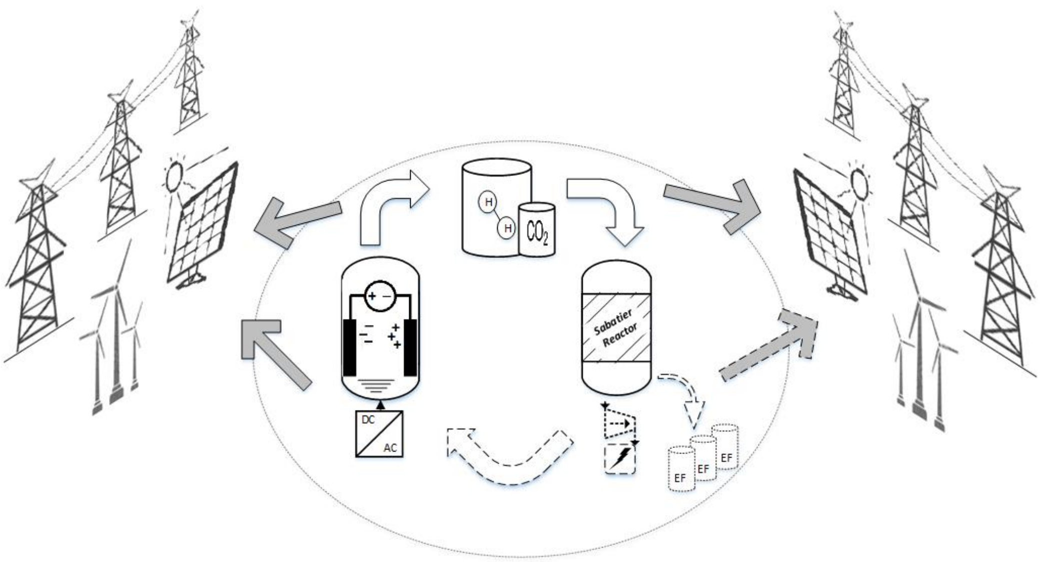
CHALMERS

Electric Power System Ancillary Services of Electrofuel Production

Case Study Sweden



Master's thesis in Sustainable Energy Systems

Haifa Asadian

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

A MASTER OF SCIENCE DEGREE PROJECT

Electric Power System Ancillary Services of Electrofuel Production

Case Study Sweden

Haifa Asadian

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Electric Power System Ancillary Services of Electrofuel Production
Case Study Sweden

Haifa Asadian

Master of Science Thesis
Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Electric Power System Ancillary Services of Electrofuel Production
Case Study Sweden
Haifa Asadian
Department of Energy and Environment
Chalmers University of Technology

Abstract

In the future European energy system, with high penetrations of fluctuating renewable energy generation along with the increased demand for rapid reduction of fossil-based energy and the growing disinclination towards and phase-out of nuclear-based power, the development of reliable technologies, which can cope with the system's rapidly altering profile becomes increasingly important. In this context, the necessary services to support the transmission of energy through the power network is a potential economic market. While electrofuels are a promising alternative to fossil-based fuels, their production process might prove prosperous in terms of addressing the challenges faced by the modern power systems. This project addresses the impact of a large-scale employment of this technology on the composition and operation of Swedish power market, where supply of ancillary services is regarded as a potential source of income. In this context, three services, namely reactive power regulation, congestion release, and reserve services in form of demand-response, have been studied. The possibility of investment in each of the four Swedish marker price areas with regard to these three ancillary services have been examined. The results for all the three services are in favor of investment in electrofuels, and Sweden's Stockholm area (SE3) is found to be the most suitable location for large-scale investments in the technology.

Keywords: Ancillary Services, reactive power, transmission system, electrolyser, electrolyzer, electrofuels, congestion release, mathematical optimisation, power system, power regulating market, Nordpool, imbalance, voltage regulation, reactive power supply

Acknowledgements

Writing this note of thanks is the finishing touch on my thesis. For me, it has been a period of learning at a scientific as well personal level. I would thus like to reflect on the people who have supported and helped me so much throughout this period.
Firstly, I would like to express my sincere gratitude to my thesis advisor and examiner Dr. Jimmy Ehnberg of the division of Electric Power Engineering at Chalmers University of Technology. The door to Dr. Ehnberg's office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.
In addition, I would like to thank Dr. Saeid Haghbin and Researcher Pavan Balram, of the division of Electric Power Engineering, for their valuable guidance. They generously provided me with the theoretical knowledge that I needed to choose the right direction and successfully complete my thesis.
Finally, I must express my very profound gratitude to my one true friend, and life partner, Mahdi, for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without him.

