each paper and collected for the purpose of this master thesis. A summary of the results from the case study are presented in Table 23 below. The cases reviewed are presented in alphabetical order.
<table>
<thead>
<tr>
<th><strong>Background:</strong></th>
<th><strong>Context:</strong></th>
<th><strong>DR-Option:</strong></th>
<th><strong>Policy impact:</strong></th>
<th><strong>Key findings:</strong></th>
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<tbody>
<tr>
<td>(California Energy Agency, 2005)</td>
<td>The pilot study was a technical and academic pilot which aim was to estimate the feasibility of automated Demand Response. Hence the cost was not regarded. The gas based Californian electricity market is becoming increasingly regulated due to the energy crisis 2,000 and new emission targets.</td>
<td>Direct Control Customized, technical solutions which were programmed to optimize consumption with regard to price signals and process specific data.</td>
<td>The pilot study showed positive operational signs; Direct Control worked well for industrial purposes. When prices rose with 150 % from 500 to 1250 SEK/MWh, demand was reduced by 10 % on average. The maximum peak load reduction from a large industry facility was 27 %</td>
<td>Automated Demand Response is a feasible option for large industry facilities. The implementation is complex and expensive as the infrastructure needs to be customized to fit each facility. To ease future large-scale implementation, following measures are required: - Information to facility managers - Reduces cost</td>
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<tr>
<td>California, 2005</td>
<td>Five large industry facilities participated in a pilot study.</td>
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<tr>
<td><strong>Quality assessment score: 12</strong></td>
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<tr>
<td><strong>(Ming, et al., 2013)</strong></td>
<td>China has a regulated electricity market with coal as predominant source. Some provinces have experienced significant powers shortages which has been a growth limiting factor. Hence the DR programs until 2005 was focusing on peak load reduction. Newer DR programs are focusing more on emission targets.</td>
<td>Time of Use ToU combined with administrative and legislative measures.</td>
<td>The program reduced the overall electricity consumption with 130 TWh in 2003. Than corresponds to over 6 % of the total Demand In terms of capacity, the peak load reduction reached 10.1 GW in 2003, which is &gt; 5 % of total peak load. Industrial Demand Response had a significant impact on the results</td>
<td>Demand Response has played a positive role as an important mean to: - Adjust grid load in tense situations - Ensured security of supply and social stability - Optimize resource allocation ToU is proven to be a powerful mechanism. But far more the Chinese example indicates the strength in a synchronized policy making; different government agencies worked together, combining legislative, administrative, economic and technical measures.</td>
</tr>
<tr>
<td>China, 1991–2003</td>
<td>All sectors were included. Special focus on heavy industries such as machinery, textile metallurgy, and petrochemical industry.</td>
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<tr>
<td><strong>Quality assessment score: 13</strong></td>
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<td><strong>Background:</strong></td>
<td><strong>Context:</strong></td>
<td><strong>DR-Option:</strong></td>
<td><strong>Policy impact:</strong></td>
<td><strong>Key findings:</strong></td>
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<td>(Andersen et al, 2006) Denmark, 2004–2006 Academic study with focus on welfare gain. Industrial load on 600 MW in participated in Demand Response program in eastern Denmark and 600 households took part in questionnaires. Quality assessment score: 11</td>
<td>Denmark is a country with two electricity markets; western Denmark is part of EEX whereas eastern Denmark, where the pilot was made, is interconnected with Nord Pool. Hence the results are easily transferable. The aim of this DR-policy is mainly to find and realise welfare gains in terms of lowering system cost.</td>
<td>Strategic Reserve &amp; Direct Control SR is only used in extreme events. The Strategic Reserve included industrial agents exclusively but utilized both supply and demand resources. Direct Control for household to increase demand side elasticity.</td>
<td>The SR works well in the sense that it has secured supply at manageable costs. It reduces the peak load with about 4% at a cost of 270,000 SEK/MW,y</td>
<td>Price elasticity is quite low today. Large fixed price additive reduce the quantitative adjustment. The survey showed that 8% of private customers are willing to sell flexibility by allowing DC. Extrapolated this result accumulates to a flexible load of 70 MW at a price of 750 SEK/MWh</td>
</tr>
<tr>
<td>(Yoshimura &amp; Lowell, 2011) New England, 2006–2010 Demand Response pilot program including 50 MW of manufacturing industry, large retail and aggregated residential applications. Quality assessment score: 12</td>
<td>ISO-NE is a large electricity market in the US that operates over 30,000 MW. The nuclear plants are gradually phased out and replaced by coal. The TSO aimed to investigate the option of DR as alternative to short term frequency regulation as well as to a supply based Strategic Reserve.</td>
<td>Ancillary Services Ancillary Services with an individual opportunity cost as fix payment for industries and Direct Control for aggregated loads.</td>
<td>The DR worked well in terms of magnitude; often the load reduction exceeded the contracted response. However, the DR reliability was lower than the supply. The reliability of the supply side actually increased during the pilot. Lights and air condition were the best loads to respond.</td>
<td>DR is not eligible to provide power to the wholesale electricity market. DR is eligible to constitute a reserve capacity for emergency of peak demand. AC will be expanded to cover the whole market in the future, but combined with a capacity auction to secure future supply. Weather based response and a more severe punishment for deviations are required in the future.</td>
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<tr>
<td>Background:</td>
<td>Context:</td>
<td>DR-Option:</td>
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<td>Key findings:</td>
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<td>(Saele &amp; Grande, 2011) Norway, 2006–2007</td>
<td>The Norwegian electricity market is comparable to the Swedish. Hydro power is base load and the energy intensive aluminium industry is part of a Strategic Reserve Regulation was changed to allow Time-of-Use pricing in the pilot</td>
<td>Time-of-Use pricing and Direct Control ToU was enabled through smart metering and hourly pricing. Direct Control was operated by the TSO, who remotely could regulate aggregated residential loads.</td>
<td>Load shifting, by predominantly electrical water heaters and ventilation, constituted the lion’s share of the DR Peak Load was reduced by 30 % on targeted consumption and by 4 % in total Customers reduced their average consumption by 2 %</td>
<td>The mechanisms tested can reduce peak demand with over 5 %. Residential DR and aggregation of smaller loads may not be economically profitable without subsidies. DR should be treated as electricity generation on the day-ahead market but not in intra-day market where it may cause new imbalances. DR works if it has no negative consequences on customer comfort</td>
</tr>
<tr>
<td>(Koblasa, 2010) Germany, 2010</td>
<td>EEX (European Energy exchange), a highly interconnected European market. The energy mix is varied but is based on fossil fuels and RES. The market is regulated and offers strong incentives for RES. Volatile prices, fluctuations in demand.</td>
<td>Real Time Pricing Industries and private customers are able to regulate their own consumption with regard to the electricity price. 1 MW as minimum bid size is assumed. In Germany, no capacity payments are expected.</td>
<td>Potential for industrial Demand Response: 3 GW. Costs range between 500 SEK/MWh for load shifting to max 5,000 SEK/MWh for load shedding. Commercial DR- potential on 20 GW. DR potential between 2-4 % of peak demand. Cost for balancing power &lt;20 SEK/MWh.</td>
<td>The cost of balancing power can be reduced to 20-30 SEK/MWh when distributed over the consumption on a yearly basis. The best approach is to start with a few, large, loads with high capacity and use them a limited number of hours. That is industrial DR. An integrated approach is necessary to analyse RES, including balancing costs. DR can potentially increase the security of supply.</td>
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<td><strong>Background:</strong></td>
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<td>(Chappers, et al., 2009) (PJM, 2014)</td>
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<td>Central US, PJM, 2005–2018</td>
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</table>
| The largest electricity wholesale market in US has a target for its capacity reserve margin at 15 %.
| The new policy was introduced in 2007. The case study allows a comparison from 2005 to 2018. |
| Quality assessment score: 9 |

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<thead>
<tr>
<th><strong>Context:</strong></th>
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<tr>
<td>PJM is the world’s largest electricity market, &gt; 600 TWh/y.</td>
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<td>The TSO has a legal requirement on 15 % reserve margin.</td>
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<tr>
<td>To secure future capacity, a Capacity Market with future capacity auctions has been implemented. The auction is held years in advance and accepts bids based on price but also certain availability constraints.</td>
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<tr>
<th><strong>DR-Option:</strong></th>
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<tbody>
<tr>
<td>Capacity Market</td>
</tr>
<tr>
<td>The CM in PJM is based on two programs: RPM, a pricing model, and BRA, capacity auctions with capacity payments.</td>
</tr>
<tr>
<td>PJM requires participating industries to reduce their power consumption continuously.</td>
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<tr>
<th><strong>Policy impact:</strong></th>
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<tr>
<td>The CM has secured a reserve margin at 20 % for 2017/18, way above the targeted 15 %.</td>
</tr>
<tr>
<td>Industrial DR has participated with 10,000 MW of capacity. That is over 7 % of the total peak demand</td>
</tr>
<tr>
<td>The Price for capacity was in the auction 290,000 SEK/MW, a Further DR would be available at a higher price level. Already today 1,000 MW of offered DR resources were not accepted.</td>
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<table>
<thead>
<tr>
<th><strong>Key findings:</strong></th>
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<tbody>
<tr>
<td>Capacity Markets do clear unforced capacity to the reserve margin that is essential to any electricity system.</td>
</tr>
<tr>
<td>Capacity auctions also trigger investments. Since the RPM program was introduced in 2007, generation capacity has increased with 27 % from 130 GW to 166 GW.</td>
</tr>
<tr>
<td>The DR contribution has exploded from 1,000 MW 2005 to 12,000 MW in 2017/18.</td>
</tr>
<tr>
<td>Constraints on certain types of capacity, such as DR and import, need to be introduced with regard to security of supply.</td>
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<tr>
<th><strong>Background:</strong></th>
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<tbody>
<tr>
<td>(Schwartz, 2012)</td>
</tr>
<tr>
<td>Salt River Project, the local utility and TSO, has worked with DSM for decades. All sectors are included on voluntary basis.</td>
</tr>
<tr>
<td>1,000,000 private customers and industry such as manufacturing</td>
</tr>
<tr>
<td>Quality assessment score: 8</td>
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<thead>
<tr>
<th><strong>Context:</strong></th>
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<tbody>
<tr>
<td>Salt River Project is a part state owned part commercial, TSO and utility that also supplies Arizona with water. Energy resources are hydro, geothermal and gas</td>
</tr>
<tr>
<td>The main approach of the DR has been to create an integrated system that satisfy customer needs in terms of low prices, security of supply and freedom of choice for the customer.</td>
</tr>
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<thead>
<tr>
<th><strong>DR-Option:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Informative measures</td>
</tr>
<tr>
<td>Wide variety of DR-options. Customers choose program participation voluntary.</td>
</tr>
<tr>
<td>Direct Control, Time of Use and Real Time Pricing are options for residential customers, Strategic Reserve for industry.</td>
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</tbody>
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<table>
<thead>
<tr>
<th><strong>Policy impact:</strong></th>
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</thead>
<tbody>
<tr>
<td>Participating customers save annually 6 % on electricity costs.</td>
</tr>
<tr>
<td>Industrial Demand Response in SR is 500 MW (&gt;7 % of system peak demand)</td>
</tr>
<tr>
<td>Residential customers help to reduce peak demand: 4 % for RTP, 6 % for ToU and roughly 10 % of the end users prefer emergency DC.</td>
</tr>
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<table>
<thead>
<tr>
<th><strong>Key findings:</strong></th>
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<tbody>
<tr>
<td>Voluntary programs are more successful. 95 % of the end users in SRP are satisfied.</td>
</tr>
<tr>
<td>It is possible to combine DR-designs but programs must be coherent and not contradictive.</td>
</tr>
<tr>
<td>Informative measures and communicative programmes, such as refrigerator magnets, increase DSP substantially.</td>
</tr>
<tr>
<td>A key rationality is to offer customer pricing that more accurately reflects the true cost, =&gt; invest in smart grid</td>
</tr>
</tbody>
</table>
### Background:

Smart-Grid Gotland is a pilot project including 30 industries, 2,000 households and a high share of RES. Budget: 30 MSEK

Quality assessment score: 10

### Context:
Smart-grid Gotland is a project in which different agents, such as utilities, grid operators, end users and local authorities, are working together to integrate a high share of RES in an island power system.

The Smart-grid Gotland focuses on the technological challenges but do investigations and test in market design.

### DR-Option:
Real Time Pricing, Time of Use and, Direct Control

The pilot offers the customers different DR-options.

The customers are equipped with a smart meter and can visualize the consumption and price in an interface application.

### Policy impact:
Over 70 % of the participating end users are positive to the project so far.

The grid works technically, also with a high penetration of RES.

2.8 MW of industrial DR has been released.

The flexibility is still relatively low as many customers have long term fixed electricity contracts.

### Key findings:
The interest for, and will to participate in, the DR-project is significant.

The RTP are not incentive enough to trigger DR-participation for the time being.

It is possible to lower system cost with 25 % by implementing a smart grid.

Smart grid requires interaction between grid operators, electricity wholesalers and government agencies.

---

### Background:
(Warren, 2014b) UK, 2000–2013

All sectors included, but DR focuses on industries.

Systematic review of 200 policies globally from 1970 an on, focusing on UK

Quality assessment score: 14

### Context:
The market is regulated by overlapping national and European laws to reduce consumption, secure the power balance, regard national security and cut emissions.

Traditionally the generation has been based on nuclear and gas but wind power is increasing in share.

Capacity Market is being introduced.

### DR-Option:
Strategic Reserve and Capacity Market

A Strategic Reserve supports the balance market.

A Capacity Market is introduced to tackle gap in investment.

80 % of the end users has smart meters

### Policy impact:
The Strategic Reserve includes 1,500 MW DR. However, only 200 MW is consumption reduction and the rest on-site generation.

The CM has helped to secure future capacity The current price is 265,000 SEK/MW, y and another 2,800 SEK/MWh shedded.

The industry has experienced some confusion due to the many overlapping programs.

### Key findings:
DR should be integrated in the wider energy policy. The success of DR depends on regulation and financial incentives.

Too many overlapping policies (regional, national, international regulations from different departments etc.) create confusion and uncertainty for the industry.

The future potential of industrial DR is up to 4 GW (~10 % of the total 40 GW in the non-domicsectors). Best applications are aggregates of lights, heating and ventilation.
7 PERSPECTIVES ON DEMAND RESPONSE

The chapter gives a record for the interview series conducted with respondents from different stakeholders in the electricity market. The interview series were complemented with literature research and data from e.g. annual reports from the companies included in the study. The results are divided by industry and are to be regarded as an industry perspective rather than the opinion of any specific company.

In order to support the argumentation and analysis in chapter 8, this chapter gives an account for the current situation within the energy intensive industry and the Swedish electricity market from a DR perspective. The results from the interviews series conducted lay the foundation for the following sections. Where needed however, the interview answers have been complemented by data from external sources of information.

7.1 INDUSTRIAL ELECTRICITY CONSUMER

This section summarises the results from the interviews with the energy intensive industry in Sweden, their view on DR-programs and the existing Demand Response potential.

The interview series included 10 energy intensive companies that together consume over 18 TWh per year which equals 12 % of the total electricity consumption in Sweden (148 TWh). With regard to the scope of this study, that is industrial DR, the interview series included companies’ whose electricity consumption amounts to 35 % of the total industrial electricity use in Sweden (52 TWh/y) and represent industries which aggregated electricity consumption constitutes over 95 % of the same. (SEA, 2013).

The examples given in the sections below are typically collected from the different companies interviewed. The opinions however, are a more general and only findings which have been true for a majority of the interviewed respondents are regarded as generalizable results in this master thesis.

GENERAL RESULTS FROM INTERVIEWS

The DR potential is varying significantly between different industries and even between companies within the same industry sector. Depending on factors such as utilization rate, storage capacity, order stock etc., the DR potential could even differ greatly between different points in time for the very same production facility. For example, INEOS in Stenungsund has an electrolyse process on 50 MW which, in theory, is flexible and up to 30 MW load can technically be shifted in time at a low variable cost (Interview INEOS, 2014). However, if the order book is full and a customer awaits immediate delivery, the flexibility is either 0 MW or only accessible at a considerably higher cost. The interviews conducted confirm that there is no exact border between load shifting and load shedding in practice. Hence, it is important to map what processes are actually powered by the consumed electricity and understand what characterizes the different industries. For this purpose, the following paragraphs will discuss the industry-specific situation with regard to the results from the interviews.

Before moving on to examining the individual industries however, a few findings are general across the industrial sector and have been confirmed by all the participating respondents. There is a widespread understanding of the importance having a well-functioning electricity system and an awareness of the challenges and opportunities that might arise in a scenario with an increased proportion of intermittent production in the electricity system. Many companies within the pulp and metal working industries, such as SCA and Vargön Alloys, even have representatives in national energy councils and grid development groups.
A vast majority of the companies (8 out of 10) included in the study have an energy manager or even entire departments working on optimization of energy efficiency in terms of cost as well as general consumption. Although companies within the energy intensive industry long have been working on efficiency to reduce their overall energy use, the price spikes in 2009–2010 were a common trigger for many companies to become more active on the electricity market and to start discussing flexibility as well as efficiency. AGA is e.g. building a new plant in Finland, in cooperation with Fortum, which will have a build-in load flexibility of 20 MW (Interview AGA, 2014). Several respondents suggest that an increase in electricity price, or even more so a more volatile price curve, would accelerate this trend.

Energy intensive industries in Sweden do regularly trade actively on the Nord Pool markets. The flexible bids are predominantly offered on the Nord Pool spot market, since a production facility generally can plan their consumption quite accurately on a day-ahead basis. Some companies are also participating actively on the hourly Nord Pool base market with smaller quantities. The trend is unambiguous; companies which weren’t regarding electricity as a trading good before are doing so now and companies which have been active a longer period of time are accelerating their participation through a larger proportion of flexible bids also as response and not only as a planned activity. The more energy intensive the industry, the more prominent the commitment to manage the electricity procurement process becomes. Moreover, many companies included in the survey already participate in the power reserve procured by SvK. This engagement is however, according to the results from the interviews, only partly exhausting the existing DR-potential.

The industry representatives have themselves identified several measures which, according to them, would facilitate the realization of the DR potential. Firstly, the 10 MW minimum limit for bids on the balancing power market excludes many potential market participants. It could either be small industries or larger industries which have only minor processes that are flexible. Today, these companies can only participate through external agents and are thereby charged with extra costs in terms of administration and commissions. Another important factor which is limiting the interest for active market participation, according to the respondents, is the existing payment model that encourages electricity users to maintain a smooth consumption profile.

The prospect of saving or making money is the predominant driving force for increased DR. In many producing companies, especially within the paper & pulp, metalworking and chemical industries, the electricity costs are above 10 % of the total cost of the end product. Consequently, any possibility to lower the average electricity price will be regarded since the benefits are becoming evident on the bottom line. One example is Sandvik where an increase in electricity price on 100 SEK/MWh leads to increased costs of 6 Million SEK (Interview Sandvik, 2014). Therefore, many respondents see industrial DR as a natural reaction from businesses who want to gain competitive advantages and increase their margins.

Another essential factor which the representatives of energy intensive industry regard as a reason for participating in DR programs are the own vulnerability for system failures. Many industries have processes for which the security of supply is crucial and even short unplanned stand-stills would cause extremely high costs. Within the manufacturing industry for example, companies such as Scania build their processes on the principle of lean production where the flow of components are continuous and the stock levels close to zero. In such a system a minor stop due to power shortage or inadequate power quality would drive major costs and delays in the entire supply chain (Interview Scania, 2014). Another, more technical example is the processes which require continuous operations not to fail. If the power fails a melt oven in the metal working industry more than a couple of hours, the temperature falls below critical levels.
which requires a complete re-start of the process to clean and reheat the metal. This process can take days and cause huge cost, actual as well as opportunity cost. With this perspective, many companies argue that if a participation in DR-programs with some more easily shifted loads can contribute to increase the SoS for other, more critical processes, it is a strong logical reason in doing so.

Other factors which drive the development of DR in Swedish industries are environmental care and social responsibility. Whether the actual cause for the engagement is value based or market driven branding matters little as the consequences of the actions remain the same. Some respondents also emphasise on the importance of education and information. Before an issue is highlighted, very little is done, but once it gets hold on peoples mind the long-lasting consequences of a changed behaviour can be extensive. So was the case with general energy savings and so could be the case with the importance of flexibility. Despite the awareness of the future challenges and the many factors driving increased industrial DR participation in Sweden, the results from the interview series indicate that there are strong forces working against an increased flexibility in load management as well.

First of all, the industry desires another conceptual solution on the energy problem; many industrial representatives are in favour of nuclear power. The nuclear power is, according to several respondents, not only producing electricity to a manageable cost but is doing so in a consistent and predictable way. For the industry a stable, or at least predictable, electricity price is as important for the planning process as a low electricity price is for the financial results. This underlying disagreement with the energy policy perused has created a noticeable disinclination to deal with the consequences of the very same.