Haifa Asadian
Göteborg, May 10, 2016

List of Symbols

i and k	Set of areas in the system
j	Set of generating units
PD_i	Power demand in area i
$PG_{i,j}$	Active power output of generator j at area i
$CG_{i,j}$	Production cost of generator j at area i
$PS_{i,j}$	Maximum active power capacity of generator j at area i
$NeT_{i,k}$	Net power transfer between area i and area k
$TM_{i,k}$	Maximum transmission capacity between area i and area k
S_{DF}	Size of design flow [kW]
S_{DF_0}	Size of base design flow [kW]
C_{DF}	Construction cost of design flow [EUR]
C_{DF_0}	Construction cost of base design flow [EUR]
n	Empirical scaling factor (assumed to be 0.6)
FV	Future Value
PV	Present Value
r	Discount Rate
y	Number of Years
ΔC_M	Marginal investment cost of rectifier
ΔC_R	Marginal cost of shunt reactor
ΔC_C	Marginal cost of shunt capacitor

C_{Ps}	Investment cost for passive rectifier
C_{Ac}	Investment cost for active rectifier
PB_t	Payback period [years],
$Cost_{cap}$	Installation cost of required up-regulation capacity[MEUR],
Rev_p	Total potential revenues from demand balancing[MEUR].
Cap_{up}	The required up-regulation capacity[MW]
Vol_{up}	total up-regulation volumes [MW]
nH_{im}	Number of hours of imbalance

List of Abbreviations

AS	Ancillary Services
DSM	Demand Side Management
EFP	Electro Fuel Production
GAMS	General Algebraic Modeling System
GHG	Green house gas/es
ISO	Independent System Operator
MATLAB	Matrix Laboratory
PF	Power Factor
SF	Scaling Factor
SvK	Svenska kraftnät
TSO	Transmission System Operator

Contents

Chapter 1

Introduction

The increase in the integration of intermittent renewable energy sources in the energy systems is concomitant with the increase in the requirements for highly flexible technologies to compensate for the fluctuations in power generation.
On the other hand, with the deregulation of electricity market, a process which started in recent decades, new problems have arisen in terms of energy pricing as well as the defined responsibilities for the different players in the network. In this context, the necessary services to support the transmission of energy through the network being a common responsibility becomes also a potential economic market.
Though still in demonstration level, electrofuel production (EFP) is a promising option in a highly-integrated renewable energy system. While it has the potential of producing "closed-carbon-cycle" fuel for transportation sector, the technology could become more profitable with the services it could provide in terms of power grid support.

1.1 Problem Statement

This project aims at studying and evaluating the economical potential of EFP process in supply of support services to the electricity network. EFP process is to be regarded for its role in the network as a controllable load.

1.2 Scope

The project investigates the ancillary services (AS) in the context of the Swedish power system. Three main areas, within the concept of AS, are the focus of this project. These areas are namely voltage regulation[1], congestion release, and reserve service, where EFP in general, and electrolyser in particular, act as a large-scale demand party in the market. The reason behind choosing these three areas lays in the nature of the investigated technology, i.e. electrofuel production. In this study, the main parts of interest, among a whole process of electrofuel production are electrolyser and the immediate steps before and after water electrolysis which are power rectification and hydrogen storage respectively.

Limitations

For the sake of simplicity and avoidance of unnecessary complications, some technical details with regard to different power plants and their operation have been excluded[2]. Among these, are the ramping rates, activation periods, and the hydro-thermal scheduling. These excluded factors could be important because of their impact on the total power system cost which have a direct affect on the calculation of prospected EFP revenues from supply of congestion release service.
The power network of the study have been chosen to be focused on only one country, even though Swedish market is a part of the larger Nordic power market. The reason is the significance of Sweden as a highly potential market for electrofuels in a fossil-free future perspective for the Swedish transportation sector, a target to be achieved by 2030 [1]. Moreover, the massive presence of extensive vehicle manufacturing industry in this country could be yet another motivating factor which might accelerate the investment and employment of EFP technology.
Moreover, it is essential to mention that, due to the several assumptions made and the differences in production and system cost from real life to the model version, the results gained based on the optimization model in 3.2 are based on the "model equivalent" of the real life situation. Hence, the model only resembles the actual Swedish power system to some extent. Covering the whole system requires complicated mathematical modeling and addition of many more factors than only the generation and demand data. Thus major simplifications in terms of transmission limits, and variety of generation type, size, and location have been assumed.

[1] With use of active rectifier

[2] Inclusion of these factors to the power system model might yield more accurate results

Chapter 2

Theoretical Background

2.1 Electricity Market

As is the case for any commodity, electricity is traded via a certain market, where the demand for power is handled in different ways such as through bids to buy or sell and/or long-term or short-term contracts between the supplier and the consumer. Buy-bids and sell-offers along with the capacity of supply and the demand levels are decisive factors in setting the price in an electricity market.

In the Nordic region, Nord Pool is the market where several European countries act in a joint electricity trading exchange. It is the first multinational power exchange in the world and the largest market in Europe. Hundreds of companies from twenty European countries, among which are Norway, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Germany and the UK, trade on Nord Pool [2], [3].

Nord Pool is mainly owned by the Nordic transmission system operators Statnett, Svenska kraftnät (SvK), Fingrid, and Energinet belonging to Norway, Sweden, Finland and Denmark respectively. The Baltic transmission system operators have some small shares as well. While the electricity is mainly traded in Nord Pool, the price of it differs from country to country and region to region due to different locational and technical conditions. These conditions are mainly the type of the energy source, the demand in the area, and the constraints in transmission capacity. However, there is more to an electricity network than only supply, demand and transmission of power. Further measures are required to make the power market efficient and reliable. Hence, the need for "Ancillary Services" which all in all contribute to a significant share of a power systems budget, roughly estimated as ranging between 5 to 25 percent of the total costs of generation and transmission depending on the system's characteristics and requirements [4].

2.2 Ancillary Services

All the generation utilities which participate in an electricity market are obliged to act for ensuring the required degree of quality and safety in the grid. Thus, in addition to power generation, these utilities should undertake other measures in order to fulfill their market obligations. These functions all gather under the general concept of AS. These services are necessary for maintaining the security and quality of power supply and include frequency regulation, system stability maintenance, reserve services, voltage control and reactive power control, black start capability services, and many more. Generation scheduling and dispatch is also considered an ancillary service [3] and [4].

2.2.1 Congestion Management

Congestion in the electricity network is a state where a transmission line or a network node is overloaded and/or the flows of electricity are constrained below the desired levels [5]. The cause of the constraints on the power flow may be the electrical or/and physical capacity of the line. However, the operational decrees intended for the protection of the grid and ensuring its reliability and security might also impose such constraints on the network. That is, if transfer of power from one point to another might be problematic to the security of the grid, or if it violates the reliability requirements of the network. Transmission constraints are thus set, usually by the transmission system operator (TSO), to avoid violations to network security and reliability [6].

However, congestion deteriorates the grid service quality and leads to higher electricity prices for the consumer, and often activation of high-cost generation in the areas where the demand is high and cannot be supplied by cheaper generations in other areas because of transmission constraints. In sever cases, congestion could damage grid reliability and make the affected areas more exposed to unpredicted power outages. In their turn, power outages lead to costly damages to the industry and public services and overall reduce the social welfare.

There are different mitigation solutions to congestion issues, among which are investment in generation utilities in the areas of high demand, development of transmission capacity and reduction of demand in the congested areas. The latest involves prioritizing the demand parties to let only the critical loads be fed during the congestion time, an strategy becoming more favorable with the increasing change of energy systems profile and is typically termed demand side management (DSM). Compared to other mitigation strategies, DSM seems more advantageous with regard to economical as well as environment aspects [6] and [7].

2.2.2 Frequency Control

The balancing of demand and generation is needed on a continual basis. The regulation is needed not only to fulfill the power demand but also to maintain the systems frequency within the acceptable range of 50 +/- 0.01 Hz. Both load and generators can contribute to this service. The important factor is quick response time (within the requirement standards of the market) in terms of generation increase or load reduction. In turn, this action, called primary frequency control, leads to unscheduled flows in the grid causing further imbalance in frequency. Further measures, secondary frequency control, are taken to restore the system to nominal frequency [3] and [4].