Secondly, from an economical perspective it makes sense to optimize the production after other parameters than the electricity price. For Preemraff in Lysekil for example, although a large electricity consumer with over 400 GWh/y, the cost of electricity is minor in comparison with the impact of oil prices or the demand of the refined products (Interview Preem, 2014). Hence the production is optimized after other parameters. Also within the manufacturing sector, the concept of DR is difficult to merge with the presently dominating production strategy which includes low stocks and a high utilisation of production resources as there is no redundancy in which loads can be shifted.

Thirdly, although the industry representative admit that the aggregation of local flexible loads amount to a significant DR potential, it is emphasised that DR-resources cannot be likened with reserve power plants in the long term. This because of the duration time of the activated loads. DR-resources are typically possible to shift 1–4 hours in time, sometimes up to 12 or 24 hours as well. SCA can for example vary the intensity of the timber dryers and even stop them a few hours (Interview SCA, 2014) and INEOS has a limited stock of finished products which makes it possible for them to shift some load up to 4 hours but no longer (Interview INEOS, 2014). Train transport may be flexible in time up to 12 hours, but normally no more than that due to further connections in the transportation chain (Interview Trafikverket, 2014). This implies that for days or weeks of power shortage, there is no significant DR-potential that is plausible to remain activated.

Also, even activations of shorter nature must not occur too often, or it will affect the yearly production of the targeted production facility and increase the cost of DR. Many respondents stress the point that the core competence of industry is to use input resources, such as electricity, in order to create value through delivering a processed product, not to create value by waiving production.
PAPER & PULP

The paper and pulp industry is the single most energy consuming industry in Sweden. In 2012 it used over 75 TWh of energy which is about 45% of the total national industrial energy demand. In terms of electricity, the paper & pulp industry consumes about 25 TWh, a remarkable 17% of the total electricity demand in Sweden (SEA, 2013). However, there is also a substantial recycling taking place, both in terms of energy recycling through district heating and in terms of material recycling where the residues from one process, typically wood chips, are closing the loop as biofuel in the same, or a close-by, factory.

The industry is characterised by a few large companies with significant market shares such as SCA, Holmen and Stora Enso. The product portfolio comprises a wide variety of different product groups including paper, cardboard, sanitary articles, timber and synthetic materials. Apart from electricity, the main inputs are pulpwood and recycled paper goods. As a proportion of the production costs of the industry, electricity amounts to about 10%.

There are two different ways to make the pulp, through a mechanical process or a chemical process. The chemical process is actually a net-producer of energy whereas the mechanical process is very energy intensive and the electricity is the used energy resource to power the process. This implies that the primary DR potential in the industry is connected to mechanical pulp production (Interview Holmen, 2014). Since pulp is a physical product that can be stored, there is a possibility to shift the electricity intensive production in time. The average utilization of pulp plants in Sweden is about 80% (Nilsson & Hammarstedt, 2014). Combined with the short lead time of the supply chain, this potential is practically realisable on either the day-ahead market or even the intraday markets. Technically, the loads of mechanical pulp production can be shifted on a 15 minutes basis. From a cost perspective however, each activation and shutdown wear on the components and extensively so if they are following each other in an immediate sequence. Hence, the interval between separate activations of DR-potentials must be counted in hours and not minutes (Paulus & Borggrefe, 2010).

The paper and cardboard machines are also very energy intensive but lack the basic characteristics of a DR-friendly process as they are operating on a continuous basis with a high utilization. But as a cluster, the paper and pulp industry has significant DR potential due to the fact that they are operating around the clock which makes it theoretically possible to shift loads without having to take in extra personnel costs or legislative issues into consideration. This is partly done already today. One example is Ortviken plant outside Sundsvall, owned by SCA. It is a facility with a max power demand on 260 MW and has a variable build-in flexible load of 80 MW which is bid on the spot market. This corresponds to DR potential of 30% and is technically way ahead of the industry average and comparable industries. (Interview SCA, 2014)

Looking at the long term potential, there are three important issues. Firstly, the flexibility is likely to increase as a result of more investments in technology and capacity. For the paper & pulp industry, DR is also possible by increasing the utilization when prices are low and this opportunity is being examined already today. Secondly, the market share for mechanical pulp is decreasing in relation to the chemical refinery process which is negative for the future DR potential. The cause behind is an increased demand for products which are made by chemically processed pulp, e.g. sanitary articles, and a decreasing demand for traditional forestry products such as newspaper and timber which is typically refined mechanically (Interview SCA, 2014).

METAL WORKING & MINING

Metal working and mining are two interconnected, and highly energy intensive industry segments in Sweden. Together, the mineral extraction (~3 TWh/y), steel- (5 TWh/y) and
aluminium industry (~3 TWh) in Sweden consume over 7% of the total electricity demand in Sweden. Regarding the total energy consumption is even higher due to the high use of fossil fuels and other energy resources in the extraction and refinery process of metals (SCB, 2013).

For mining and raw material extraction the energy costs are above 20% and for the metal working industry only the electricity costs varies between 15–30% (Paulus & Borggrefe, 2010). This implies a significant price sensitivity and thereby a willingness to find solutions, including DR, which help to reduce the costs. The industry is competing with Asian and African companies which have no, or at least less strict, regulation and taxes on CO₂ emissions. Due to the fact that domestic electricity prices are predicted to rise in the base case scenario, combined with the absence of environmental imports duties to the European Union, domestic metal industries must lower their electricity consumption or be more flexible when to produce if they are to remain competitive (Nilsson & Hammarstedt, 2014).

Theoretically, many loads such as extraction, transportation, heating etc., which combined amount to a large proportion of the total consumption, can be shifted. Vargön Alloys facility in Västergötland has for example a maximum power demand of 110 MW. 35 MW, or about 30%, of that capacity is regarded as flexible and is being traded on the spot market. The limiting factor is, apart from the technical restrictions, the relation between incoming orders and stock levels (Interview Vargön Alloys, 2014). Since the stock is tied up capital, the cost of realising this potential load flexibility it is ultimately a question of recovering capital costs.

Steel can be produced from either primary resources or recycled scrap. About 30% of the Swedish steel is produced from scrap, which is a very energy intensive process as the scrap is melted in an electric arc or heat is generated through induction. Technically the process can be load shifted with only a short notice. However, if the metal is cooled down for a longer period of time than 30 minutes, the process needs to be restarted to reduce the risk that the metal solidifies. Hence the DR-potential is limited to the start of each melting cycle, which typically is about 45 minutes plus another 15 minutes for cleaning and refilling (Paulus & Borggrefe, 2010). Although the cost of load shifting varies between processes, the results from the interview series indicate that companies start acting at prices about 800 SEK/MWh. A problem with shifting smaller loads, or a load proportionate to the price increase, is that many processes such as melting or refining metal has an optimal efficiency rate. Therefore, a complete standstill would sometimes be less damaging than a disadvantageous utilisation rate since the production numbers would be more drastically reduced than the electricity consumption.

Another example from the industry is LKAB, producing 90% of the total iron ore within the European union. LKAB is one of the largest electricity consumers in Sweden with a yearly demand on over 2.3 TWh (>1.2% of total electricity use in Sweden). The company is working with general efficiency measures which limit the DR potential. However, the company is also undertaking a transition from fossil fuel to more electricity which will increase the DR potential. If the total production process would be electrified, the cost for electricity would exceed 10% of the company's total cost, adding further incentives for DR (LKAB, 2014).

The perhaps most energy intensive industry in the Nordic countries is the aluminium electrolysis which produces refined aluminium and oxygen from aluminium oxide. This industry is especially large in Norway and does thereby affect the Nord Pool market, but large facilities is also situated in mid- and northern Sweden (Interview Vargön Alloys, 2014). To produce one ton of aluminium, about 15 MWh of electricity is required. This can be compared to 0.5 MWh for steel (Paulus & Borggrefe, 2010). Being a capital intensive industry, the utilisation is high, above 95% in average, and leaves little potential for load shifting. Representatives from the industry confirm that it would be technically possible to decrease the production for up to 4 hours by 25% at a variable cost of about 800 – 1200 SEK/MWh.
At very high prices, there remains a possibility to shed load. This implies, a temporary, complete shutdown of the process. If the company has a contracted price it might sell back the pre-purchased volumes to the balance market and thereby not only save money but also make money. If price of contracted electricity is high enough there is always the option of a complete shutdown of the process and to sell back power on the spot or balancing markets. The cost of load shedding in the mining and metal working starts at 1,000 SEK/MWh but increases quickly depending on the volumes and especially the duration time (Nilsson & Hammarstedt, 2014).

**CHEMISTRY**

Chemistry is a very electricity intensive industry, consuming over 5.5 TWh annually. If, as in this interview series, the plastic fabrication processes (1.5 TWh) and the refining of energy resources (1 TWh) is added the industry sector of chemistry and energy consumes about 8 TWh of electricity yearly (SCB, 2013). That equals 5 % of the total energy consumption in Sweden and 16 % of the industrial demand which also is the scope of this master thesis.

One example of a very energy intensive industry is the production of industrial gas. AGA has 6 large facilities, operating on 15 MW in average, and consume in total 1.5 TWh annually in Sweden. The different products vary in energy intensity between 10–30 %. The most energy intensive product is industrial gas, which basic principle is to liquefy air, transform it to gases and thereby separating nitrogen from oxygen and argon etc. These products are typically produced in, or transported in pipelines to, the nearby area of the end consumption why no expensive packaging or transportation is needed. This implies that the cost of electricity is the major variable parameter which affects the financial results. In such an industry, it is important to work with flexible production (Interview AGA, 2014).

Today, AGA is active on the spot market and is offering a flexible bid on about 10 MW. This number is small in comparison to the potential but since the prices are low there is little incentive to realise further potentials at the moment. If provided enlarged storage capacity, most of the demand could be regarded as flexible. Today, the customers of AGA need a continuous supply of gas, why load cannot be shifted given the current lack of intermediate storages. That however is a question of investments. In Finland, a new plant with 20 MW of build-in flexibility is constructed in cooperation with Fortum. In Italy, where the utilization of the plants is significantly lower, about 70 %, AGA is part of a Direct Control program where the TSO can remotely shut down the plant. That concept has worked well in Italy but would not fit the Swedish circumstances which include high capacity utilization. Today, the gas industry would be able to shift about 15 % of the power demand at price level of 1,500 SEK/MWh. The trigger price would be about 1,000 SEK/MWh. For even higher electricity prices, the response would be even greater. In the future the potential might be doubled, even at a lower cost, due to more volatile electricity prices which enables return on investments in flexibility (Interview AGA, 2014).

Another energy intensive chemical industry is that of producing plastics such as PVC. For the purpose, chlorine is needs which can be produced through the extremely electricity intensive chloralkali process. The inputs in the process are salt (solved in water) and electricity. Through the electrolyse process, the chlorine is separated from the hydrogen and lye. The Lye is a rest product which can be sold to applications in other branches such as bleach in the pulp industry, the hydrogen is typically energy recovered through combustion to power other processes at the production site and the chlorine is extracted to fabricate plastics. The production is linearly proportional to the power input and the process is immediately controllable. INEOS has a chlorine factory with a maximum power demand of 60 MW and can shift between 50–100 % in production capacity utilization without technical or economical complications. This flexibility enables a significant DR-volume. The load is easily adjusted and technically there is no limit for
how long the response duration may last. One problem however is that the high utilization level needed in such a capital intensive industry prevents a fast catch-up when production is reduced. Hence INEOS do not shift loads longer than 4 hours. There is a possibility that the company will invest in further chlorine capacities in the future which would increase the flexible load available (Interview INEOS, 2014). 800 SEK/MWh would be an approximate price level where industries in the chemistry sector starts to curtail load.

Another example on extremely energy intensive plants within the chemical sector is oil refineries. Preemraff in Lysekil refines 11 Billion tons of crude oil per year. The total energy demand of that process is about 7 TWh alone. However, that includes the residual oil products from the process which are recovered and burned internally at the refinery. The Preemraff in Lysekil consumes about 0.4 TWh electricity per year with a fairly stable load profile and an average power demand of 45 MW. The processes which are powered by electricity are pumping, compressing, ventilating etc. These processes can be shifted for shorter periods of time. Moreover, the blending process, in which different products are produced by mixing carbon hydro chains of different length, can be shifted in time. At the facility, there are parallel pumping systems, one powered by electricity and one powered by natural gas. Because of the relation between the price of gas and electricity and the fact that electrical motors are more efficient, the gas powered pumps are only used when the refinery has a surplus of gas which otherwise would be released in the air as waste. It would approximately be 4 times more expensive to power the system with gas. However, it is possible to shed electrical load by substituting the energy resource. Today that would occur at prices above 4,000 SEK/MWh but depending on technical development of gas motors and other parameters, the price might well be significantly lower in the future which would be beneficial for the DR potential (Interview Preem, 2014).

MANUFACTURING

The manufacturing industry, which includes vehicles, machinery, white goods and appliances among others, is important for Swedish exports. Also, it is a large electricity consumer with a yearly consumption of 9 TWh, corresponding to 6% of the yearly Swedish electricity demand (SEA, 2013). However, in comparison to other industries with high electricity consumption, the manufacturing industry is processing more highly refined and valuable products and is thereby less dependent on the price of raw materials such as electricity. The cost of purchasing electricity, which also is the main energy resource of the industry, amounts only to a small percentage, typically between 1‒5%, of the total costs (SCB, 2013).

The DR potential within the manufacturing industry appears limited. The production system is typically designed after the lean principles and since stock margins and over capacity are being reduced to a minimum there are only sporadically loads that can be shifted. Not all manufacturing companies have such a strict lean profile but the general tendency is increased production efficiency. One example of this is Scania in Sodertalje that is consuming nearly 0.4 TWh yearly. Of the process which is actually taking part within the company, only the casting (10 MW) is allowing load shifting. The lion’s share of the processes is assembling different components that arrive at the production site just in time and are expected to be picked up for immediate delivery. In such processes load shifting is impractical (Interview Scania, 2014).

Also the second technical DR option, load shedding, is unlikely to be used on a large scale in the manufacturing industry. The main reason for this is the relatively little effect the electricity has on the financial results. Due to the low energy intensity, and the high profit margins on the manufactured goods, extremely high electricity prices would be required before it would be economically sound to shed load. Still other reasons for DR remain, e.g. environmental care, but the economic incentives are week for the manufacturing industry. On top of that, the strategic
aspect of production needs also to be considered; if the price peak is judged to be of transitory nature, it may well be that the manufacturing industry prioritises the production volumes and delivery targets over cost optimization (Paulus & Borggrefe, 2010).

However, apart from the electricity price, the power quality in the grid is very important for the manufacturing industry. The automated machines of today are very sensitive against fluctuations and even short disruptions, voltage drops or frequency variations can cause relays to drop out. This can lead to unexpected standstills in the production or even to damages on advanced technical components which in both cases would be costly. The results from the interview series confirm that the power quality has declined in the last decade and industry representatives fear that the development might accelerate in a scenario where the nuclear generation is phased out and replaced with RES. Hence, the manufacturing industry might be willing to pay a higher price but with the requirement of improved power quality. Another way of dealing with the problem would be for the manufacturing industry to have on-site back-up generation. This infrastructure already partly exists. Scania is planning on building 15 MW of diesel generators to secure the electricity supply and quality for their painting process in Oskarshamn (Interview Scania, 2014). Such on-side generation could also be regarded as DR in the sense that if the market price exceeds the variable cost for back-up generation, typically 1,000–2,000 SEK/MWh, companies would activate their own system and thereby reduce the net-demand on the national grid. Some respondent stresses that the back-up generators needs to be unoccupied to serve their purpose of reserve capacity to balance system failures and does not want to use them to optimize the average electricity cost.

COMMERCIALS

The tertiary sector, including commercial buildings, service companies and retail, is not always regarded as a large energy consumer. Whilst it is true that the businesses are less energy intensive than the industrial counterparts, the aggregated demand is over 30 TWh, which is about 20 % of the total electricity consumption in Sweden (SCB, 2013).

The typical processes powered by electricity are lights, ventilation, cooling, heating, waste treatment and appliances. Some of these processes, as e.g. ventilation and heating, are possible to shift in time for a shorter period without any severe negative consequences. The average load of commercial ventilation that can be shifted theoretically is substantial, over 400 MW (Gils, 2014). Yet others, such as lightning, are possible to regulate on different power levels and can thereby offer DR in terms of partially load shedding. The theoretical potential for this commercial load shedding, if the power demand can be reduced by 10 % instantly, is about 700 MW (SEA, 2013). However, these potentials are theoretical and require both an installed smart grid and a working business model for DR to be realised in practice.

One example of a large electricity consumer within the retail sector is ICA. The large grocery federation consume yearly 1.5 TWh in their 1.300 grocery stores, about 1 % of the total energy consumption in Sweden. The consumption is divided on the different processes: cooling 30 %, lightning 15 %, ventilation 15 %, kitchen 10 %, storage and others, 30 %. Apart from cooling and kitchen, the other processes are representative for other retailers. The cooling is more branch specific and can be deducted from the need of cooling dairy products and others which is a large constant load of 40 MW aggregated over the grocery federation. If there were technologies for storing energy in thermal reservoirs this potential could be realised. Today however, it needs to operate continuously. The kitchen, where bread and ready meals are produced, is energy intensive and a more flexible production would make sense. Still, the cost of personnel and the routine of the organisation make it difficult to react to the price or supply of electricity. Instead, ICA and many other companies are working with general energy efficiency programs to lower
their electricity cost and thereby the total electricity demand. ICA reduces their electricity intensity with 1% per year in average and has a project that new shops shall use 25% less electricity requires investment in energy efficient systems (Interview ICA, 2014).

**OTHER INDUSTRY BRANCHES**

One sector which is becoming increasingly electrified is transportation. Today the branch uses 3.3 TWh, over 2% of the total national electricity demand. The lion's share of this consumption is ascribed to the railways but as electrical vehicles are introduced at the market this may change drastically over the next decades (SEA, 2013).

The Swedish Transport Administration is responsible for purchasing electricity to all agents within the railway industry, today that volume amounts to 2.6 TWh per year. The electricity cost constitutes a respectable share of the total variable costs, about 10% for commuting trains and 20% for freight trains. The commuter trains must go according to time table but it would be possible to shift the load of goods transportation a few hours. The average load of freight trains is 200 MW. This is not done today but it is an option which is considered for the future. All the electricity is purchased one day in advance on the spot market. There is a slight price elasticity within the industry but not very many loads can be shifted easily due to the high utilization rate of the rail road network. One option is to load manage the electrical heaters (on 15 kW/each) which are placed at each switch (about 7,000 in Sweden). Approximately 25% of these could be shifted in time, which offers a DR potential on 25 MW. To install such a system an initial cost of minimum 5,000 SEK per installed switch results in an investment on 35 Million SEK. On top of that is yearly maintenance. Also, supporting processes such as lights, signals etc. could be shedded if the circumstances and security aspects allow. These processes accumulate to 20% of the total demand of the railway, but it would only be realistic to shed a small proportion of that potential due to safety requirements (Interview Trafikverket, 2014).

A final remark on the railway infrastructure is that the Swedish Transportation Agency possesses an own distribution network; a high voltage transmission grid with connection points to the national grid in several price areas (SE1, SE2 and SE3). Today, the system network is only used for internal distribution purposes and as a back-up network that provides SoS. However, possessing the significant transmission capacity of 50 MW it could serve as a DR to level price differences between the price areas. I.e. if supply is short in southern Sweden, and price levels are high in SE3, then the Swedish Transport Agency could purchase its electricity in SE1 and SE2. This would save money to the organisation as well as providing a noticeable load reduction in the stressed areas (Interview Trafikverket, 2014).

Another energy intensive industry is the cement industry. The recovery of limestone and the pulverisation of the same in cement mills, both vital parts of the industry’s value chain, are very energy intensive processes. Theoretically, the electricity consumption in cement mills is flexible as the process characteristics allow the plant to be shut down and started again within a short period of time (Nilsson & Hammarstedt, 2014). The scale of the industry however is limited and only three plants of Portland cement still exist in Sweden. The average DR potential which is theoretically available in the cement industry is about 34 MW (Gils, 2014).

### 7.2 OTHER INTERVIEWED RESPONDENTS

This section gives a broader perspective by giving an account for the interviews with other respondents such as representatives from utilities and government agencies.
The original scope for the interview series was the end users of electricity, more specifically representatives from the Swedish energy intensive industry. However, to get a more nuanced picture, some other market agents were also interviewed.

**UTILITIES - POWER PRODUCERS**

The interviews with utilities have resulted in following findings. Utilities...

- ... are concerned with the remuneration of capacity investments.
- ... desire long term market design policies.
- ... are scattered in the view of, and attitude towards, DR.
- ... are not convinced about the ability of DR to stabilize an electricity system.
- ... would prefer DR to operate on the existing markets and be based on the spot price.

According to the utilities, there is a gap between the stream of revenues from electricity and the investments needed to secure future capacity. This gap is labelled missing money in literature that supports the claim (IHS CERA, 2014). This missing money-gap is caused by the marginal pricing; the power producer is only paid for the variable cost of production. The fixed cost such as capital costs or maintenance are not included. Hence, the power industry hesitates to invest. More specifically, some representatives from the power industry advocate a *Capacity Market* and imply that the absence of such can lead to serious power shortages on the long term.

Capacity markets do already exist in Europe to some extent, e.g. the English government recently guaranteed a long term price for a specific capacity investment in nuclear. However, such uncoordinated mechanisms add further uncertainty to investment calculation and budgeting.

This new English policy is an example of the second great concern of the utilities which has become evident through the interview series. Utilities need and desire long term energy policies and a consistent market design. The power industry requires significant investments, the yearly investments in the electricity sector varies between 5–6 Trillion SEK per year globally (IEA, 2013), and is affected negatively by the uncertainty that ever changing policies contributes to.

The utilities are in a difficult position when it comes to the attitude towards DR. On the one hand they make more money on higher electricity consumption and higher electricity prices. On the other hand, they have to satisfy customer need and maintain good customer relations. Many utilities are offering customers to participate in DSM-programs and help them reducing their consumption. Reducing the general power consumption is good from a marketing perspective but it also enables the producers to postpone large investments. Still, a completely flexible demand structure combined with a continued marginal pricing method would make it difficult for utilities to pursue a profitable business.

Moreover, the utilities are reluctant that DR could replace gas turbines or other peak generation capacity on a larger scale. Whilst it is admitted that the implementation of DR could reduce peak demand during certain hours or extreme situation, an electricity user cannot be expected to shed load too often or for long periods of time. After all, consumers buy electricity to get use of it, to produce and to generate value in terms of comfort. A system based on load shedding would in that sense be counterproductive and would, since electricity typically creates much higher values than the cost of the resource, also be an expensive solution.

However, utilities accept the DR concept and see it as part of a future patchwork of solutions to cover the gap between net-demand and generation capacity which could arise in a system with a high share of RES. In such a system it would, according to the utilities, be beneficial if the end-users were to trade more actively with flexible bids on the existing markets Nord Pool spot and Nord Pool bas. Thereby, the most cost-efficient solution would be favoured and utilities can
invest in gas-turbines to counter capacity shortages if they predict price levels to exceed the remuneration cost for such an investment.

**GOVERNMENT AUTHORITY & POWER TRANSMISSION COMPANIES**

SvK acknowledge their responsibility for the power balance and the SoS in the national electricity system. The outspoken ambition is to provide a limited regulatory framework and let the market principle allocate the resources. However, since the technical development is accelerating, and there are new political constraints to take into account, the market design needs to be updated continuously for the market to work (Interview SvK, 2014).

If three nuclear reactors were to be closed a power shortage on 2,200 MW would arise in SE3 and SE4, price areas which already today are importing electricity to balance their consumption. This gap can either be filled by gas turbines or wind power. In the latter case, extensive regulating power must be available to cover up for the imminent production from wind power. DR is possible solution for balancing power but SvK cannot count on its endurable availability. (Interview, SEA, 2014).

If the nuclear power was to be phased out, as exemplified above, SEA is aware of the impending power shortage. To handle the situation, the government authority is cooperating with other market agents to find technical solutions which could relax the stressed situation. The means of the government are twofold:

- Incentives and grants. SEA has a yearly budget for supporting start-ups within new energy sources as well as pilot projects within smart grid and DSM.
- Legislation. One possible option is to assign the responsibility for capacity reserves on the electricity producers.

Regarding future DR-potential, the government authority assesses the lion’s share to the residential sector and aggregation of smaller loads which can be shifted in time with only minor financial consequences (Interview SEA, 2014). One example on governmental support, SEA supports smart grid Gotland and the DR pilot project for residential customers in Norra Djurgårdsstaden which have previously been mentioned.
In the first section, the results from the case study and the interview series are analysed separately. Subsequently, the results are merged through a synthesis and put into the context of the base case scenario, which is resulting in a typology for DR-options as well as a demand side Merit-Order curve for future DR potential. In the final section, a summary of results is given.

8.1 ANALYSING RESULTS FROM THE CASE STUDY

In this section, the results from the scientific review are analysed in accordance with the analysis model presented in section 5.3.

The case study is summarised in Table 23, chapter 6. In line with the methodology described in chapter 5, the following analysis is based on a change of basis. Each DR-program is described below based on the data and key findings from the case study. The following analysis lays the foundation for the translation of results to the base case scenario in section 8.3. The focus of the paragraphs below describing the different DR-programs are on the parameters cost, volume and feasibility in order to support the creation of the typology of DR-programs which was one of the targeted results of this report with regard to the purpose of this master thesis.

REAL TIME PRICING (RTP)

Real Time Pricing is a DR-program based on the free market principle (Vlachos & Biskas, 2014). In a visionary future, all electricity users will have smart meters, allowing hourly metering of consumption and corresponding hourly charge according to the spot price. Access to information is a prerequisite, as is an active consumer or at least an automated regulated system. It can be argued that with RTP, all demand is per definition flexible since, in case of power shortage, the electricity prices will continue to rise until enough end-users decide to reduce their consumption. Consequently, the theoretical DR-potential is very large (Vine, 1996).

In practice however, the RTP-programs have had difficulties to provoke sufficient DR-potentials. In the case of smart-grid Gotland in Sweden for example, RTP has been used in the pilot project. The context is favourable for the implemented DR-program; the system involves a high share of RES resulting in price fluctuation and over 70 % of the participating customers are positive to the program (Chatziioanou et al, 2013). Still, RTP alone has not been incentive enough to trigger DR-participation and other incentive mechanisms such as Time-of-Use and Direct Control have been introduced to support the program. It has also become evident, that long-term electricity price contracts neutralizes the effect of RTP. Although in theory, customers can sell back the electricity to the grid during price spikes, risk adversity leads customer to avoid losses rather than realizing profits.

Another example on RTP from the case study is found in Germany. Germany applies a RTP-model with 1 MW in minimum bid size and no capacity payments which enables industries to regulate their own consumption with regard to the electricity price (Koblasa, 2010). The German context aligns with the base case scenario as the system hosts a very high share of RES and prices fluctuate greatly. The German case has also given examples of negative electricity prices, which highlight the fact that DR is not only about consumption reduction but also comprises the useful utilization of power surplus. The DR-program has been successful in Germany, triggering an industrial DR on 2–4 % of maximum capacity to a cost ranging between 500–5,000 SEK/MWh. One disadvantage of RTP that has become evident in Germany is that it reduces the SoS. One way to deal with this is an expansion of existing balancing power plants, predominantly gas turbines. The cost of this extra balancing power is estimated to be around 20–30 SEK/MWh when distributed over the total yearly electricity consumption (Koblasa, 2010).
The Salt River Project in Phoenix, Arizona, is another pilot project that has used Real Time Pricing as a DR-program in order to lower the system cost. Over 1,000,000 customers, including large industry facilities in mining and manufacturing, have taken part in the program which is largely based on informative measures (Schwartz, 2012). By informing the customer about consequences of the power consumption profile, and providing pedagogical tools to enable customers to change their behavioural patterns, the demand side flexibility has increased beside the general reduction in electricity consumption. The local TSO offers customer to choose between different programs which enable a good comparison between the same. The RTP program has lowered peak demand with about 4% and allowing participating end-users to save up to 6% on their yearly energy bills. Key learnings from the Salt River Project indicate the importance of voluntary participation and that the electricity price more accurately must reflect the true cost (Schwartz, 2012). RTP meet both these requirements (Albadi & El-Saadany, 2008). However, the program context differs from that in Sweden in several ways. For example is the energy system partly based on geothermal energy and natural gas that enables a stable production and a low electricity price. Moreover, US industries have been working with DR-programs since the late 70s and are hence further ahead in the learning process that their European counterparts. These factors may complicate the transfer of results.

In summary, RTP is a DR-program which operates at a low system cost since no subsidies or capacity payments are disbursed. Some extra investments in balancing power resources are however needed. In terms of volume, RTP has potential to trigger large DR-volumes in case of high price volatility. In the cases reviewed above however, the response has been fairly moderate, between 2–6%, but that also reflects the price structure of the studied markets. A German simulation of the electricity system in 2020 shows even larger volumes of DR-potential. RTP is a DR-program which is rather straightforward in its design and the investment costs are low in comparison to the other DR-programs included in the study. The principle is being tested in Sweden (Gotland) and has already been implemented in neighbouring countries. The one conceptual disadvantage is the dependency on a smart grid, but such an infrastructure is already available/under development in Sweden. Cumulative these characteristics indicate that RTP is a feasible option on the future Swedish electricity market.

**TIME OF USE (TOU)**

Time-of-Use is a price based DR-program that has predefined charges depending on the hour of consumption. Preferably it is used to counteract seasonal or daily cycles in the load profile (Vine, 1996). ToU in one of the most tested DR-programs and is credited for being comprehensive and powerful (Aghaei & Alizadeh, 2013). However, theoretical disadvantage is the lack of precision; whilst ToU-programs help to reduce general consumption and cyclic demand peaks it offers no incentives for short term DR.

In Norway, Seale et al. (2011) conducted a pilot study based on a ToU pricing model during the period 2006–2007. The pilot project involved industry as well as residential customers who all got smart-meters installed for the purpose of the study. The policy impact indicated a peak load reduction on 30% for targeted resources. On a system level, the result corresponds to a 5% cut in peak demand and a general reduction in electricity consumption on 2% (Saele & Grande, 2011). A key finding from the Norwegian example is that ToU works well if it has no negative consequences on customer comfort. Therefore, best practice would be to combine ToU with an automated system which regulates residential water-boilers or industrial processes after the current price level as well as user defined constraints (US DoE, 2006). Being part of the Nord Pool market and having a largely hydro based energy mix, the Norwegian context is very similar to the Swedish and the results are easily transferable.
A third example of an implemented ToU-program included in the case study comes from China. China has a long history of regulating its electricity market and through ToU-tariffs; the government and regional TSOs have managed to reduce peak demand with over 5% and the general electricity consumption with over 6% (Ming, et al, 2013). The Chinese situation differs in many ways from the Swedish environment and also from the assumptions made in the base case scenario. For example, China has experienced severe power shortages due to an accelerating demand that chronically has exceeded supply. Still, some key findings are of global interest; the Chinese example indicates the possibility of government program to influence the demand structure and highlights the strength of ToU-programs to counteract predictable peak loads due to cyclical variations (Ming, et al, 2013).

Compared to Real Time Pricing, the ToU-program is considered less complex since the information on fixed price levels for given time periods is easier to distribute and comprehend than is real-time price information. In short, ToU offers large DR-volumes to a very low system cost. The case study has proven ToU to be a potent DR-program. However, previous experiences have shown that it works best in highly regulated markets with predictable load variations. Since the European market is fragmentized, and the increasing share of RES is predicted to add to the short term fluctuations, the ToU might be a less feasible option for the future Swedish electricity market despite all other advantages.

**CAPACITY MARKET (CM)**

Capacity Market is a collective concept for electricity market mechanisms which adds fix payments on top of the variable electricity price. Electricity producers typically receive yearly payments per MW capacity they provide to the system, instead of just the variable revenues from produced MWh that are associated with an energy-only market. Examples on CM are capacity auctions and fix capacity payments (Hobbs et al. 2006). The prospects of CM are becoming increasingly debated as the low marginal production costs of RES, combined with a marginal pricing model on energy-only markets, prevents utilities to recover their investments and capital costs (IHS CERA, 2014). In the US, CM-programs exist for a longer period of time and European countries have also started to design CM-programs. In the case study, two examples of Capacity Markets were reviewed.

PJM, located in the central US, is the world’s largest electricity wholesale market. It supplies over 60 million customers with an aggregated demand on approximately 700 TWh. The TSO has a requirement on a 15% capacity reserve margin and has organized a CM to achieve this goal (PJM, 2014). In practice, the capacity auctions are held 3 years in advance. For example, the CM-program has secured a reserve margin on 20% for 2017/2018 which is more than the set target. Examining industrial DR, about 10,000 MW of industrial DR-volume has been cleared in the auctions. This corresponds to over 7% of the total peak demand of the system. From an economic perspective, price on DR-resources is about 290,000 SEK/MW yr (Chappers, et al., 2009). Divided on the total yearly consumption, this corresponds to an additional cost of 70 SEK/MWh. The PJM case presents some interesting key findings. Firstly, the DR-contribution has exploded from 1,000 MW in 2005 to 12,000 MW in 2017/18 as a consequence of the increased
capacity payments. Moreover, it is evident that CM can trigger a significant scale of unforced DR if DR-resources are treated as capacity. However, PJM acknowledges that constraints on DR-volumes, just as for import/export capacities, must be limited to a subset of the system capacities to ensure security of supply (Chappers et al, 2009).

Another example on a CM-program is found in the UK. The British power system has traditionally relied on nuclear power and natural gas but the trend is heading towards ever more wind power (European Commission, 2013). The British government is concerned with the long term SoS and are therefore gradually replacing an energy-only market with a Strategic Reserve with a pure CM. In particular, the CM is expected to boost investments by guaranteeing capital remuneration (Warren, 2014b). The CM-program has helped to secure future capacity. The current fix price for DR-resources is about 265,000 SEK/MW\(\cdot\)y and another 2,800 SEK/MWh for shedded load. Given the price levels above, the long term potential for industrial DR in the UK is estimated to reach 4 GW. That is a dramatic increase from the present day 1,500 MW of DR that is included in the existing Strategic Reserve.

In conclusion, CM is a powerful tool to secure large scale DR. The reviewed cases indicated potentials on 7-10 % of peak load. However, the program is expensive and many costs are hidden from the end user which can decrease the price sensitivity of the system. Distributed over the yearly consumption, the additional capacity payments add about 50-100 SEK/MWh in costs. Moreover, the British price for industrial load shedding on 2,800 SEK/MW is on a level where many industrial electricity users in Sweden already would have acted. Apart from the relatively high costs, the system is complex and needs a lot of regulation (Hobbs, et al, 2006). Different market agents have strong opinions about the underlying principle of CM. According to the results of this master thesis, industrial end users typically oppose CM whereas many utilities and some government representatives advocate it. The unclear public opinion together with the cost and complexity of the system makes CM a possible, but not plausible option for the future Swedish electricity market despite the significant DR-volume it has potential to release.

**STRATEGIC RESERVE (SR)**

A Strategic Reserve is a limited version of a Capacity Market within a general energy-only market design. The SR is typically procured yearly and includes both supply-side generation and DR-resources which are bound to be available for the TSO to call-off in case of power shortages or price spikes (Fritz, et al., 2013). Most countries that apply marginal pricing have a SR due to the fact that the intersection of the demand and supply curves, that gives the lowest system cost in a free market, might not always align with the governmental ambitions of SoS. In the scientific review of previous DR-experience, two cases of SR-programs are studied. Moreover, the Swedish power reserve is also included in the analysis as a cross-reference between the case study and the purpose of this study.

In Sweden, a version of SR called power reserve is being gradually phased out. The power reserve was initiated in the early 2000s to ensure SoS. Initially, the power reserve amounted to 2,000 MW of peak generation capacity exclusively. Thereafter a gradual decrease of the total power reserve has been combined with an increase of DR-resources in its composition. The SR in Sweden is to be dissolved completely in 2020 to make room for a market based solution (SvK, 2014). In numbers, the Swedish SR-program is currently triggering DR-volumes of 630 MW which is about 6 % of industrial peak demand. The average cost of accepted DR-bids for 2013/14 was 89,000 SEK/MW\(\cdot\)y compared to 69,000 SEK/MW\(\cdot\)y for production resources (SvK, 2014).

Denmark has an electricity system which in many ways is comparable to the Swedish electricity system, e.g. in terms of legislation. The eastern part of the country belongs to the Nord Pool areas whereas western Denmark belongs to the continental market EEX. The regions are divided
through a frequency barrier. However, the study conducted by Andersen et al (2006) was conducted in eastern Denmark which implies that the results are transferable to a Swedish context. Concretely, 600 MW of industrial DR participated on average in the SR during the studied time frame 2004–2006. The case study indicated that SR can ensure SoS at a reasonable cost. In the case of Denmark, peak demand was reduced by 4 % at an average cost of 270,000 SEK/MW.y (Andersen et al, 2006). However, the authors argue that even larger welfare gains are to be obtained if a system which increases the price elasticity among the customers even further was to be implemented.

A third example of an existing SR-program is found in the UK. The British context is described in the paragraph regarding capacity markets on the previous page. The SR in the UK has since year 2000 ensured the SoS in the UK but is now gradually replaced by an emerging Capacity Market (Torriti, et al, 2009). As for 2013, 1,500 MW of DR-resources were included in the SR. That is about 3,5 % of the industrial power demand of 40 GW. However, only 200 MW is actual consumption reduction in terms of load shifting or load shedding (Warren, 2014b). The lion’s share of the DR-resources in the British SR is basically on-site generation. Another key finding from the British case is that too many overlapping policies can create imbalances on the market and confusion among investors. For example, UK is struggling with aligning national programs with European policies whilst at the same time engage a SR and an emerging Capacity Market. Warren (2014) argues that this uncertainty will further postpone investments necessary to realize the full DR-potential.

According to the cases presented above, the concept of SR is considered a most functional option for operations in the future Swedish electricity market. In terms of DR-volumes, the potential might be significantly lower that for example Real Time Pricing or Capacity Market, varying between 1–4 % of total peak demand. The cost of capacity for the SR is comparable to the price level of a Capacity Market, however the payments are only received by a few percentages of the total capacity resources and are not the principle market mechanism. In numbers, based on the case studies included in the scientific review, the average costs of DR-resources in SR are about 200,000 SEK/MW.y for the availability of capacity and another 3,000 SEK/MWh when activated.

In summary, SR is a most feasible option for the future Swedish electricity market but lacks the potential of triggering large scale DR. Moreover, the Swedish TSO, SvK, has stated a desire to phase out the existing power reserve, why other alternatives must be considered.

**DIRECT CONTROL (DC)**

Direct Control is a concept in which the regional TSO, or a local utility, can monitor and control the load of end-users remotely (Albadi & El-Saadany, 2008). The system can be either automated or manual but the decision making and response lies in the hands of the balance provider in the control room. In that sense, DC is clearly distinguished from any other DR-program included in the study. The underlying principle is old and tested but it is argued that DC might experience an upswing associated to the new possibilities that a smart grid brings to a system based on remote control and information technology (SmartGrids ERA-Net, 2012).

Several of the cases in the scientific review included DC-programs in their policy portfolio. The most explicit example is found in California where five large industrial facilities participated in a pilot study in 2005. Having experienced a severe energy crisis in the early 2000s, the Californian government and TSO:s attempted to estimate the feasibility of DC. Technically, the industries were involved in the planning process and the program was individually adapted to each customer (California Energy Agency, 2005). The results were encouraging; when prices rose from 500 to 1,250 SEK/MWh, demand was reduced by 10 % on average. The maximum reduction in peak load reached 27 %. The program was funded by the state of California and
would not have been economically profitable on own merits. Hence, incentives and subsidies are needed to get participants to DC-programs. The Californian Energy Agency (2005) states that for large-scale future implementation of industrial DC-programs, the initial investment costs must be reduced and the awareness of the problem must increase among the industry managers.

Apart from industrial loads, DC is often considered a feasible option for residential customers and aggregated loads of e.g. water pumps, ventilation fans and electrical heating. In such cases, the load reduction could be distributed over different consumers and over time. In Denmark, Andersen et al. (2006) made an inquiry among 600 households about their attitude towards DC as a DR-program. The survey showed that about 8 % of the private customers were willing to participate in DC-programs. Accumulated, that corresponds to a flexible load of 70 MW at cost of 750 SEK/MWh. Compared to the existing system with a Strategic Reserve, the system cost would be lowered by 1 Billion SEK per year for the society, or 30 SEK/MWh if distributed over the yearly electricity consumption (Andersen et al, 2006). This is a remarkable relation which indicates that residential DR through DC might possess a significant potential in the future.

The Salt River Project in Phoenix, Arizona, also included DC in their policy portfolio, letting participating private consumers choose between DC or price based programs. About 10 % of the private customers choose DC. However, the volume of flexible load among these consumers was less than from those who had chosen price based programs (Schwartz, 2012). This depends largely on the authority of the remote controller, e.g. how much power the TSO or utility is entitled to cut or constrain.