2.2.3 Reactive Power Supply

Reactive power is needed to maintain the system voltage within the acceptable limits, to reduce the losses in the system and to release congestion on transmission lines. Reactive power should be supplied locally as its transmission over long distances is very impractical. This voltage control service is provided by TSO which calls upon the reactive power sources for the supply of the required support in the demand area. Voltage control service can be supplied via voltage regulators, transformers, synchronous generators, synchronous condensers and capacitors [3] and [4]. The generators are usually required by ISO/TSO to devote a portion of their reactive power capacity for voltage control services. However, Svenska kraftnät (SvK) does not compensate the generating units for the provided reactive power. The service is rather supplied as an obligation to the system [3], for the purpose of which, the utilities are obliged either to decrease the power generation or invest in independent reactive power units such as capacitors and inductors.
The variable costs of providing reactive power are comparatively smaller than active power generation due to the fact that reactive power generation does not involve fuel consumption, however, the opportunity costs of reactive power generation is high due to the decrease in active power generation [3].

2.2.4 Reserve Services

The ability of a system to increase the generation in times of contingencies is dependant on its available active power resources, also called spinning reserves, to respond to the fluctuations in real time. Supplemental reserves are another type of reserve services which do not necessarily provide immediate response but are usually available within a short time. [8] classifies operating reserves into two different categories: event and non-event. The later includes the regulating reserves which are intended for automatic optimal dispatch correcting the current fluctuations in the system, or manual optimal dispatch for regulating the expected changes within short time. On the other hand, the event category includes contingency reserves and ramping reserves. While the former is intended for instantaneous responses in times of system faults or outages to stabilize frequency and bring it to optimal value, the later is for non-instantaneous events as operating as secondary reserves for the cases of a second event. The differences in the technical characteristics and the deployment and standby costs are the decisive factors for the suitability of different technologies for different reserve services. Yet another type of reserve is controllable or interruptible loads, directly or indirectly connected to the transmission grid. The concept is quite well researched, but on a commercial level it could be considered a quite modern phenomena. In a Nordic context, projects involving demand side as actor in reserve market started in mid 2000s and were followed by legislation on dynamic taxes and tariffs and other relevant technical and legal measures [9]. While the integration of controllable load is a field being continually under study nowadays, there are systems that employ the service to different extents. The Swedish legislation for example requires at least 25 percent of the 2000 MW power reserve to be maintained by demand side [10], [11] and [12].
Nevertheless, the participation of demand side in the Swedish regulating market depends on the fulfilment of certain criteria. Briefly mentioning, the acting utility is required to be connected to the grid and must have at least 5 MW of interruptible load available with an activation time of at most 30 minutes. The 5 MW consumption capacity must be offered in at least one bid in the balancing market to be activated for at least two hours [11].

2.2.5 Black Start Capability

In the Swedish power system, due to a well-designed transmission system, a major breakdown is estimated to occur only every twenty years [13]. Nonetheless, sufficient restoration capacity with adequately quick response time is needed for the rare occasions of restoration need after a major power outage in the system. TSO/ISO is usually responsible for arrangement and deployment of this service [3].

2.3 Ancillary Services in Sweden

Swedish national grid, SvK, is the independent system operator in charge of the Swedish national transmission grid. This state-owned utility is also responsible for providing the main AS for the support of the grid as there is no independent market for these services in Sweden. SvK handles the reserve and regulation services through "Regulating Markets" and through short-term contracts ensures demand-supply balance and voltage quality in the grid. To maintain the later on a minute-by-minute basis, SvK applies the two-step method, the primary and secondary regulation While the primary regulation is handled through long-term contracts with power generators, the secondary regulation is maintained by choosing the most favorable bids from different players, i.e. generators or large consumers, in terms of the price and amount of the bids. The agreements between SvK and electricity users concern reduction of power consumption by these users in times of over load, which is usually the coldest season. The parties must be ready to actively and instantly reduce consumption or increase generation between 16 November and 15 March every year. For the years 2015-2017 and 2017-2020, SvK is obliged to ensure a reserve capacity of up to 1000 MW and 750 MW respectively. The share of consumption reduction must be at least 25 percent of the total available power reserve [10] and [12].

2.4 Electrofuel Production Process

Electrofuels (EF) is an umbrella term used to refer to those types of carbon-based synthetic fuels for the production of which electricity is used as the main energy source. These multi-purpose fuels either in gas form, E-Methane, or in the form of liquid , the so-called E-Methanol, E-ethanol, Bio diesel, etc., can serve in different sectors for heating, industrial processes, transportation, and others. Electrofuel production is gaining the attention of many different investors in transportation and power sectors. Two examples are Audi's 6 MW plant in Germany for e-Methane production and CRI's "power to

methanol technology" in Iceland [14], [15].
Probably, the most ideal locations for installation of electrofuel production are geographically or technically isolated areas where renewable power generation is abundant but transmissions capacity is limited.
It is difficult to find detailed cost calculations for installation of a whole power-to-fuel process. That is mainly due to lack of experience. However, some sources estimate the costs to be around 2000 EUR/kW of electricity, for installation of a complete system [16], [17].