In summary, DC is a proven, functional DR-program that however is expensive and has failed to gain popularity among policy makers and other market participants. Pilot projects around the world have shown the potential DR-volume for DC-programs to be around 5‒10 % of total peak demand which is more than i.e. Strategic Reserve but less than for example the price based programs. In terms of cost, DC is rather expensive due to the high investment costs. At the moment, the infrastructure that is a prerequisite for DC is expensive and complex which complicates a large-scale implementation. If looking only at the variable cost, DC-programs are competitive and it is plausible that the concept has a future, especially within the niche of residential DR. Among the industrial customers however, there is a widespread resistance towards DC. Managers perceive losing influence over in-house processes. Private companies are often positive towards voluntary demand side participation but reject DC. This attitude makes DC a less feasible mechanism for industrial DR in the future Swedish electricity market.

ANCILLARY SERVICES (AS)

Ancillary Services are a collective term that includes various programs and actions necessary to support the transmission of electricity from producer to consumer and maintain reliable operations (US DoE, 2006). In terms of power balance and DR, examples of AS could be different reserves, frequency regulating reserves, power reserves etc. These are often small in scale. The advantage however is typically a short response time (Martinez & Rudnick, 2013). Traditionally the regional TSO:s have possessed the resources needed to offer AS in-house but in line with the global trends of outsourcing and to increase demand side participation, DR-resources are increasingly being involved in AS-programs.

ISO-NE is a large electricity market in north-eastern US. The aggregated demand in the region, that is called New England, is over 30,000 MW which is comparable to a mid-size European country. The energy mix comprises mainly nuclear power but coal and gas are trending upwards (Yoshimura & Lowell, 2011). In New England, the regional TSO has performed a pilot study to investigate DR as an alternative to traditional AS, alternatively how to integrate the former in the latter. In total, 50 MW of industrial load, mainly in the industries manufacturing and retail,
participated in the pilot. The system required individually adopted infrastructure and pricing models for each participant. Depending on industry, regulating software was programmed to manage the load of the specific facility. In addition, the individual pricing model offered a fixed payment for demand side participation (Yoshimura & Lowell, 2011).

Because of the high level of customization, it is difficult to generalize about cost levels or potential volumes. However, the key findings from the pilot project in New England allow a qualitative analysis. It was found that the reliability of DR-resources was lower than other AS-resources e.g. peak generation capacity. For example, if a factory is already down, due to technical problems or lack of order, no response potential is available. Even if the response is possible, individual DR-resources might add individual constraints to the contract, defining under which times or circumstances the response is activated. Hence the potential DR-Volume for AS-programs is considered to be low. In terms of cost, the AC programs are considered expensive due to the high level of customization that is needed. The case included in the scientific review supports the assumption.

Yoshimura & Lowell (2011) concludes that DR is not eligible to provide sufficient resources for AS is the future but must be combined with reserves of peak generation capacity of capacity auctions. AS, as a general concept, will continue to be an important element of a working electricity system but in terms of realizing the potential of DR, AS-programs are considered less feasible options for the future Swedish electricity market. The major reason for this is the cost distribution; in AS markets the cost of balancing power is typically severally distributed via the grid fee which reduces the incentives for individual customers to adjust their own consumption since the cost of capacity are divided on all electricity consumers regardless of flexibility.

### 8.2 FINDINGS FROM THE INTERVIEW SERIES

This section summarizes the findings from the interview series with the energy intensive industry in Sweden. The underlying data is to be found in chapter 7.

In the results from the interviews with energy managers from the energy intensive industry in Sweden, some reoccurring patterns emerged. These results are presented in Table 24 below and later described and exemplified in the text. The results are supposed to represent entire industry segments and are not representable for any individual person or specific company. Although the opinions are based on answers from individual interviewees, they have been anonymized through a process in which only findings and opinions that were true for at least 70% (7 out 10) of the interviewed representatives were considered as general and thereby included in the summary below.

<table>
<thead>
<tr>
<th>The energy intensive industry in Sweden...</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Results on general awareness of the problem and attitude towards DR</td>
<td></td>
</tr>
<tr>
<td>... are increasingly aware of the importance of electricity for their own prosperity.</td>
<td></td>
</tr>
<tr>
<td>... judge the electricity prices will be more volatile in the future and will adopt their processes.</td>
<td></td>
</tr>
<tr>
<td>... hedge against electricity price fluctuations through long term contracts or own generation</td>
<td></td>
</tr>
<tr>
<td>... argue that DR is a natural reaction, however a necessary rather than a desired one.</td>
<td></td>
</tr>
</tbody>
</table>
... would prefer an electricity system that offers a stable price level and constant supply in order to facilitate
  o facilitates process design
  o production planning
  o budgeting

... have experiences from different DR-programs in Sweden and abroad

Results on DR-programs and policy design

... prefer programs with voluntary participation over legally binding obligations

... would prefer a system with the lowest average cost to secure long term competitiveness

... need a mechanism that guarantees a high security of supply.

... are reluctant that SvK will be able to terminate the Strategic Reserve in 2020 as announced.

... identify a number of obstacles which are limiting the DR-potential and its realization.
  o the limit on minimum bid size on 10 MW excludes large DR-potentials.
  o the lack of real-time price information hinder consumers to make decisions
  o the price levels.

... hold a re-regulation of the electricity market for likely.

... suggest that information and education could contribute to rapid progress for DR and flexibility as have been true in the case of general energy efficiency.

Results on existing and future DR-potential

... have some processes, of significant volumes, which are possible to shift in time.
  o Potential load shifting today equals 600–900 MW.
  o the cost varies from 600–3,000 SEK/MWh and is on average 900 SEK/MWh.

... predict the flexible loads that can be shifted are likely to increase in the future.
  o Driving factors are price fluctuations and program incentives.
  o Flexibility can be purchased through overcapacity and storage capability.

... emphasise that load shifting can only support, not replace, reserve generation due to respond time & duration time. Many processes can be shifted hours, not days

... might shed load if the cost of production exceeds the economic and strategic gains
  o Volumes for load shedding are strongly correlated to price level.
  o At a price level of 1,500 SEK/MWh load shedding is initiated.

... have processes which are impractical to interrupt and hence subjects to load shedding only at very high cost. For these, security of supply is more important than price.

AWARENESS AND ATTITUDE

The general expression of attitude towards DR, among the interviewed representatives of Swedish energy intensive industry, can be summarized by reluctant awareness. All interviewees were familiar with the terminology and worked for companies which had either already partaken in DR-programs or were having discussion on future flexibility projects. However good
the understanding of DR is among industrial electricity users, they tend to view the issue as a problem rather than a possibility. This could be explained by the fact that electricity is just one input in an often complex and expensive process. The core business of the industry is to create value by producing goods, not to create values by refraining from consuming electricity. The typical industry representative is sceptical to the nuclear shutdown and expansion of wind power. This hesitant attitude is important to understand when estimating industrial DR-potential based on the industry’s own admission. For example, an interviewee who wishes to remain anonymous stated:

“I know from my own experience that industry representatives exaggerate the costs and complications of industrial Demand Response when asked”

Contrariwise to the ideological resistance, the economic rationality of a private business helps the energy intensive industry to accommodate the changing environment and find new business models to make money or increase their competitiveness. Several interviewees argue that in a scenario with more volatile electricity prices, the industrial DR-potential will be increased. For example, an energy manager at a large Swedish industry group said:

“In the end, our business is about making money, not producing goods. We will shed load if that course of action generate higher revenues than using the electricity for production would”

The technological solutions to increase flexibility are often simple, but the investments would need to pay off or be subsidised. For example, there is a direct correlation between storage space and load shifting potential. Since storage requires an initial investment however, and ties up capital, the industry is not incentivised to realise that potential given the current situation.

**DR-PROGRAMS AND MARKET DESIGN**

Some of the interviewed industry groups, including SCA and INEOS are already taking part in the Swedish power reserve. Others, as in the case of AGA participating in a *Direct Control*-program in Italy, have international experience from other DR-programs. For large industries, the reasons for participating in DR-programs vary but can be categorized into three principle causes:

- Economic benefit. Assuming that the revenues from participation exceed the specific cost, the DR-program is an attractive business case.

- Responsible approach. This includes companies who are willing to shifts some load in order to ensure the SoS for other processes which are more sensitive to interruption. However, it could also mean green wash in the sense that the organisation want to create an image of acting responsibly.

- Learning and development. When participating in DR-programs that increase the flexibility, employees are challenged with a re-evaluation of the existing processes which potentially leads to increased knowledge creation and process optimization.

While being open-minded about expanded future involvement in DR-programs, the interviewed industry representatives much agreed on the importance of creating a system that is based on voluntariness and the market principle. A program that is legally binding or involves remote regulation of production facilities is regarded as restrictions on free enterprise and is considered to be negative for the business environment.

Moreover, the energy intensive industry is anxious to promote a DR-program with a low system cost and is confident that a price based solution is to prefer over an incentive based programs in
that sense. In a price based market, prices might peak at very high rates. For the industry however, this would be temporary obstacles for the production manager to handle, similar to a technical or logistical problem, and are arguably to prefer over a high average electricity price.

More important, most interviewee argue, is that the market principle is allowed to lower the average electricity cost. It is feared that complex DR-programs, involving subsidies such as capacity payments or incentives to lower the variable costs, will add overhead costs and hence increase the total electricity costs in terms of grid fees, taxes etc.

However, despite praising the market principle, industry representatives believe that some sort of regulation is likely if a high share of RES is to be implemented in the system. Some interviewees even suggest a full re-regulation of the electricity market as a plausible option to ensure the SoS in the future Swedish electricity market. SoS is essential to the industry and, apart from the average electricity price, an important competitive advantage. Many companies have chosen to establish facilities in Sweden the last decades due to the stability of the electricity grid. One example is Facebook who has built three server parks in SE1. Some companies are building own back-up generation capacity to handle reduced power quality in the grid. One example on this is Scania who are currently building 15 MW of diesel generators in Nynäshamn.

**DR-POTENTIAL AND UNDERLYING PARAMETERS**

The results from the interview series in terms of available DR-potential is presented in the demand side Merit-order curve in Figure 40 below. In accordance to the methodology described in section 5.4, the potential was first investigated for each participating company and thereafter extrapolated across the industry.

![Demand Response Potential 2014](image)

**FIGURE 40 - DEMAND RESPONSE POTENTIAL 2014 BASED ON DATA FROM THE INTERVIEW SERIES**

The demand side Merit-Order graph above includes information on cost levels and volumes, for load shedding and load shifting respectively, for the branches Paper & Pulp, Metal & Mining, Chemistry, Manufacturing, Commercials and Others. However, in line with the purpose of this thesis to provide a basis for decision makers and investors on a system level and with respect to the participants in the interview series, the specific price and volume data per industry is not listed explicitly.
To give some understanding of the model however, the most cost efficient load shifting responses are found within the chemical industry and the largest potential DR-volumes consist of load shedding of mechanical processes in the paper & pulp industry.

Based on the results from the interview series, and a linear extrapolation of the results over each industry, the existing industrial DR-potential for 1-4 h response activation is estimated between 600 and 900 MW at a cost of 2,000 SEK/MWh.

It can be observed in Figure 40 that the available DR-potential depends on the duration time of the response. Typically a longer response time is more expensive, especially in case of load shedding, since more production is lost and delivery contracts are threatened. In the case of load shifting it is not only the cost that differs but also the available DR-volume. Depending on facility utilization and internal storage capacity, most loads are only possible to shift within a limited period of time. Too short stops are also expensive since an activation cost typically is associated with DR. A persistence of 1h defined a flexible load in this study. However, most identified DR potential is also available in the interval between 1‒4 hours. Between 4‒12 hours of DR, the volume drops significantly and the cost of continued response activation increases dramatically.

To validate the results above, which are based on information from bias sources and extrapolated linearly, some benchmarks are presented below. In Figure 27 on page 40, the DR-potential in Sweden is estimated by various independent studies. Regarding the studies that concerned the current potential of industrial DR, the mean estimate is about 750 MW, ranging from 530 MW to 1,000 MW. The results presented in Figure 40 above are in the upper region of the interval. One reason for this could be the fact that the companies interviewed to a large extent are working with DR already, for example through participation in the power reserve. To extrapolate their results across the entire industry could be regarded as an optimistic estimation since other companies might not have the competence or resources to create corresponding flexibility at the moment.

Moreover, the case study which compared experiences from previous DR-programs concluded that an industrialized market with a Strategic Reserve in average has a DR-potential of 4 %. With an average power demand in Sweden of 20,000 MW that gives a benchmark on 800 MW. As the results on present day, industrial DR potential are compatible in scale, the results are judged to be credible. Since the contexts differ however, it could for several reasons be argued that the actual industrial DR-potential is even higher. Firstly, the Swedish industrial demand structure is, compared to the situation in many other countries, very suitable for DR-programs. The consumption is highly concentrated to a few, large processes controlled by even fewer owners which facilitate information dissemination, decision making and response coordination. Secondly, the electricity prices in Sweden have been very low and stable during the last few years and year over 500 MW of DR is presently taking part as DR-resources in the power reserve. The case study suggests that the actual industrial DR-potential is far greater but a higher, or at least more volatile electricity price is required to release the potential.

8.3 TRANSLATION OF RESULTS TO THE BASE SCENARIO

Sections 8.1 and 8.2 have regarded the past. This section provides the tools to use historical data in order to generate projections on the future and specifically to the base case scenario. The translation of results are done through extrapolating the existing DR-potential on the future assuming a continuation of the trends of the base case scenario and regarding the qualitative input from the respondents of the interview series.

The base case scenario implies a gradual phase-out of existing nuclear plants to 2050. The proportion of RES will increase drastically, with wind alone accounting for more than 40 TWh
per year by 2050. Also, the capacity of international connection cables is expected to double. The implications of such a scenario, on the DR-programs discussed in section 8.1 and the current DR-potential presented in section 8.2, are discussed below.

**FACTORS AFFECTING THE DR-PROGRAMS**

The surrounding environment has a decisive impact on the effect of a specific policy or DR-program (Torriti, 2014). The analysis of the case study in section 8.1 highlighted what type of context is beneficial for each DR-program. Below follows a discussion on some trends which are assumed in the base case scenario and how they affect the parameters cost, volume and feasibility for each of the different DR-programs included in the study.

The trends that affect the cost, volume and feasibility of the studied DR-programs in the future Swedish electricity market are:

- The European market remain geographically fragmented

The European electricity market is likely to remain fragmented for the foreseeable future (SEDC, 2014). Despite the fact that the European Commission has set up common standards for technical components of the smart grid (European Commission, 2011) and are working to integrate the different regional markets economically (European Commission, 2010), there are clear indications that countries will go ahead making own regional policies and new national laws. For example, Germany is subsidising RES heavily to close down nuclear reactors whereas France are investing in the latter technology (European Commission, 2013). Also, despite the stated objective of a price based energy-only market, countries are introducing various forms of capacity payments. The British government e.g. guaranteed a strike price on a level double to the current spot price for 35 years to come for a private investor building a new plant. Such policies complicate the integration.

For the DR-programs included in this study, it has the impact that what happens within a country, or a given region such as the Nord Pool area, becomes even more important. If politicians and large enterprises agree regionally, they are more likely to implement their preferred proposals in the absence of a common European strategy. For this master thesis this implies that more weight is given to the opinions of Swedish market agents and the development in neighbouring countries and less weight is given to trends in other European countries which would be more important if the markets were to be integrated within a foreseeable future. In practice, this trend favours *Real Time Pricing* and *Strategic Reserves* whereas the feasibility of e.g. *Capacity Markets* and *Direct Control*, DR-programs which are more popular in more distant European countries, are influenced negatively.

- Strong forces are working for an electricity system based on the free market

Focusing on Sweden, and the Nord Pool region with regard to the limitation of this thesis, the forces that promote a free market are strong. Firstly the Swedish TSO, SvK, explicitly states that they are resolute in abandon the power reserve for an entirely price based solution. (SvK, 2014). Moreover, the neighbouring countries within the Nord pool area are sharing SvK’s attitude and policy to a large extent. According to SEDC (2014) the Nordic countries, which have abundant of balancing power potential in their hydro power capacities, have been reluctant to introduce *Capacity Markets*. Also, the results from the interview series indicate that representatives from the Swedish energy intensive industries are more positive towards a price based design for the future Swedish electricity market. Together, these conditions result in a strong driving force for a DR-program which builds on the principles of a free market.
In the typology of future DR-programs, this market trend obviously influences the feasibility parameter. In defining feasibility in Table 18, two influential factors are the desire among market participants and the policy choice of neighbouring countries. Consequently, the trend assumed in the base case scenario favours price based programs over incentive based programs as market participants expressly prefer a price based market design and neighbouring countries are choosing that path as well.

For the translation of results to the base case scenario, this development are influencing the feasibility of *Time-of-Use* and *Real Time Pricing* positively whereas more centralized incentive based programs such as *Strategic Reserve*, *Capacity Market*, *Direct Control* but also *Ancillary Services* are considered to be less feasible in the future.

- Technological development leads to more flexible control systems and lower costs

Due to economies of scale, competition, innovation and research, technology is generally getting cheaper over time. This has also been the case of the automation and control related technology connected to DR (Garg, et al., 2011). In previous cases of highly automated DR-programs, the initial investment costs have been very high which has hampered a large scale implementation. If the current trend of decreasing cost of technical equipment continues, as is assumed in the base case scenario, the automated DR-programs such as *Direct Control* and *Ancillary Services* will both cheaper and consequently more feasible as required investment is one of the factors that constitute feasibility according to the definition in chapter 5.

However, the technological development does not only lower the cost due to continuous improvements; technology leaps also enable new tools to be implemented that were not available before. One industry that has experienced significant technology leaps the last decade is the information industry. Moore’s law states that the cost of storing date is reduced exponentially, approximately by a factor 2 in 18 months. Actually, the cost of transferring data has been reduced with double the speed over the last decade (Google, 2014).

The possibility to transfer data fast and cheap implicates excellent conditions for DR-program based on real time information such as *Real Time Pricing*. DR-Programs that have been under depending on manual work, such as *Strategic Reserve* and *Capacity Markets* will either need to adopt or probably be out competed. The great benefactors of this trend however are highly technology intensive DR-programs such as *Direct Control* and *Ancillary Services* since they now can embrace larger aggregated potentials at a lower cost due to the technological development.

- Future demand peaks are expected to occur stochastically and last between 1 and 4 h.

In the base case scenario, a surplus in electricity generation is assumed on a yearly basis (Profu, 2010). The electricity balance is, during the observed time frame, expected to be more than sufficiently satisfied by new installations of RES (SEA, 2012). The concerns regard the power quality and the cases when net-demand exceeds available peak capacity. Professor Söder (2013) plots in figure 19, the profile of 10 demand peaks. The average demand peak endures 1–4 hours. In the base case scenario, it is assumed that the price peaks will increase both in number, duration and amplitude. That implies that in extreme situations, power shortages up to 3,000–5,000 MW might last between 1 and 12 hours in a scenario with a share of RES-capacity corresponding to yearly production of over 40 TWh.

As illustrated in Figure 25 on page 33, different DR-programs operate on different market levels in the time dimension. In practice, this means that they are designed to counteract different kinds of problem. The *Capacity Market* for example is operating years ahead and is designed to ensure the long term SoS (Torriti, 2014). In contrast, *Ancillary Services* operate during the
delivery hour and are aiming to ensure the power quality in the grid (Martinez & Rudnick, 2013). However, the assumed profile of the power demand peaks, described above, indicates the need of DR-programs which address the time dimension between 1–12 h. The demand peaks are likely to last for hours but might be possible to forecast and respond to some days in advance. In such a case, DR-programs such as Real Time Pricing and Direct Control are more feasible to mobilize sufficient DR-volumes.

Moreover, the problem description in section 1.2 highlights the challenges related to power balance in a system with a high share of RES such as presented in the base case scenario. The variation in electricity production is rather due to intermittent production than seasonal or daily variations, although a certain correlation exists since solar panels for example generate more electricity on summer days than during winter nights. However, collectively the variations are of stochastic nature rather than cyclical patterns as has often been the case when previously implementing DR-programs. This impacts the feasibility for different DR-programs depending on how flexible they are.

In practice, programs which are operating on very long term time horizons, e.g. Capacity Markets, are affected negatively in terms of DR-volume and feasibility. Also programs that offer small DR-volumes with very short response times, such as Ancillary Services, are less feasible to fit the market characteristics of the future Swedish electricity market. With regard to the problem specification, this trend favours a successful and economically possible implementation of programs operating on the Nord Pool spot market, e.g. Real Time Pricing and Direct Control

PARAMETERS THAT INFLUENCE THE FUTURE DR-POTENTIAL

In section 8.2 the current DR-potential in the Swedish industry was estimated based on the interviews with representatives from electricity intensive companies. In this paragraph, some trends assumed in the base case scenario are discussed in order to estimate the future industrial DR-potential in Sweden. Following trends are regarded in the translation of results:

- Electricity prices are expected to fluctuate more greatly.

As described more closely in chapter 3, the base case scenario, prices are expected to become more volatile as a consequence of the increased share of RES in the energy mix (Cui, 2011). Assuming that marginal pricing remains to define the spot price, a high share of wind power e.g. will contribute to very low electricity prices over long periods of the year. Because no fuels are needed, the marginal cost of production is typically low (Gruber, et al., 2013). However, on occasions with no wind or sunshine, power shortages may arise which causes significantly higher price peaks than what is experienced today as the nuclear power, which has a lower marginal production cost than the often fossil based peak production capacity, is assumed to be discontinued. In 2009 and 2010, electricity prices peaked at 12,000 SEK/MWh during winter days with low production from nuclear reactors which were being repaired. Intermittent price peaks of similar scale must be considered as possible also in the future.

As the economic incentives for load flexibility increase with more volatile electricity prices, this assumption made in the base case scenario suggests that a larger DR-potential will be available in the future. For example some measures to increase flexibility, such as increased internal storage capacity that is technically possible and conceptually simple, are not utilized fully today due to the lacking economic return on such an investment. was price to fluctuate more greatly, the respondents in the interview series conducted in this study deem it likely these kind of investments are made and thereby the flexible load, predominantly load shifting, will increase.
In practice, when determining the future DR-potential in the base case scenario, this trend is taken into consideration through determining the DR-potential in the demand side Merit-Order curve at a price level of 2,000 MW. This can be compared to the average price level at the Nord Pool spot which in year 2013 was at about 400 SEK/MWh.

- New market designs and market entry's enables increased demand side participation.

Today the DR in the Swedish electricity market is rather inflexible. An end-user must either trade actively on the Nord Pool spot market or be part of the power reserve (SvK, 2014). In the future it is possible that utilities or new market agents, in terms of aggregators, are able to manage portfolios of smaller electricity consumers and thereby offer aggregated flexibility potentials to the market (Eriksson & Sandwall, 2014). There is of course an option to involve also the residential and commercial sector in DR-programs but also a possibility to exhaust the industrial potential by letting small and mid-sized industries participate. There are already signs on the market that new start-ups are addressing the issue. For example, Expektra is a company that offers services for safer prediction of power demand and has developed a method to use flexible demand as a new balancing power (Interview, Expektra, 2014).

The base case scenario assumes that legislative measures to enable new market entries and aggregation of demand side resources will be taken in order to realize the potential described above. Another option would be to create new market designs. E.g. a possible increase in the accessible DR-potential could be obtained through a relaxation of the required bid size on the balance power market from todays 10 MW (5 in SE4) to 1MW which is the bid size in Germany for example (Gruber, et al., 2013).

When estimating the future industrial-DR potential, all industrial loads over 1 MW are included in the potential in relation to the 10 MW limitation that restricts the existing potential. This added about 20 % of industrial DR-potential in the heavy industries that constitutes the lion’s share of the existing potential but also enables further industries to participate.

- Additional industries become involved in DR-programs

Traditionally, DR in Sweden has been limited to a few industry segments such as paper and pulp, metal working and chemical industry (Nilsson & Hammarstedt, 2014). These branches have, due to their energy intensity, been a natural collaboration partner for the Swedish TSO SvK. However, a study performed by Gils (2014) estimates the DR-potential to be over 2,500 MW out of which only about 800 MW are assigned the branches traditionally associated with participation in DR-programs. Examples on large potentials that are not at all regarded for the time being is pumps in water supply system of cities (110 MW in average available load shifting) or ventilation of commercial buildings (470 MW), so Gils (2014).

In the base case scenario, it is assumed that these potentials are partly exploited as a consequence of increased automation of processes and the economic incentives to save money on supportive processes. In practice, this has implies that new types of load are included in the estimation of the future industrial DR-potential which were not contributing to the existing potential. In numbers it is assumed that, by 2030, about 20 % or the technical load shifting potentials described by Gils above will be commercially available as DR-resources on the future Swedish electricity market.

- The conditions for production and value creation are changing

The general trends in production systems over the last decades have been efficiency and minimization of waste. One example is lean production system that is taught at most universities.
and strived for by many producing companies. The principle builds on just in time delivery with a minimization of internal storages (NE, 2014). This development has reduced costs but is limiting the potential load shifting available for DR; if production utilization is very high, or stock levels negligible, it is not possible to shift any major loads in time (Paulus & Borggreve, 2010).

Moreover, the characteristics of the value creation in industrialized countries are increasingly shifting from the secondary to the tertiary sector, meaning services and skilled manual work such as design, research and development etc. are replacing goods production as the back bone of the European economy (European Commission, 2012). In such an environment, the energy intensive industries are becoming fewer, reducing the potential load shedding available from the industry sector in case of power shortage. Also, since the remaining industry are focusing on differentiated, edge cutting technologies that offers higher profit margin, the cost of load shedding would logically increase.

The base case scenario assumes a continuation of the macro-trends described above. Consequently, despite the many factors which are indicating enlarged DR-potentials, there are strong forces working in the opposite direction. There are some industry segments that today can offer some load shifting due to redundancies in the production capacity but will not be able to do so in the future. This has been taken into account when estimating the future DR-potential in Sweden, as has the increased cost of load shedding due to lower energy intensity and higher profits margin. Concretely, when estimating the future Swedish industrial DR-potential the cost levels are assumed to increase with 50 % by 2030 due to higher value on production shed, lower over capacity in the production which lowers load shifting potential and inflation.

Not all loads are affected by this trend since it regards primarily value creating processes. Supporting processes, such as heating, ventilation, pumping etc. are not affected and the cost level for DR have consequently not been up revised upwards.

### 8.4 DEMAND RESPONSE OPTIONS; A TYPOLGY

In this section, the DR-programs defined in section 4.1 and described in section 8.1 are categorised in the typology of DR-programs based on the parameters cost, volume and feasibility, given the base case scenario of this study.

Based on the systematic review of previous experience of DR studied, the results for each included DR-program have been discussed. A summary of the extracted data from the case study can be found in table 23 in chapter 6 and the analysis of the results per DR-program was performed in section 8.1 above. The translation to the base case scenario (section 8.3) provided the essential input to create a typology of different DR-program that, with regard to the purpose of this thesis, is customized for the future Swedish electricity market.

The underlying structure of the typology is described in detail in the methodology chapter, section 5.5. To give a short repetition, the model has three dimensions. The Y-axis indicates the system cost efficiency. A DR-program with a low Y-coordinate is regarded as an expensive policy option. The X-axis is labelled DR-volume and indicates the DR-potential released by the specific DR-program. Hence, a high X,Y value is regarded as positive since affordable DR-programs that release large DR-potentials are requested. Furthermore, the feasibility parameter is added through a traffic light colour code. Green indicates the most feasible option for implementation on the future Swedish electricity market, assuming the base case scenario, and red corresponds to a highly implausible option.

When considering the typology below, it is important to regard the fact that the axis are deliberately unscaled; the typology is design to enable relative comparison between different
DR-programs, not to put a fixed value on the system cost or DR-volume with respect to any of the specific programs. The important relation that can be inferred from the typology is the internal order between the different DR-programs, not the scale of the number which separates them.

The purpose of this thesis was to contribute to the understanding of industrial DR in the future Swedish electricity market. Concretely, the method chosen to satisfy the purpose was to create a typology based on the parameters cost, volume and feasibility of possible DR-programs given a scenario with a high share of RES. The result is presented in Figure 41 below and thereafter each parameter is discussed separately. The different DR-programs classified by the typology below are defined in chapter 4. However, the figure below also contains a reminder of the used abbreviations to increase the readability of the typology.

**Typology of DR-programs**

![Typology of DR-programs](image)

**FIGURE 41 - A TYPOLOGY OF DR-PROGRAMS BASED ON COST, VOLUME AND FEASIBILITY**

**COST OF DR-PROGRAMS**

In the typology above, the plotting of the DR-programs on the Y-axis, representing the system cost efficiency, are based on their internal system cost rating. The system cost of a DR-program was defined in chapter 5. Based on the results from the case study of previous DR-experience, Table 25 below gives an indication on how big the different expenses were on each cost item for the different DR-program. For each cost item, the indexation 100 corresponds to the most expensive DR-program. To accumulate the total costs, an average weighting coefficient was given to each cost item based on the relation of cost in previous DR-programs. Since the information in the table below can be difficult to interpret, a qualitative analysis of the different DR-programs from a cost perspective is given subsequently.

**TABLE 25 - SYSTEM COST EFFICIENCY RATING OF DR-PROGRAMS**

<table>
<thead>
<tr>
<th>DR-program</th>
<th>AC</th>
<th>I</th>
<th>S</th>
<th>VC</th>
<th>LR</th>
<th>∆EP</th>
<th>COST</th>
<th>System cost efficiency Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTP</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>100</td>
<td>100</td>
<td>30</td>
<td>39</td>
<td>2</td>
</tr>
<tr>
<td>ToU</td>
<td>10</td>
<td>30</td>
<td>20</td>
<td>60</td>
<td>80</td>
<td>40</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>CM</td>
<td>100</td>
<td>50</td>
<td>90</td>
<td>20</td>
<td>50</td>
<td>70</td>
<td>65</td>
<td>4</td>
</tr>
<tr>
<td>SR</td>
<td>50</td>
<td>40</td>
<td>80</td>
<td>50</td>
<td>30</td>
<td>50</td>
<td>48</td>
<td>3</td>
</tr>
</tbody>
</table>

105
Since the numbers of the different cost items extracted from the case study were in different currencies and from different points in time, Table 25 above compares the relation. The following argumentation highlights the different dominating cost items for each DR-program and how this relation may come to change in the future assuming the base case scenario.

Previous experience has shown that price based solutions, such as Real Time Pricing and Time-of-Use, are most cost efficient from a system perspective. They do not involve any fixed payments or subsidies and the initial investments needed to implement the system are typically very low (US DoE, 2006). In the case of Sweden and the Nordpool region, where a spot market and a balancing power market already exist, the additional cost would be mainly administrative. Especially a network for distributing real-time price information would be necessary as well as informing customers about how their behavioural patterns affect their energy bills as well as the environment (Garg, et al., 2011).

According to the case study performed, the incentive based programs, that includes Capacity Market and Strategic Reserve, are fairly cost efficient policies to ensure long term security of supply, but more expensive than the price based solutions. The incentive based programs typically requires capacity payments on top of the variable electricity price (Torriti, et al., 2009). It is argued that the average electricity price will be lowered by the abundance of capacity (IHS CERA, 2014). Whilst this is confirmed by the case study, the total system cost including incentives, administration of procurement etc. adds to a general overhead cost that is exceeding the cost of the price peaks which would be the alternative of an energy-only market. Also, there is the time perspective. If capacity auctions are held years in advance, or programs are guaranteeing strike prices on electricity over time, the potential gain of technology leaps or structural changes is lost (Torriti, 2014).

Programs which involve highly automated systems and a customized infrastructure on the consumption site have according to the case study been the most expensive systems. Examples on this are Ancillary Services, which are only used to a limited extent to ensure power quality, and Direct Control. Direct Control has been tested in pilot studies among industrial users (Californian Energy Agency, 2005) as well as on residential customers (Saele & Grande, 2011). In both cases, the installation of the system was so expensive that it could not have been carried out without governmental subsidies. Whilst the automated programs remain complex compared to the monetary based solutions, the relative cost difference is assumed to diminish due to the continuous technological development. If automation control technology become cheaper and more customers are connected to large data bases, as is assumed in the base case scenario, Direct Control is assessed to be a competitive DR-program in terms of system cost efficiency.

**DR-VOLUME RELEASED BY DR-PROGRAMS**

As with the cost parameter, the plotting of DR-options on the X-axis, representing the DR-volume in the Typology, were based on the internal order of the DR-programs regarding their DR-volume. The scale of the axis is not linear but relative and only a comparison between the different DR-programs can be inferred from the typology. Table 26 below shows the average DR-volume as percentage of total peak demand based on the case study. The numbers are not globally applicable but give a foundation for further qualitative analysis.
### Table 26 - Average DR-Volume Per DR-Program Included in the Case Study

<table>
<thead>
<tr>
<th>DR-Program</th>
<th>RTP</th>
<th>ToU</th>
<th>CM</th>
<th>SR</th>
<th>AS</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR-Volume</td>
<td>19.0%</td>
<td>5.0%</td>
<td>11.0%</td>
<td>4.3%</td>
<td>1.5%</td>
<td>10.0%</td>
</tr>
<tr>
<td>DR-volume ranking</td>
<td>.</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

The percentages in the table above correspond to the average DR-volume released by the different DR-programs from each category included in the case study. To give some examples on what potential DR-volumes that are discussed, a short summary of the case study of previous DR experience is given from a DR-volume perspective.

The case study has shown that the **Real Time Pricing model is releasing the largest DR-potential**. This is supported by theory in the sense that a RTP-program is affecting all available demand, not just a small proportion that is participating in an auction or an automated system (Fritz, et al., 2013). It is argued, that in a RTP-program, all demand is flexible since the actual cost of consumption matches the true cost of production, end-users will adopt when prices rises. Looking at some examples, such as the Salt River Project in Phoenix, the RTP-program is outcompeted by DC and ToU in terms of DR-volume. However observing the context, the electricity prices in the region were very stable during the pilot period (Schwartz, 2012). If the price fluctuations were to increase, as is assumed in the base case scenario, the DR-volume provoked by RTP would be even greater.

Pilot studies such as the capacity auctions performed by PJM in the US have also indicated that **Capacity Market** is a program design which releases large potentials of unforced DR. For example, since the initiation of the capacity auction program in 2005, demand side participation has increased from 1,000 MW to 12,000 MW in 20017/18 (PJM, 2014). The **Strategic Reserve** includes capacity payments but in a more limited scale. Consequently, the released DR-potential is fairly low. In average, SR-program includes DR-resources corresponding 4.3% of the total peak demand. It is argued whether on site generation is to be regarded as a DR-resource equal to load shifting or load shedding. If not, potential DR-volumes among existing SR-programs are even lower (Warren, 2014b).

In terms of volume, **Direct Control** has proven to be a competitive DR-program. The average DR-potential corresponds to about 10% of the total peak demand in the cases reviewed in this study. A concrete example is the pilot study in California, involving five large industrial facilities in an automated DR-program. When prices rose with 150% from 500 SEK/MWh to 1,250 SEK/MWh, the average demand reduction was on 10% and the maximum reduction from an industry customer was 27% (California Energy Agency, 2005). Also European studies have indicated the large volumes which could be released by DC. However, these studies have been of rather theoretical character and Andersson et al. (2006) admits that the technical infrastructure needs to be improved and new business models developed before the full potential of DC can be realized. Assuming a smart grid and the presence of aggregators, as is done in the base case scenario, the future DR-volume released by DC-programs are estimated to be higher relative the previous experienced potentials.

**Feasibility of Implementing DR-Programs**

In the typology of DR-programs above, the feasibility of a specific DR-program is indicated by the colour code varying from green (high feasibility) to red (low feasibility). Feasibility is a complex parameter that is accounting for how well suited a DR-program is to match the requirements of the base case scenario and thereby estimating the likelihood of an
implementation of the same DR-program. The parameter depends on five factors which are all listed and defined in section 5.5. In the following paragraphs, the different factors that support the feasibility definition are discussed and in parallel some of the most important arguments for evaluating each DR-program are repeated.

In 27 below, the score is presented for each DR-program and respective feasibility factor. It must be observed that a high score is favourable for the feasibility of a DR-program. Consequently, a high score on cost in the table below e.g. indicated low costs associated with the specific DR-program because a low cost increases the feasibility of successful implementation.

TABLE 27 - RESULTING SCORE FROM FACTORS THAT UNDERPIN FEASIBILITY

<table>
<thead>
<tr>
<th>DR-Option</th>
<th>Complexity</th>
<th>Cost</th>
<th>Desire</th>
<th>Neighbours</th>
<th>Technology</th>
<th>Σ Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTP</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>ToU</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>CM</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>SR</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>AS</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>DC</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

When evaluating the different DR-programs, the policy impact and key findings of the case study were, based on their context and background, translated into the base case scenario in accordance to section 8.3. The analysis below gives an account for the argumentation that underpins the feasibility ranking in the table above.

According to the results of this procedure, a Strategic Reserve is the most feasible option for DR on the future Swedish electricity market. Regarding the fact that Sweden already possesses a SR-program, this is not surprising. More interesting is the observation that Real Time Pricing, apart from the existing SR, is the most feasible DR-program for the future Swedish electricity market. RTP is a concept that releases a large DR-volume to a low system cost, the technology is available and neighbouring countries are likely to choose the option. Moreover, the TSO in Sweden has declared its intention to abandon the Strategic Reserve for a price based market design in 2020 (SvK, 2014).

From the feasibility ranking can also be deduced that Time-of-Use is considered a highly improbable DR-program to be implemented in the future Swedish electricity market, despite having a low design complexity and being able to release large DR-volumes at a low system cost. The main reason for this is that the strength of the program design does not match the problem description of the base case scenario. The power shortage that is a likely result from a system containing a high share of RES is not of a cyclical nature and can therefore not be opposed by a program with predefined charges based on the hour of consumption.

Having observed the main implications of the feasibility ranking of the typology, each feasibility factor will now be discussed. Beginning with complexity, the logical argument is that a less complex system is more easily implemented and adopted. The case study indicates that programs with predefined targets and price levels are easily comprehended by the end users and manageable to administer for the utilities, the TSO and the state. Examples on such DR-programs are Time-of-Use, which can be introduced in any electricity contract, and Strategic Reserves which is already operating in most Nordic countries. Programs that involve many
active participants do become more complex per se and if, such as in the case of Capacity Markets, different rules and requirements apply to different competing resources then the complexity rises even further. Ancillary Services are deemed even more complex than Direct Control due to the extremely short response time. To organize responses, and find reasonable business models for Demand Response and finding a settlement with reasonable remuneration for participating DR-resources would be a complex challenge for a system based on Ancillary Services.

The system cost is also influencing the feasibility of a system, since a more expensive system will be more difficult to finance and hence to implement. Typically, the cost of a DR-program correlates quite well with its complexity. The results from the case study indicated that Time-of-Use and Real Time Pricing are the most cost-efficient DR-programs historically, followed by Strategic Reserve and Capacity Markets. However since the cost associated with Direct Control is largely technology related, and the cost of hardware and automation systems in the base case scenario is assumed to decrease over time, DC will be a more feasible option from an economical point of view than has it previously been. The internal ranking in of this parameter is taken directly from the cost-parameter evaluation previously conducted as part of the typology of DR-programs.

Desire is a multifaceted factor. It includes the ambitions of politicians nationally and internationally, the expectations from utilities and energy intensive industry which has large influence as well as the, perhaps more emotionally based, public opinion. The Real Time Pricing model is considered most desired. The case study has shown positive response from the broader public and the interview series has concluded that the energy intensive industry in Sweden would prefer a price based market design for future DR-programs. Moreover, this conclusion is supported by the fact that SvK explicitly has expressed a desire to move away from the incentive based power reserve in 2020 and replace it with a market based solution that is to operate on the existing Nord Pool platform. The concept of Capacity Markets is also regarded as desired. Utilities are pushing the issue and they have large influence on policy makers. Moreover, politicians fear that an energy-only market might not ensure the SoS and that a CM could be a stable solution for a long period of time. Direct Control is however a markedly unpopular DR-program, especially among industrial users who do not want to share the control over in-house operations. It is also discussable whether private customers will allow utilities or other market agents to install control system in their houses. Although it may seem uncontroversial, a movement against global monitoring of private affairs must not be underestimated. Time-of-use pricing programs are considered less feasible for the simple reason that they, as previously described, do not successfully address the specific problem described in the base case scenario and are hence not relevant from that perspective.

Another factor which is influencing the feasibility of future implementation of a program is the policies of neighbouring countries. Since the base case scenario is assuming a fragmentised world however, it is arguably sufficient to consider the Nord Pool region outside which policies are likely to differ greatly anyway in the foreseeable future. If studying the neighbouring countries, Strategic Reserve is the most feasible option. The case study has revealed that pilot projects regarding Direct Control programs have been carried out in Norway as well as in Denmark. Despite the encouraging results; Seale & Grande (2011) showed that peak load could be reduced by up to 30 % with DC and Andersson et al. (2006) estimated that 8 % of the end-users were willing to participate in DC-programs, there are no signs of a full scale implementation.

Finally, the more technology is needed to implement a DR-program, the greater the risks, costs and consequently the lower the feasibility. Adding technical components is a practical risk as
well as a financial one. A technically complex system is more prone to bugs or crashes, especially in the first phases of implementation and the cost of installation is often a risk that no private enterprise wants to carry. In this perspective, the Strategic Reserve is a good option since the investments are limited, in absolute terms as well as in number of locations. This factor is also the one disadvantage of a Real Time Pricing program since, for it to operate optimally, such a system would require each end user to have both real time price information and means to conveniently and effectively adjust the consumption instantly.

8.5 DEMAND SIDE MERIT-ORDER

In this section, an estimation of the future industrial Demand Response potential is made based on the existing potential and the translation to the base case scenario.

An estimation, based on the results from the interview series, of the existing industrial DR-potential, is plotted in section 8.2. The total flexible volumes amount to about 900 MW when regarding one hour duration. Out of this, approximately 600 is load shifting which is accessible under 2,000 SEK/MWh. The lion’s share of the economically beneficial DR is to be found in the paper and pulp industry. Because the industry is very energy intensive, up to 20% of the cost for certain products are variable electricity costs, a flexible approach towards electricity is a prerequisite for profitability. Moreover, the large and highly automated process industry is well suited for DR-purposes. Other significant loads are found in metal- and chemical industries.

It can be observed that most flexible load, about 600 MW, can be utilized up to four hours. For longer demand peaks however, the available DR-volumes shrink quickly and the cost of the remaining DR-resources increases significantly. The volume decreases because existing redundancies in the productions, that are used to shift load over time, are typically very limited. The cost of load shedding increases because when load shedding, production to stock is shed first, thereafter orders with lower profit margins followed by more profitable production. Given the assumptions of the base case scenario; more volatile electricity prices, a full scale implementation of a smart-grid, a higher awareness of the possibility of DR etc., the DR-potential in the Swedish industry is estimated to increase significantly. Figure 42 below show the result of this study which is based on the current potential, qualitative input from the interview series and translation of results to the base case scenario.

![Demand Response Potential 2030](image)

**FIGURE 42 - FUTURE DEMAND RESPONSE POTENTIAL ASSUMING THE BASE CASE SCENARIO**
In an energy-only market with Real Time Pricing, which according to this master thesis is the most feasible market design for the future Swedish electricity market, the industrial DR-potential is estimated between 2,000–2,500 MW. The future industrial DR-potential is larger than the existing for several reasons. The main arguments are listed, motivated and exemplified below. A sensitivity analysis regarding the result is given in the discussion chapter.

- Full adoption across industries exhausts unexploited potential.

More companies are likely to follow the early adopters and be active participants on the electricity market. Today, most of the participants in the power reserve and on the spot market are large industry groups. However, as small and mid-size industries are consuming over 30 % of the industrial electricity demand, a large potential is currently unexploited. In the paper and pulp industry for example, the large industry groups have separate departments managing energy flows and specific energy managers who are responsible for the purchase of large amounts of electricity. The interview series indicates that mid-size companies are often aware of the possibility of DR but have no resources or incentives to increase their flexibility or implement DR-programs at the moment. For small businesses it is assessed that they lack both knowledge and tools to participate actively on the balance market.

Also, this adoption also means full implementation of DR-principles within the companies that are currently working with DR. For example, many interviewees have indicated that there is more to be done and that several projects to increase the share of flexible loads are in the pipeline. For example AGA are expecting to double their amount of flexible loads from 15 MW to 30 MW in 2030 (Interview AGA, 2014) and INEOS in Stenungsund will, if a new chlorine factory is build, increase their flexible loads from 20 MW to 50 M (Interview INEOS, 2014).

- Aggregation of smaller loads enables new industries to participate in DR-programs.

Technological development and automation will enable new industry segments to increase their agility. Today, DR-resources are typically large, homogenous processes such as melting or electrolyse. In the future it will be possible for industries to aggregate smaller loads such as pumps or ventilation and offer load shedding by rotating the operations between different system components.

For example ICA, the largest grocery retailer in Sweden, consumes 1.5 TWh per year. It is a significant amount of energy corresponding to 1 % of the total yearly electricity demand in Sweden (Interview ICA, 2014). Yet no measures are taken to increase demand flexibility due to the high dispersion of loads on different processes and places. However, work is initiated to monitor and control processes such as heating, lighting and ventilation and it is possible that these systems can be utilized for DR-purposes in the future. ICA also stated during the interview that such an approach would be in line with both the low cost trend in the retail industry as well as the green and environmental profile that ICA and many other commercial firms pursue.

- Increased price volatility enables economically sound investment in flexibility.

The perhaps most important factor related to the base case scenario, is increased price volatility. Fluctuations in spot prices will enable investments to increase production flexibility which previously has been unprofitable.

The result from this master thesis indicated total industrial DR-potentials on 2,300 MW for response durations under 1 h and identifies DR-resources 1,500 MW of industrial DR-resources that can endure a response time up to 4 hours. Both DR-potentials are accessible at a variable cost below 2,000 SEK/MWh. In chapter 4, previous work on the DR-potential in Sweden was presented. The average estimation of the future industrial DR-potential is 1,450 MW. Moreover, the results from the case study indicate that 7 % of maximum peak demand is a good benchmark.
for a Real Time Pricing-program in an industrialized electricity market. Given that the maximum demand in Sweden is about 27,000 MW, the benchmark derived from the scientific review indicated an industrial DR-potential about 1,900 MW. This benchmark is obviously somewhat imprecise but collectively, having three independent sources indicating industrial DR-potentials in the same magnitude strengthen the estimation of this thesis to serve as a basis for future decision makers and investors.

8.6 SUMMARY OF RESULTS

This section summarizes the results on the future of industrial Demand Response in Sweden, based on the case study and the interview series, assuming the base case scenario of this thesis. Also, the section gives a sensitivity analysis of the results presented in this thesis.

Previous reports have estimated the existing industrial DR-potential to be between 500 and 1,000 MW. The results from the interview series, conducted as a part of this master thesis, indicate an existing potential in the upper part of the interval, about 900 MW. For the winter 2014/2015, 628 MW of DR-resources are included in the power reserve.

In the long term however, the power reserve is to be phased out until 2020. SvK are advocating a price based market design for DR on the future Swedish electricity market and this study agrees on a Real-Time Pricing-model being the most feasible DR-option, given the base case scenario of this thesis. The Typology of DR-programs also acknowledges Capacity Market and Direct Control to be possible options for DR on the future Swedish electricity market. Capacity remuneration mechanisms have the advantage of encapsulating both megawatts from supply capacity and “negawatts” from DR-resources, adding a downward price pressure on capacity whilst ensuring long term SoS. DC, a concept that requires an extensive technical system to enable aggregation and control of loads, is considered to inhabit large potential and is likely to become the prevailing DR-program in the future. However, the complexity of the system and the cost of implementation are yet too high. In comparison, a RTP-program offers larger DR-volumes at a lower system cost. The RTP system is more easily administrated than e.g. Capacity Markets and requires no subsidies or incentives from utilities or the government to involve demand side resources in the balancing power market. Moreover, a price-based solution offers a combination of manual and automated response mechanisms, allowing implementation to continue during a phase of infrastructural transition. Supported by a smart grid which can automate the control over electricity usage, RTP becomes an even more powerful tool that might be able to include not only industrial resources but also the large residential sector in the future.

Assuming an energy-only market, and the energy mix of the base case scenario, the industrial DR-potential is estimated to be within the interval of 2,000–2,500 MW. However, the available potential depends on several factors such as spot price and response duration time. About 1,500 MW of industrial DR can be accessible for 4 h response duration at a cost below 2,000 SEK/MWh.

SENSITIVITY ANALYSIS

The results regarding the existing industrial DR-potential is relatively stable since the assumptions are few and the extrapolation linear. The potential response volume from the Swedish energy intensive industry has been identified through interviews with energy managers. This approach may have given indications rather than precise results. However, although the price levels and volumes in the demand side Merit-Order graph could vary, the changes would be minor since the relation between input and output is linear and the basic characteristics of the graph would remain the same. Also, as described in the previous section, international benchmarks and results from previous work support encloses the existing industrial DR-potential estimated in this report between 600–900 MW by giving the broader
interval of 500 – 1,000 MW. The performed sensitivity analysis indicates that the existing industrial DR-potential remains within the broader interval, which corresponds to changes within an interval of +/- 15 % of the estimated potential, even when the assumptions and parameters of the Merit Order model are adjusted.

The future industrial DR-potential depends, in contrast to the existing potential, on many parameters and assumptions. It has previously been discussed; see section 8.3 translation of results to the base case scenario, how these parameters influence the future potential. Since industrial DR-potential is greatly depending on the market design, the most important parameter to adjust in the sensitivity analysis is the choice of future DR-program.

To assume Real-Time-Pricing for the analysis of the future Swedish electricity market was based on the Typology of DR-programs which strengths and weaknesses have previously been discussed. If Sweden instead would implement the second most feasible DR-program, according to the Typology in the case that the Strategic Reserve is phased out according to plan, it would mean a Capacity Market. The sensitivity analysis, which is based on previous DR-experience and the interview series, suggests that the industrial DR-potential would remain relatively stable in terms of volume.

The practical implications of a different market design would be mainly two. Firstly, the characteristic of the demand side Merit-Order curve (Figure 42) would change as CM typically offer larger potentials at lower electricity price levels compared to RTP but the trade-off is lower response-volumes at higher price levels. This is because the reduced price sensitivity that follows fixed capacity payments. Secondly, the average electricity price would probably increase with a CM as the program design includes overhead costs which do not correlate with the actual need for balancing power. E.g. is it theoretically possible that the DR-resource not is activated during a period of time for which capacity payments have disbursed due to weather conditions, demand structure etc. In short, if Europe and Sweden were to have a CM instead of RTP, the industrial DR-potential would remain rather constant in terms of volumes but accessible at higher costs. The balancing power problem however would be less critical since a CM-program typically includes power generation resources and hence incentivise new capacity investments.

Another assumption which greatly influences the future industrial DR-potential is that the existing best practise identified in the Swedish industry will be adopted among all market participants. This can in a way be regarded as an optimistic estimation since all companies, especially small and mid- sized enterprises might have difficulties to apply the processes and procedures which generate flexibility among the market leaders. Hence the sensitivity analysis indicates that the future potential might be lower than the estimation 2,000-2,500 MW.

If regarding the technical prerequisites from a holistic perspective however, the estimation is a rather conservative one since no technology leaps are assumed. In this master thesis present day best practice is the yardstick also for future industrial DR. A more optimistic approach would be to assume a more rapid technological development. If, as have been the case with other technical processes as e.g. energy efficiency or cost of production, the cost of flexibility were to be reduced with 1.5 % annually, then an industrial DR-potential of 3,000 would be available at 2,000 SEK/MW by 2030. This change is significant since the future industrial DR-potential differ over 30 %. However, looking at the time horizon it is actually not a very large spread. Since the many of the parameters are exponential, such as price development on technical components as is the example above, small changes can lead to big differences in results over 20-30 years.

In summary, according to the sensitivity analysis, the future potential could vary within a greater interval than is estimated in this report. Previous work and international benchmarks however support a future industrial DR-potential about 2,000 MW and the number can therefore be regarded as a reliable indication for decision makers and investors to base their future decisions on. This of course assumes the base case scenario.
If any other future scenario were to become reality then obviously the industrial DR-potential would change drastically. A lower overall electricity consumption would e.g. relax the stress on the currently available balancing power resources, leading to reduce need for DR. Also, if Europe were to integrate the different electricity markets entirely, the capacity and availability of import possibilities would increase and thereby reduce the need for DR.

One beneficial feature of DR, in relation to the sensitivity analysis, is that the future available DR-potential correlate positively with the scale of the power balancing problem. Severe power shortages causes high spot prices. This study has shown that the available DR-potential depend heavily on the spot price level. Hence, since monetary profit is a strong driving force behind industrial DR, more loads will be made flexible in a situation with frequent and severe power shortages. Likewise, a future scenario with few power shortages and stable spot prices would trigger a smaller industrial DR-potential. In such a scenario however, the balancing problem would also be less critical.

Apart from the parameters that drive the increase in future DR-potential, other external factors may strongly influence the need for, and potential of, industrial DR. For example, technology leaps in other flexibility options such as energy storages, but also in general electricity production resources, may replace or outcompete DR in the long term. If e.g. the cost of batteries were reduced, or electricity production made more local and flexible, then the use of industrial DR would be reduced from a power balancing perspective and the financial incentives for investing in demand side flexibility would diminish. It is also possible that the demand structure in Sweden and Europe changes. If industries keep moving their production facilities abroad it would mean less available DR-potential in the future. However, in such a scenario it is also likely that Sweden as a country would face over capacity in terms of electricity generating resources instead of power shortages. For the time being the demand structure is relatively stable and the representatives that participated in the interview series were positive to continued domestic industrial production in the future.
9 CONCLUDING DISCUSSION

This final chapter includes a short discussion section giving some perspectives on the previously presented results before presenting the conclusions of this master thesis. The focus of the chapter is to answer positively on the purpose of the thesis and thereby address the knowledge gaps of previous works.

9.1 PERSPECTIVE ON THE RESULTS

This section discusses industrial Demand Response as a concept in more general terms and given an example of a business case how industrial DR can save economic resources on a system level.

It is the view of the author that industrial DR is just one minor element in a patchwork of policies, technologies and business models that collectively attempt to satisfy the requirements of a future electricity system; safe, environmentally friendly and affordable. This patchwork of partial solutions, called the electricity market, is currently undergoing several transformations simultaneously.

Firstly, the macro trends of globalisation and European integration changes the preconditions for utilities and TSOs which previously have had a very nationally limited focus. By regulation and incentives, the European Union tries to increase the amount and capacity of the international connection cables to reduce regional variances in supply and demand. For the power balance, this implies that the available balancing power in the future will be sold to whomever pays the highest price, be it within a nation or abroad. It has been deemed unjust to block export cables. Consequently, despite the positive impacts on the power balance that import has as a resource of variable capacity, this actually increases the importance of easily accessible DR-resources in case of critical power shortage in several countries simultaneously.

Secondly, the electricity market is experiencing a technological revolution. New high frequency transmission grids enable more efficient power transmission and hence longer transportation distances. Moreover, the smart grid provides the technical solutions to make DR scalable, cost efficient and convenient. In Sweden, smart meters with hourly metering are already rolled out to a large extent. The trend indicated that the Nord Pool market will have full smart meter coverage in 2020 and the EU possibly in 2030. This enables many DR-programs which have previously been limited by the absence of such infrastructure, including Real Time Pricing and Direct Control, which both are feasible options for the future Swedish electricity market. Thirdly, and perhaps most importantly when discussing the transformation of the electricity market, the deregulation is still an ongoing and fragile process. Since the initiation of the deregulation in the 90s, policies and regulation have been continuously added to the market, resulting in an uncertain environment based on a mixture of national and international regulation. The free market principle only prevails on certain sublevels of the market. For the prospect of future DR, it entails that all possibilities must be regarded; from an energy-only market, via Capacity Markets with predefined payments to a complete re-regulation of the market can nothing be categorically excluded from examination. It is the view of the author of this report that, given the base case scenario, a re-regulation of the market is plausible.

Regardless of the future market design however, it is important that the framework is consistent and that the policy making process is transparent. There is a risk that DR will be used as a cover for protectionist subsidies, as is already the case in many other countries. When constructing the typology of DR-programs, it became evident that it is most difficult to separate what costs are actually related to a specific electricity policy program and what is general governmental support and grants. The case study indicated that DR-programs in many cases are as much subsidies to domestic energy intensive industry as a solution on the power balance problem.
The underlying principle of DR is actually nothing controversial. That consumers are adjusting their demand of a product to the price is generally the basic principle on most markets. Due to the electricity dependency of society for prosperity and comfort however, this service has long been subject to monopolists and many market agents have been used to a constant supply of affordable, often subsidised electricity. As now the true system costs become evident, including the cost of balancing power, all market agents must revaluate their procedures and look for new possibilities.

In the long term, it is possible that other solutions to the power balance problem given a high share of RES will outcompete DR. For example, the supply resources may become more agile or large scale electricity storages might become economically profitable. Power-to-gas, producing hydrogen gas from water through an electrolyse process, is one feasible option, high capacity batteries in residential areas another. Also, e-mobility may provide the flexibility and storage capacity that a system with a high share of RES needs as a buffer. However, these concepts have yet to be further developed both technically and economically before implementation is possible. This implies that industrial DR will have a role to fill during the foreseeable future.

There are large inherent DR-potentials to exhaust. Many researcher and policy makers have put great confidence in studies revealing significant DR-potentials. McKinsey are estimating the DR-potential in the US to be 188 GW or 20 % of the total peak load (McKinsey, 2010). Translated into economical terms this equals a societal benefit on 36 Billion SEK yearly. The potential economic gain from DR is evident, although the calculation focuses on the power system cost and do not account for e.g. other economic consequences such as losses in production. Also European studies have indicated great potentials. Gils (2014) estimates the aggregated potential of load reduction in Europe to be about 93 GW; varying between 7 % and 26 % of peak demand in the different European countries depending on demand structure.

It is also possible to examine the potential economic gain of industrial DR in Sweden from a system perspective. The base case scenario suggests that an electricity system based on a large proportion of RES could, despite a general yearly energy surplus, be exposed to power deficits some hours of the year due to the low availability factors of i.e. wind and solar power. Based on the simulations made by Professor Söder (2013) at KTH, Stockholm, a system with 40 % wind and solar power replacing the existing nuclear plants is in need of peak capacity about 750 hours per year. The maximum power shortage is over 5,000 MW. Schröppel (2014), who has analysed a similar system based on high share of RES, argues that the most feasible source of back up generation would be gas turbines which only would need to operate only a few hundred hours per year. Given that the capacity cost of gas turbines is about 300,000 SEK/MW, and the variable production cost around 900 SEK/MWh, DR can help to reduce the system cost.

According to the base case scenario, the demand peaks are expected to last about four hours in average. Assuming such a profile on the reoccurring power shortages, the available industrial DR-potential in 2030 would be about 1,500 MW available to a variable cost of 2,000 SEK/MWh. The economic savings on a system level was calculated by including the fixed and variable cost of power capacity. Insertion of the numbers above in the formula below gives a yearly reduction in system cost on 350 MSEK.

\[ \Delta \mathcal{SC} = V_{DR} (FC_{DR} - FC_p) + A_{DC} (VC_{DR} - VC_p) \]

Where \( \Delta \mathcal{SC} \sim \) system cost reduction/increase, \( V \sim \) industrial DR-volume in MW, \( A \sim \) activation in MWh of DR-resources, \( FC \sim \) fixed capacity costs, \( VC \sim \) variable cost of activation and the indexes DR and p represents DR-resources and production resources.
If, as illustrated in Figure 43 below, industrial DR could reduce the need of peak capacity gas turbines, the system cost would be reduced by over 350 million SEK, y. Divided by the total electricity consumption this corresponds to an average benefit of 2.5 SEK/MWh. Given that the average electricity price is about 400 SEK/MWh, the identified DR-potential can help reduce the cost of electricity with about 0.5%. For a company like Sandvik for example, such a difference in average electricity costs equals 5 MSEK per year that can be invested in new technology and personnel. The cost of lost production is included in the variable cost of industrial DR since a continued production at such high spot prices would be unprofitable.

When observing the time dimension and activation, the example above would imply DR-resources to be active for about 80 hours per year. Divided by the peak demand duration and the average response volume, a typical industrial DR-resource would be activated 10 times a year. According to the interview series with the energy intensive industry in Sweden that was a part of this master thesis, such a response frequency would be acceptable to the industry.

Given the economic potential estimated above, it is likely that new industries and even other sectors will be interested in increasing the flexibility and thereby adding further DR-potential. Especially processes such as ventilation, heating and pumping are transferable in the time dimension and hence subject to load shifting. In a recent study, Gils (2014) estimated the average available DR-potential in Sweden to be about 3,000 MW. The study makes an important distinction between average DR-potential (over time), and maximum DR-potential in case of an extreme event. Whilst the industrial sector has the largest average DR-potential also in the future, huge maximum potentials are to be found in the residential (~2,000 MW) and commercial (~1,000 MW) sectors. If automated control system were to connect, regulate and aggregate these often small individual loads, the DR-potential would be far greater and able to reduce the system cost even more.

A further remark is that all demand is flexible in one sense; if prices are high enough market agents will either find a substitution for electricity or cut their use entirely. If there is money to be made, industrial DR will occur regardless of market design. The question is not whether the demand will be responsive but whether the response is acceptable for the society. Moreover, the interview series has indicated that although many people talk about DR, few actually want it. Many industries want to be able to plan their production in advance and optimize it after other parameters than the price of electricity. If other options arise, such as an economic large scale storage technology, this would probably be preferred.
9.2 CLOSING THE KNOWLEDGE GAPS

This section concisely addresses the knowledge gaps identified in section 4.6 with a starting point in the results of this master thesis. Also, recommendations and directions for further research are given with regard to the findings of this master thesis.

The purpose of this thesis was to contribute to the general understanding of industrial DR in the future Swedish energy market. This is partly done below through addressing the, in previous studies, identified knowledge gaps. A full discussion of the individual knowledge gaps are to find in section 4.6. These knowledge gaps will be presented as a bullet points below and subsequently addressed by the relevant findings of this master thesis.

- Which market design and business models for DR will be used?

An energy-only market, or more specifically a Real Time Pricing model, is the most feasible market design for the future Swedish electricity market. Other possible options would be a Strategic Reserves can offer SoS but limited DR-potential, a Capacity Market that triggers large DR-potentials but at higher cost levels or a Direct Control-program with advantageous properties in terms of respond time but would be struggling with economic profitability and weak support among market participants. The typology of DR-programs, Figure 41 on page 104, and in particular the feasibility parameter of the same, addresses this question directly. In particular, the contribution of this report has been to put the different market designs in a Swedish context and to translate the results to the base case scenario. Thereby, the understanding of what a nuclear phase-out would imply for the power balance and the future market design has increased.

- What potential economic savings can be achieved through DR?

The economical savings that can be achieved through industrial DR amount to 350 MSEK per year, given a system perspective. The savings constitute of reduced over capacity. The full business case can be examined in section 9.1 above. For individual market participants however, the potential savings can be substantially larger. The greatest economic potential are to be found within the electricity intensive industry as efficient DR can reduce the average cost of electricity, and for the TSO which carries the balancing responsibility of the power grid. The savings calculated in this report only include industrial DR-resources. Previous studies have indicated that the total DR-volume is yet greater. Therefore, the above estimated saving is to be regarded as a conservative assessment.

- What is the future potential of Demand Response?

The future potential of industrial DR, for 4 h response duration, is estimated between 2,000-2,500 MW, given the base case scenario and a spot price at 2,000 SEK/MW. However, the actual potential depends on many factors such as price level and duration time. Hence the question is best answered by Figure 42 on page 109 and the thereafter following discussion. This thesis has only estimated future industrial DR-potential. Previous works have estimated the total future DR-potential between 3,000 and 5,000 MW. When studying previous work, it become evident that the existing industrial DR-potential has been examined by many studies, as have the future DR potential. However, to assess the future industrial DR-potential is a more unique contribution of this report to the general knowledge base.

- What are the advantages and disadvantages of DR as a capacity mechanism?

DR has many advantages as a capacity mechanism. Firstly, DR can reduce the system costs. The investment costs are low since the infrastructure is available. To realize the potential however, new business models for aggregation and beneficial market designs are needed. Secondly, it is a
more environmentally friendly to shift production than to satisfy peak demand with gas turbines. However the analysis of this study also identifies some weaknesses of DR. E.g. the availability factor is low and the response duration time is short. Hence, DR-resources cannot be compared with capacity production resources on a larger scale. Another significant disadvantage is the lacking desire for DR. Many market participants are aware of the possible advantages of DR but few actually want it according to the interview series. The reason for this differ between market agents; utilities typically want to sell as much electricity as possible and the electricity intensive industry would rather optimize its production after other parameters than the electricity price which they would prefer to stay low and stable. Today the cost of imbalances are distributed via the grid fees on all consumers and individual electricity users do not need to consider all cost associated with their consumption.

- What parameters drive customer flexibility?

Increased customer flexibility is driven by mainly three parameters. Firstly, technological development allows cost efficient control and aggregation of micro loads and enables implementation of technology intensive DR-programs. Secondly, education and information gives private agents the knowledge and opportunity to participate in DR-programs. Thirdly, financial incentives, such as electricity price fluctuations and governmental subsidies, initiates investment in load flexibility and energy efficiency.

**FUTURE RESEARCH**

Despite the many reports published on DR, much remain uncertain and this master thesis only contributed to closing minor parts of a few knowledge gaps. Hence, further research is needed. For example, one interesting task would be to ascribe DR-resources an availability factor similar to the convention for generation sources. To examine how this could be done, and what the availability factor for DR-resources is, would be a purposeful starting point for future research. To analyse the DR-potential for even longer response periods than 12 hours would be another interesting area of research that requires further attention. Also, as this report suggest a *Real-Time-Pricing* model to be the most feasible DR-program for the future Swedish electricity market from an industrial DR-perspective, more research on how such a policy would affect nearby areas such as the electricity price, the SoS etc. is needed in order to provide future policy makers and investors with a broader decision base. A final remark is that the results of this thesis are largely based on the assumptions made in the base case scenario. To elaborate on the results, further calibration of future scenarios are needed to be performed, by SEA and SvK but also other market participants.

**9.3 CONCLUSIONS**

*This final section formulates the conclusions of this thesis.*

Planning and operating an electrical power system is challenging since production must equal demand at all times. In a future electricity system, in which wind power and other RES have replaced the existing fleet of nuclear power plants, imbalances may arise due to the intermittent production. Industrial DR is a flexibility option which can be part of a patchwork solution to handle this problem.

Through load shifting and load shedding, industries can contribute to the power balance during peak hours. The existing industrial DR-potential in Sweden is estimated between 600 - 900 MW. The largest potentials today are found within the pulp and metal industries. To exhaust the existing potential, following measures SEA and SvK should consider regulatory measures, financial incentives as well as information and education. In the long term, the single most decisive factor for the extent of future DR-potential is the choice of market design.
From a DR-perspective, *Real Time Pricing* is a feasible market design that offers large DR-potentials at low cost levels. It is questionable whether a price-based solution can shoulder the balance responsibility already by 2020 when SvK have announced a phase-out of the existing the *Strategic Reserve*. One option would be to continue with a SR based exclusively on DR-resources. Other possible options would be a *Capacity Market*, which also has potential to satisfy the requirements in terms of SoS but at a higher system cost.

Apart from the choice of market design, the key factors influencing the future industrial DR-potential are the technological development and the financial incentives. Assuming the base case scenario of this master thesis, the future industrial DR-potential is estimated between 2,000 – 2,500 MW. There are strong indications that even larger potentials will be available in the residential sector when aggregation of smaller loads is regulatory allowed and economically profitable.

In practice, the industrial DR-potential can replace peak generation capacity in terms of gas turbines. Hence, industrial DR is a tool which can help to lower the cost of, and increase the SoS in, the power system as part of a patchwork solution. However, DR is not to be regarded as capacity since the availability is very limited and the opportunity cost of waived electricity consumption is high. In addition, the review of previous work on DR indicates that industrial DR will probably be outcompeted by other flexibility options, including residential- and commercial DR as they have lower opportunity costs for load shedding. A further development of the smart-grid, allowing aggregation of processes such as ventilation and heating, would accelerate this trend.

In a future electricity system with more volatile electricity prices, as could be a consequence of a high share of RES, large economic and environmental benefits are connected to demand side flexibility. Consequently, government authorities make wise to improve the regulatory framework in order to give private market participants the stable business environment that is needed to incentivize long term investments. In addition, energy intensive industry should work on improving the flexibility of their processes because DR also implies an efficient handling of periodic surpluses of cheap electricity.
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This initial section gives an overview over technical aspects of electricity generation and distribution. It puts electricity into an energy context, introduces various concepts for generating and storing electricity and provides the reader with important definitions and units of quantities.

Energy is all around us. According to the first law of thermodynamics energy can never be destructed, instead it is repeatedly transformed between other types of energy, for example kinetic-, potential- or chemically bound energy. Energy is a force that, when canalizes properly, can help us perform useful wok. To canalize energy we use different energy carrier; different resources that can be produced, transported or transmitted and finally power an engine of a process of some sort at preferred location. Oil is one major energy carrier globally, electricity another.

Electricity, or more correctly an electric current, is an electric charge that results in moving electrons. Notably is that the flow of positive charge is defined in the opposite direction of the movements of electrons. This current has several implications. Most notably it creates heat as the electrons are moving through a material. Moreover, the current creates a magnetic field. It is the magnetic field that enables the use of electric generators and motors.

It is custom to distinguish between direct current and alternating current. In the latter, the direction in which the electrons are moving is periodically reversed. The electric power that is used in industries and buildings are almost exclusively alternating current.

Another important term is voltage, or electrical power difference. Voltage is the difference in electric potential of the unit electrical charge that is transported in the circuit and is measured in volts.

Production of Electricity

A better word that production would be generation of electricity, since one form of energy is seized from another source of primary energy. There are numerous ways of generating electricity including electrochemistry, piezoelectricity as well as the thermoelectric and photoelectric effects. However, the by far most commonly used principle is that of electromagnetic induction where a generator or dynamo transfers kinetic energy into electricity. The method is based on Faraday’s law and ultimately the connection between magnetism and electric current. The generator is a device that converts a mechanical movement, by moving a magnet through a coil, to a flow of electric current that is subsequently forced to an external circuit.

Any source of kinetic energy may power the generation process. Either it could be flow sources such as wind or water that wheel the turbine, or the flow may be powered by a therefore intended flow of gas or water vapour heated in coal, gas or nuclear plants.

Usage of Electricity

Electricity is a very useful and highly flexible energy resource. Only for the current to flow through different materials could be sufficient to create heat or light. Nevertheless, the transformation from electricity to mechanical work by an electric motor is the most commonly usage of electric current. In principle, an electric motor is the very invers of a generator; letting an electric current flow through a coil that creates an ever shifting electromagnetic field that causes a movement of a magnet and thereby generates a movement that could be used to perform various types of work.
TRANSMISSION OF ELECTRICITY

Electrical conductors are material that allows flow of electrical charge. Through a wire consisting out of an electrical conductor with isolation, it’s possible to transport electricity along its length. The electric-power transmission grid is a network of such transmission lines. During transportation, the electricity suffers some losses of charge that depends of the distance as well as the voltage. Higher voltage entails lower losses. For this reason, the national transmission grid, the backbone of SvK, operates at 400 kV respectively 220 kV. The equipment that uses the electricity to perform work requires a significantly lower voltage. For this reason the transmission system also includes transformers which interconnects the different levels of the power grid while at the same time adjusts the voltage. A schematic representation of the described process is provided by Figure 44 below.

STORAGE OF ELECTRICITY

Energy storage is conceptually accomplished by a physical media or a technical device that has the ability to transfer the useful process of performance in the time dimension. Such storage can also be called accumulator since the electrical charge is accumulated over time.

Electricity, unlike other common energy resources including oil or come, must be simultaneously used as its being produced or immediately converted into another form of energy that can be accumulated. Because of the huge economic potential this field of research had been assigned great resources over the last decades and some options to store electricity are actually available.

One long-standing method is the pumped-storage hydroelectricity where electricity, in times of abundance, is used to accumulate potential power by pumping water to increase the reservoirs in hydro plants. The technique has been criticized for low efficiency but in over supply situations, any storage is considered better than no storage. A more serious limitation is the dependence on disposable hydropower, as large and important regions on the world lacks the geographical conditions needed.

The battery was another early solution for storing electricity. A battery is a circuit with limited electric charge that offers a flexible use, however the cost is very high relative the capacity.

There have been made extensive research on the topic of chemical storage that is to bind the energy in chemical compounds and to generate electricity when those compounds are dissolved.
thorough combustion or other means. The most famous example is hydro storage where the exothermic reaction between hydrogen and oxygen forms water as well as a surplus of energy. Hydrogen has many disadvantages that are yet to be solved. Firstly it’s not a stable and hence not exploitable from the nature but must be produced and this process is energy intensive. Moreover, hydrogen is an explosive gas that poses a public security risk.

Another widespread storage options are thermal storage, where electricity is used to heat a medium, i.e. water or oil, when demand is low and that this medium subsequently used to heat industrial or residential buildings instead of electricity when demand peaks. This is useful way of capitalize from otherwise spilled energy but it’s no way off actually transferring physical electricity in time.

Over and above the storage methods mentioned above there are plenty of less well known techniques and pilot experiments being performed globally. Examples on this being superconducting magnetic coils, flywheel storage and compressed air storage. Still, there is no method of storing electricity in a quantity the system would require at a cost its users could afford.

**BALANCE IN THE TRANSMISSION GRID**

As described above, there is no large-scale, cost-efficient way of storing electricity and hence no substantial buffer in the transmission grid. Therefore the electricity system, as illustrated in Figure 45, needs to be in balance at each given time which implies that generated electricity must with certain margin match used electricity.

From a technical perspective the system is always in balance, the question is at what frequency the equilibrium arises. The Nordic power system is designed to operate at a frequency of 50.00 Hz ± 0.10 Hz. Any change in at either side of the balance equation effects the frequency; over supply increases the energy intensity of the system and thereby the frequency whereas a shortage in supply during peak demand results in lower frequencies.

The electronic devices that are used in our society are designed for a specific voltage and hence frequency in the transmission grid, in the case of the Nordics 50 Hz. If the frequency is too low, the light from the lamps may die away and the electrical engines might fail to empower the process it supposed to whereas a too high frequency vice versa could endanger the stability and life time of the connected equipment.
**THE ELECTRICITY MARKET**

The electricity market is complex and many agents are involved in the system, producers and end-users of course but also grid owners at various levels, government authorities, energy trading companies, transmission system operators (TSO) just to mention a few crucial importance. The market represents, as most markets does, two main flows. A flow of goods, in this case electricity, is continuously transferred from producers via system operators and local distributors to the end customer and in tandem a flow of money is heading in the opposite direction, through the hands of electricity traders and aggregators.

**MARKET LEVELS**

There are different conceptual levels of the electricity market. It is not only the amount of electricity that is transferred to and used by the customer during the operational hour that is subject for trade, but the market has a time dimension to it. Moreover, the capacity to deliver power has also a value. Figure 46 below shows a simplified model which distinguish the different market according to the parameters time and the good traded.

**SPOT MARKET**

The spot market is one where the different bids from electricity producers and consumers are put forward and matched. The traded good is electricity and the parameters are volume and price. A producer typically offer lower quantities at low price levels but has the ability to increase the generation at higher price levels. This is much depending on the technology portfolio of the individual producer. The aggregated information from all producers forms the supply curve. Likewise, all electricity consumers are announcing how much they want to by depending on the price. Normally consumers want to use more electricity if prices are low but this depends on the price elasticity of the individual customer. Some household or industries have but small possibilities of substitution and will by the electricity which ever spot price. All information from the users is included in the aggregated demand curve. The quantity where the two curves intersect defines the market volume. The highest accepted bid will determine the spot price for the following day; a price that all accepted customers on the spot market will have to pay. The trading closes normally one day before time of delivery, which is why the spot market is also called day-ahead market.
INTRA-DAY MARKET

The intra-day market reminds a lot of the Spot market. Electricity volumes are traded between producers and consumer of electricity, the main difference is the shorter time horizon. Another difference is that producers and users are able to trade internally. This typically occurs if for example an industry, which has bought a certain amount of electricity on the spot market but are now experience technical problems on the production site with no chance of consuming it, wants to sell their share to another user who might need it. Another example is an electricity producer who has sold a fix amount of future generation but may not fulfil his commitments, perhaps due to weather conditions or other reasons, and need to buy generation from another producer to compensate. The intra-day market normally opens after the closure of the Spot market and closes about one hour before time of delivery, at which point the accepted volumes are becoming financially binding for producers and users alike.

CAPACITY MARKET

A Capacity Market is a market on which the capacity to generate power is the traded good rather than the generated electricity itself. This market does not exist in all system. The Nordic system for example has historically been an energy system and no power system. However, since the electricity generation is becoming increasingly intermittent due to RES, many European countries are having, or plans to implement, different types of Capacity Markets so secure the long term security of supply for their systems. In short, governmental subsidies on energy sources with low variable generation costs combined with a RES-friendly regulatory framework has dumped the electricity prices in large parts of Europe. This has made parts of the base load generation unprofitable and threatens to force fully operational plants to a pre mature closure. Such a development would adventure the security of supply on the long term, as base load and regulating capacity is needed when there is peak in demand or no wind to serve the market. To tackle this problem, many countries has implemented different capacity remuneration mechanisms (CRM) to give incentive for a prolonged operation of existing plants as well as trigger new investments. Figure Y below shows the state of Capacity Markets in the different European countries.

ANCILLARY SERVICES MARKET

During the operational hour, it is important that the frequency in the system is maintained around 50 Hz and that eventual deviations are compensated for. This requirement is met by the Ancillary Services market. FERC, the Federal Energy Regulatory Commission in the US, defines Ancillary Services as follows:

"Those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system”

This includes load following and loss compensation and well as a reactive power and voltage control to secure the energy balance according to the scheduling.

A TSO normally has the responsibility for the Ancillary Services and are by law obliged to provide reserve capacity and emergency generation. However, the TSO can do this either by own means or to procure parts of the capacity and competence from external agents through the operational hour ancillary service market.
APPENDIX II - ENERGY MARKET OUTLOOK

Appendix 2 gives the background to the Base Scenario presented in section 3.4. The underlying factors for the energy market outlook are listed and analysed separately. Thereafter, some different possible scenarios are presented and the Base Scenario highlighted.

Energy market forecasting is as difficult as it is important. Major agents such as government authorities, electricity producers, heavy industry and customer with smaller consumption alike depend on forecasting of i.e. prices on energy and availability of electricity and other energy resources in their planning. In this master thesis, the aim of the forecast is to provide a very specific market scenario, a problem context in which different solutions can be discussed and applied. For a theoretical representation of such market, following data is needed:

- **A demand curve**
  *Giving information about the demand structure in terms of Volume, Price, Time of Use*

- **A supply curve**
  *Representing all generation capacity, price and availability of supply*

- **A regulatory framework**
  *Geographical, regulatory and market specific delimitations that provides a framework for the market*

There are uncountable factors that affects the future electricity demand, generation capacity and market design that ultimately forms the complex system of a future electricity market. The most influential factors are presented in Figure 47 below.

![Figure 47 - Factors which influences future demand and price of electricity](image)

All listed parameter are themselves highly complex aggregates which are difficult to forecast. Moreover, they are all interconnected and depend on underlying assumptions about the surrounding world. This is why the market outlooks vary between different institutes and organizations. To compare and evaluate a greater number of forecasts would be an interesting work on its own merits, however not the focus of this master thesis. All following research and discussion are based on the scenarios presented by SEA in its report Roadmap to 2050.
DIFFERENT SCENARIOS

The Swedish parliament has set a zero target on national net emission of greenhouse gases year 2050. Consequently, the Swedish government has given SEA the assignment to compose a roadmap that marks out a pathway through which the ambitious goal can be achieved. While performing the task, SEA mapped the four possible scenarios in their report. Basically, all the presented scenarios share the following assumptions.

- Political direction
- Population development
- Technical advances and inventions

The variable parameters that tensions up the different scenarios are:

- Electricity consumption
- Level of internalization and globalization
- Price development on natural resources

The different scenarios are presented in a summarized version on page Y, after which a base scenario is chosen and described. Below follows a discussion regarding the nature of each parameter as well as its projected impact on the forecast.

POLITICAL DIRECTION

The policies of governments and international organizations such as EU or UN have a major impact on the development on any market. Especially so on markets which are sensitive in terms of national security and long term economic prosperity which is the case of the energy market. There are many thinkable agendas that can be set by a regulating authority, i.e. environmental care to prevent pollution or reduce the effects of global warming, low system costs to boost the domestic economy or a high level of energy independence to secure national interests etc. Having chosen a path, or a more accurate a certain mixture of different interests and manoeuvre directions, there is still many ways to obtain the target and uncountable tools to use. Example of such tools are legislative steering, incentive based programs as well as informative and educating programs. Stated below is a set of regulations that SEA assumes will prevail during the considered time horizon.

- Sweden shall be a carbon emission free economy, which includes the energy system, in year 2050. The ambition to reduce emission is considered to be a given course of action, regardless of the development of the economy or the surrounding world.
- EU-ETS. The system for trade with emission allowances continues and operates on a European level. It is considered to be the most important control mechanism operating in the time horizon studied.
- Other areas under government influence that have been taken into consideration are waste treatment, water reserve management, and transportation and radiation protection.
- National tax on energy and CO₂. In Sweden, the energy tax is based on the energy content of the resource that currently amounts to 80 SEK/MWh for energy generally and 290 SEK/MWh for electricity more specifically. On top of that is the CO₂ tax that correlates with the emissions, 1,080 SEK/TCO₂. An important remark is that all energy and CO₂ taxis are paid by the end user; the production of electricity has full tax relief.

In a final step of this forecasting process, a further constraint is added to the political direction with regard to the purpose of this thesis; no new investments in nuclear power will be
conducted. SEA does no such assumption but rather a parallel simulation of two sensitivity cases, one scenario with new nuclear and another without. In this report, the phase out of Swedish nuclear is considered a fix constant.

**POPULATION DEVELOPMENT**

The population affects the structure of the electricity demand through multiple areas of influence. Most importantly, a growing population puts an upward pressure on the long term accumulated demand, as more people needs heating, transportation etc. Moreover, the structure of the population, i.e. demographics, ethics and similar characteristics that influences the life style and pattern of habits also affects the demand structure and hence the electricity market. In this case, the composition and growth of the Swedish population is based on data from SCB and remain a constant throughout all the presented scenarios.

In Figure 48 below, data from SCB are illustrated. A constantly positive growth rate is predicted over the time horizon, mainly as a consequence of high expected birth rates in the 2010s and extensive immigration.

![Figure 48](image)

**TECHNICAL ADVANCES AND NEW INVENTIONS**

The technical aspect has huge influence on the electricity system as it ultimately is a physical system that consists of uncountable mechanical and electrical components. The technical development influences the system through all its levels; production through new sources of electricity generation and increased efficiency in existing plants, consumption through ever more efficient electrical devices and possibly also in transmission and storing.

Investment in new electricity generation methods has been steering over the last decade and there are many concepts under development. Some research regards existing technology, that is to increase the efficiency in generation (all resources) or improve other aspects such as reduced emissions (fossil fuels), improved security (nuclear power), durable reliability (wind power) or reduce cost (Solar power). Other program supports the development of energy generation systems that have yet to be established on the market including wave power, fission power and a vast spectrum of new concepts which can be encapsulated by solar energy. Several projects are in the pipeline. However history has proven that new technology needs time to adopt and develop before reaching required efficiency and security of supply, often several decades. Moreover, to build or restructure the energy system is capital intensive, practically challenging and ultimately a political decision. All together it seems unlikely that any critical technology leaps will have occurred before the first nuclear reactors in Sweden are mantled down in the late 2020s.
In all fields of industry continuous improvement is pursued. In the case of energy efficiency the trend has had an even greater impact the last decade due to high prices on electricity and other energy resources as well as environmental concern. The European Union for example has declared a targeted 20% improved energy efficiency to 2020 compared to 1990. EU uses an Energy efficiency index (ODEX) to measure and analyse the improvements made. Simplified, ODEX is a weighted average that includes 10 different manufacturing branches and measures the specific consumption per unit work performed. In Figure 49 below, the development for the most energy intensive branches are illustrated. From the data, a general trend corresponding to 1.4% improved efficiency per year can be deduced. In mapping the scenarios, there is reason to assume that this trend will prevail.

![Energy Efficiency Trends](image)

In the field of transmission, pilot projects involving superconductors are being launched. Moreover, heavy investments in R&D for storage technologies for electricity are made by government agencies and the private sector alike. One visionary concept that is commonly discussed is the E-mobility, where the aggregated battery capacity of a predominantly electrically based vehicle fleet serves as mid-term electricity storage for the entire system.

Despite all the possibilities however, SEA chooses a conservative approach. Continuous improvements in energy efficiency is accepted and implemented, both on the supply and the demand side, but no new technologies are introduces. The projected energy mix in 2050 consists of the same principle technologies as does the generation today. Admittedly technology leaps do occur irregularly but they are difficult to predict and even more difficult to model. Another reason for not taking major technology shifts into consideration is its, theoretically, strictly positive effect on the future system. If an invention is advantageous from a holistic point of view, regarding for instance economic, environmental and practical aspects, it will be implemented. Hence, a roadmap that reaches the emission target without wishful assumptions about the technological development will not risk to be overthrown by unforeseen advances and inventions but rather be supported by them.

**ELECTRICITY CONSUMPTION**

The amount of electricity needed in the system is a vital parameter for the energy outlook. A high demand is traditionally correlated with high prices as the buyers compete about the resource. Furthermore, a high electricity consumption also has a direct correlation to how much generation capacity that is required and hence indirectly on the generation sources used. Since
the mixture of electricity generating sources sums up to a supply curve, the consumption rate of electricity affects the price level from the supply side as well.

Historically, electricity consumption in industrial countries has been relatively constant throughout the last decades. A historical comparison between electricity consumption, energy usage and GDP in Sweden is given in figure Y below. As shown in the graph, a distinctive breakpoint in the long term trend occurs in the mid-80s. Until then, the electricity consumption and GDP-growth was highly correlated. Since the late 80s, the electricity consumption has remained on constant levels whereas the GDP has continued to rise. Also with regard to total energy consumption, GDP-growth has freed itself from strong correlation. In fields of economic and environmental science, this phenomenon is called decoupling. The American energy agency predicts in a forecast a continued but weakened correlation between energy usage and GDP-growth. In the time period between 2014 and 2040 AEI estimates an average GDP growth of 2.4% whereas the energy use is predicted to grow with only 0.9% yearly.

An analysis of historical electricity consumption is not sufficient to forecast the future consumption. It is also necessary to understand the driving forces behind the development. In general terms, there are two independent mega trends that affect the total future electricity consumption, electrification and efficiency improvements. Any prediction or conclusion about the future amount of consumed electricity needs to weight the impact of both trends in respect to the other.

Electrification implies that more processes uses electricity as primal energy source. There are different levels of electrification. The most primitive is using electricity to perform work that was previously performed manually or not at all. Examples on this would be using blender to produce fresh juice to breakfast instead of squeezing the oranges by hand. Although the blender operates on very low power, the aggregated power demand from all small devices adds up to a significant load from a system perspective and the long term trend is indicating a continuous increase in electrical devices.

Another more sophisticated level of electrification, that has far greater impact on the total amount of electricity used, is the change of primary energy resource as input in energy intensive processes such as heating and transportation. A historical example from the Swedish market was the shift from firing oil to electricity as the predominant energy resource in domestic household heating after the oil crisis in the late 70s.

A related example is the impending transformation of the transportation sector, where electrical vehicles are proposed to replace or complement the petrol driven combustion engines that dominates the market of today. Below, figure Y shows the amount of electricity used today as proportion of our total energy usage. While observing the share of fossil fuels it’s clear what potential increase in electricity consumption a change of energy resource in the areas of transportation and heating could lead to.

In contrast to the potential increase of electricity consumption that is the result of the electrification process, another mega trend, energy efficiency, provides a counterweight. In Error! Reference source not found.9 above, the efficiency in industry was illustrated and the trend is global, covering all sector and devices. The energy efficiency of all devices, from laptops and cell phones to electrical vehicles or heat pumps are continuously improved. One example is the energy consumption of refrigerators which has continuously decreased for over 40 years while performing at equal or higher standards. Table 28 below shows the annual energy use of a new refrigerator over the last half century.
TABLE 28 - ELECTRICITY CONSUMPTION FOR A NEW REFRIGERATOR

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh/year</td>
<td>1800</td>
<td>1300</td>
<td>900</td>
<td>550</td>
<td>350</td>
</tr>
</tbody>
</table>

Energy efficiency is a trend with several driving forces, including economic incentives and political will. If the energy consumption is reduced, so is the energy bill which is beneficial for consumers. Therefore producing companies needs to work on energy efficiency to meet the customers’ needs and specifications. The political aspect is also of vital importance. To battle global warming governments needs to cut down on emissions. However, as employment rates and GDP growth to a high extent relies on the energy intensive industry, authorities hesitates to take decision that would have negative influence of the economy of the sector. Instead society is hoping, through increased energy efficiency, to reach ambitious environmental commitments while at the same time remain competitive and productive.

Given the strong incentives for energy efficiency, the trend is predicted to prevail through the time horizon of this report. An American study shows an accelerated trend in energy efficiency to 2040, see figure Y below. The most significant improvements are expected to be in the field of e-mobility. The reason for this being manly product cycle related; since electrical vehicles being relatively new in larger volumes, technology has yet to adopt and develop fully.

LEVEL OF INTERNALIZATION AND GLOBALIZATION

The structure of the surrounding world, and the state of its economy, has huge impact on the national energy system for any country, Sweden included. This for mainly two reasons, firstly the structure of the surrounding world comprises a context in which the system is to be optimized and secondly the open market forces a system to be optimized globally if the infrastructure is available.

In a globalized world, more political and legislative power is transferred to supranational authorities and international organization such as EU and UN. In this case, the market will be harmonized, policies integrated and investments coordinated. In theory, such a market would be exposed to fewer constraints and have reduced risk of sub-optimization which would lead to lower total system costs and thereby lower price on electricity. Also, a global world would imply a general international commitment among the big industrial countries regarding environmental care and climate targets as well as increased cooperate social responsibility.

The opposite of a globalized world would be the national focus, in which each country operated individually to optimize, in this case, its energy system. However, a scenario build upon self-sufficient countries is highly unlikely with regard to the strong position that supranational organization possesses already today. With this reservation, the possible option to a fully globalized in the future is that of a fragmentized world in which different groups of individual nations are operating as units seeking consensus internally but without global convergence.

The base case in a fragmentized world would be a scenario in which the European Union strives against zero emission whilst other major economies don’t. This means a higher energy prices as a less strict taxation and regulation on energy resources globally will lead to increased demand and an upward price pressure whilst CO₂-taxes and energy taxes remains high in Europe.

The effects of the free market also depend on the surrounding world. Since nations and companies are allowed to trade freely with each other, regional price differences on any commodity are in theory bound to decrease over time. For example, if electricity prices are higher in a neighbour country there is a possible arbitrage in exporting electricity, provided
sufficient transferring capacity is available. In a global world such an international network would be priorities and hence reduce the regional price fluctuation whilst at the same time adding a new dimension to the planning of future energy system: the international perspective. All generation capacity and distribution infrastructure would need to be designed to fit the requirements of a whole region, as the system boundaries long has outreach that of the individual nation.

In a fragmentized world, other phenomena arise. While the regional price differences remains, industry might threaten to relocate its production sites to whatever location that is more beneficial. Also in this case, nations need to be observant on the development in its surrounding world to remain competitive in electricity prices and infrastructure.

The scenario based on a fragmentized world assumes a European Union that remains functional but struggles with its integration. The countries of Europe shares common goals when it comes to energy independence and climate targets, but the implemented programs to reach them varies greatly between countries and regions. One example is the issue of capacity remuneration mechanisms in the European Union. Almost all European countries share the problem of impending closure of system supporting power plants due to low electricity prices and lacking incentives for capacity providers. To battle the problem many countries has implemented CRM (capacity remuneration mechanisms), but only regional or national which have resulted in a patchwork of policies and markets. Such fragmental system creates uncertainties as well as complicates international trade which altogether leads to higher system cost and ultimately higher electricity prices.

To summarize, in theory a globalized world stimulates the economy while maintaining low energy prices whereas a fragmented world represents a sub-optimized scenario where a stagnated economy also have to struggle with higher electricity prices.

**PRICE DEVELOPMENT ON NATURAL RESOURCES**

Natural resources include in this case fossil fuels, i.e. oil, coal and gas, uranium, biomass etc. Extraction and distribution of natural resources are often exposed for macro risks such as political instability, war which makes the availability and price level difficult to forecast. Moreover, a major technology leap can make a natural resource redundant and thereby nullifying its influence on energy pricing. Therefore the price forecast below is manly to be seen as a context in which electricity pricing process operates.

Historically the price on electricity correlates closely to the price on natural resources. For example showed a study performed by McKenzie & Co 2010 estimates the correlation between prices on oil and electricity was 80 %. Later research as questioned this number but there is little doubt that a correlation exists. The principle is the economics of substitution. If a process in theory could be empowered by either electricity or fossil fuels, the market wouldn’t allow big price gaps between the different energy resources as such would trigger a natural reaction in the opposite direction. For example a high oil price would force consumers to change to electricity, causing a change in aggregated demand that puts an upward pressure on the electricity price while the pressure on the oil market relaxes which results in new equilibriums on both markets.

**COMPILATION OF VARIOUS SCENARIOS**

As a synthesis of the parameters listed and described above, four scenarios for Sweden have been created based on the axis globalization and energy use. In other words, ceteris paribus, the extremes we face are the combinations between high/low energy use and
globalized/fragmentized world. These scenarios, together with the major implications of each such, are described in Table 29 below.

<table>
<thead>
<tr>
<th>Fragmented world</th>
<th>Low electricity consumption</th>
<th>High electricity consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>- High electricity prices</td>
<td>- Less Fossil Fuels</td>
</tr>
<tr>
<td></td>
<td>- Wind power investments</td>
<td>- Very high electricity prices</td>
</tr>
<tr>
<td></td>
<td>- High price on CO₂</td>
<td>- Increased generation capacity</td>
</tr>
<tr>
<td></td>
<td>- Less district heating</td>
<td>- Heavy investment in RES</td>
</tr>
<tr>
<td>Globalized world</td>
<td>Scenario 3</td>
<td>Scenario 4</td>
</tr>
<tr>
<td></td>
<td>- Low prices on Fossil fuels</td>
<td>- Low electricity price</td>
</tr>
<tr>
<td></td>
<td>- Low electricity price</td>
<td>- Small capacity investments</td>
</tr>
<tr>
<td></td>
<td>- No investments in new capacity</td>
<td>- Some wind power</td>
</tr>
<tr>
<td></td>
<td>- Import is of crucial importance</td>
<td>- Gas (CCS) technology</td>
</tr>
<tr>
<td></td>
<td>- Potential need for DSM</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 29 - DIFFERENT FUTURE ELECTRICITY SCENARIOS

SEA does no further analysis regarding the probability or desirability regarding the different scenarios. Instead they provide a multidimensional analysis with four different cases as base for their conclusion. However, with regard to the purpose of this master thesis, Scenario 2 is considered sufficient to study. This is simply because a scenario containing a fragmentized world combined with high electricity usage is a most challenging one harbouring high electricity prices and large proportion of RES resulting in large fluctuations in generation and price. In such a scenario, the difficulties with a potential nuclear phase-out become evident. From an academics point of view such a scenario is beneficial because solution that has the potential of handling on a worst case scenario would per se have the capability to deal with any other outcome.

In the next section, scenario 2 will be described more closely under the label Base Scenario since it, from now on, will form the basis for all further discussion and analysis.
APPENDIX III – INTERVIEW TEMPLATE

PRE-INTERVIEW PM

Before the Interview, each respondent received following information:

**Background:** The electricity supply may in the future come to fluctuate greatly due to the increased share of RES in the system. In a scenario where the nuclear power is gradually phased out, this could lead to volatile electricity prices. To keep the electricity price low and guarantee the security of supply, it is important that find cost-efficient solutions on how to handle peak demand. This could be done either by reserve capacity on the supply side or through temporary reductions in consumption, DR (Demand Response) at such occasions.

**Purpose:** The purpose of this interview series is to examine what potential future DR has in Sweden as well as the cost for realizing this potential. Moreover, the study is interested in reasoning about market design; how different market agents would like the DR to work in practice.

**Areas of questions:** Below follows some overall questions that I’d like to discuss during the interview. These topics are presented in a more detailed form below as interview questions.

- The current situation; what situation is your company in related to energy questions? Use, flexibility, trends, costs etc.
- Attitude towards DR; how does you company, and presumably your branch, position yourself with regard to DR? Attitudes, discussions, trends etc.
- Future market design; what DR-option would your company prefer?
- Potential for DR; what are your company doing today in terms of load flexibility and what (processes, transportations etc.) could possibly be done in the future?
- Cost of DR; a rough estimation about the cost of earlier mentioned measures based on market price and opportunity cost

Moreover, I am interested in discussing the electricity market in general, how you representing the industry look at the future, e.g. trends in price, consumed volumes, market development.

**Preconditions:** The interview is part of an academic study, a master thesis written in cooperation between Linköping University and Vattenfall AB. The research questions are bases on a hypothetical situation; that of an impending nuclear phase out. No estimates about volumes and prices are in no way official or binding. The answers from individual companies will remain with the author and not be published explicitly. The final report will only present and analyse the aggregated DR potential of the Swedish industry.

Thank you for participating!
INTERVIEW QUESTIONS

- What situation is your company in related to energy questions?
  - Electricity consumption? Please feel free to present some data
  - Power requirement?
  - Electricity contracts?
  - What processes are possible to shift in time or being done so already today?
    - How long? (duration)
    - How large volume? (Power in MW)
    - What are the costs and benefits?

- How do you, and presumably your branch, position yourself with regard to DR?
  - Are your company open-minded about flexible demand as a concept?
  - Is your industry segment open-minded about flexible demand as a concept?
  - What drives flexible demand?
  - Which are the biggest obstacles and hinders for DR?

- How would your company prefer the market for DR to operate in practice? Through a...
  - Capacity Market?
    A system in which market agents who provides capacity are receiving payments for it, as a compliment to the revenues from electricity productions. This system is principally designed to secure capacity on the supply side but it is theoretically possible for large consumers to participate through bidding “negawats”.
    - Strategic Reserve?
      A selection of market agents is offered a fix, yearly payment to provide reserve capacity either in terms of extra supply or in terms of demand reduction. When activated, the participant also receives a variable payment which depends on the quantity produced or shedded. Participation is voluntary but signed contracts are binding. SvK uses a Strategic Reserve today but it is said to be decommissioned to 2020.
    - Price based solution?
      A price based solution is a system in which the price signal is the dominating control mechanism. It requires an energy manager at each company who also has the possibility to influence production planning, logistics etc. The availability of free and instant information is a prerequisite. One example is Real-Time pricing which implies a free market price at an energy only market. Another frequently applied version of a price passed solution is the Time-of-Use model where customers pay different, predetermined rates at different times.
    - Balance power market?
      A Nord Pool market were power is traded rather that energy during the operational hour. A responsible balance officer is needed at each market participant or aggregation of such. These balance officers are offering price dependent demand bids. If the bids are accepted, deliverance is binding.
    - Other options?
• Potential and cost for DR; what is technically possible in the future?
  o What processes would be possible to shift in the time dimension?
    ▪ 1 hour?
    ▪ 1 day?
    ▪ 1 week?
  o What would the estimated cost be for each mentioned DR-measure?
    ▪ Technical cost?
    ▪ Opportunity cost?
    ▪ Market price?
  o At what price would you consider to shed load?
    ▪ How large proportion of your cost consists of energy expenses?

This last question is best answered by filling in below. Note that it might be possible to restructure the production process to be more flexible if the time horizon is 10 year or even more so at 35 years perspective. The numbers are speculative and will be treated as such.

**TABLE 30 - DEMAND RESPONSE POTENTIAL MATRIX**

<table>
<thead>
<tr>
<th></th>
<th>Load shifting</th>
<th>1h</th>
<th>1 day</th>
<th>1 week</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Example of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>Power (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fix cost (SEK/MWyr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variable cost (SEK/MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td>Example of processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power (MW)</td>
<td></td>
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APPENDIX IV - CAPACITY RESERVES

SvK provides reserves which, by temporary load variations or potential disturbances in the system, can support the power balance in the transmission grid. These reserves function differently and vary both in capacity and activation time. A general distinction can be made between primary adjustment (FCR) and secondary adjustment (FRR), leaving the conventional power balancing market to be a tertiary balance regulating mechanism. The basic difference between the different capacity reserves is the activation time; FCR is almost instantaneous whereas FRR requires a longer activation time. (SvK, 2014)

As previously explained, it is of vital importance that the frequency in the system remains within the given interval around 50 Hz. The FCR is the basic mechanism that compensates for stochastic fluctuations in the production or consumption which must be adjusted for instantaneously. There are two different types of FCR; FCR-N which is operating under normal conditions and FCR-D which is only to support the system at disturbances or extreme conditions.

In Sweden, the FCR-N is mainly based on hydro power plants that are connected to real time sensors that signals deviations in the systems and triggers a response from the power generators to compensate. If the frequency in the grid is to low, the water flow through the turbines is increased and vice versa. The FCR-N operates within the interval between 49.9-50.1 Hz to keep the frequency as close to 50 Hz as possible to reduce the sensitivity of the system. The Nordic TSOs are cooperating when it comes to securing the availability and functionality of a FCR-N. The Nordic FCR-N is prescribed to accumulate at least 600 MW, of which SvK has the responsibility to procure 230 MW. The great majority of the remaining share constitutes of Norwegian hydropower. The FCR-N is traded on a short term basis, typically one or two days ahead of the operational hour.

The FCR-D is, like FCR-N, automatically regulated, hydro power response to frequency deviations. However, its purpose is to compensate for sudden disturbances such as fall out of base production capacity or regional transmission problems. In practice, the FCR-D is partly activated when the frequency in the grid goes below 49.9 Hz and is to operate at full capacity if the frequency is lower or equal to 49.5 Hz. The FCR-D is procured in the same way as FCR-N but the capacity of the reserve varies from week to week depending on the risk profile. On average, FCR-D amounts to 400 MW in Sweden and at least 1,300 MW in the Nordics. (SvK, 2014)

The FRR is a quick, active reserve that can be activated with 15 minutes preparation time. The main idea behind FRR is for it to overtake the responsibilities of an activated FCR-D which then can go back to rest and thereby offering full manœuvrability again. There are two different types of FRR, the FRR-M which is manually activated and the FRR-A which is automated.

The FRR-M is manually activated from the control room at SvK, typically through phone calls. The reserve is secured by long term contracts and SvK has full right to use the capacity when needed. The entire reserve is within the national borders of Sweden and although the capacity varies with the risk profile, its capacity is fairly stable at 1,300 MW. It’s possible though to trade or balance FRR resources in the Nordic region.

FRR-A is a recently founded balancing measure. It was formed in January 2014 to tackle the reduced frequency quality in the Nordic power system. The reserve is still being tested and developed. Its scale is relatively small in comparison to the manually activated FRR-M, amounting to 100 MW in the Nordics out of which about 45 MW are located in Sweden. The purpose of the FRR-A is to reduce the hours during which the frequency in the system drops below 49.9 Hz. (SvK, 2014)