2.4.1 ElectroFuel

The term refers to the technology of using electrolysis and Sabatier reaction processes to produce different hydrocarbon fuels, mainly methane. In an electrolysis process, electricity is used to split water into H_2 and O_2. In combination with CO_2, the former is used in a Sabatier reactor to produce the final fuel, mainly gas [18], [19], [20]. CO_2 is usually supplied from different industrial processes. The required electrical energy can come from any generation source. However, the ideal situation is when the electricity is supplied by renewable energy sources, wind and solar in particular, in times of over generation and low demand. Figure 2.1 illustrates an overview of the process of electro-fuel production.

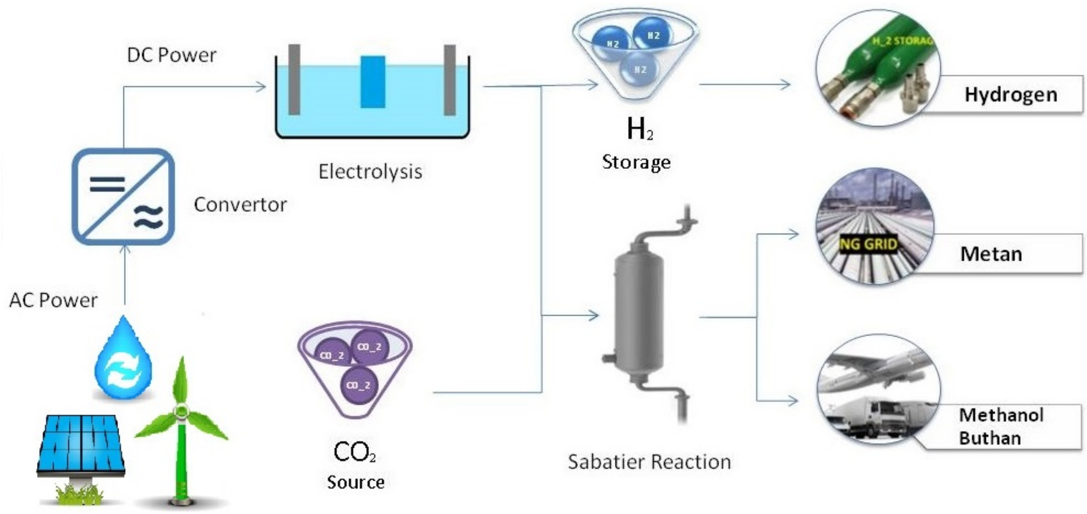


Figure 2.1: Electrofuel Production Process (some features are inspired by and [14] and [21])

Evidently, the process is expanded over at least three industrial sections, namely power production, power transmission and distribution in form of hydrogen, and energy storage and power regeneration for industrial and domestic end-use. The rest of this section is devoted to brief description of the different parts of the EFP process which are important for this project's objective.

2.4.2 Electrolysis

Making up almost 60 percent of all molecules, hydrogen is the most common element in the universe. However, pure hydrogen does not exist as a natural resource and must be extracted. The extraction/production is done in different ways, usually as a by-product in industrial processes, e.g. removal of hydrogen from hydrocarbons, i.e. fossil fuels [22], and sometimes through electrolysis of water or other material i.e. electrolyte. Later is a commercially available technology, though very energy intensive, where electricity is required to run the process of splitting water, or electrolyte, into its components, which in case of water are hydrogen and oxygen.
In electrolysis, water is decomposed into hydrogen and oxygen gases with help of a low voltage current. The optimal operation of electrolyzer depends on factors such as the current density, and the electrolyzer's capacity factor, i.e. hydrogen demand. It is estimated that electricity makes up for half of the operating costs and [19] states that it is most effective to run the electrolyzer on low production rate. Nevertheless, it is still expected to look at the electrolyzer as a potential source of income whereas by providing balancing services to the grid it can yet help integrate fluctuating power sources to the electricity system [17]. Such services could be realized with the help of power electronics.

Rectification and Rectifiers

Electrolyzers work with DC power [23], as such they are to be interfaced by converters for supply of DC power. The converter could further function as a reactive power compensator. Rectifiers are among the typical converters used in such applications, to convert alternating current to direct current, i.e. rectification process.
Historically, many different types of rectifiers, produced from various materials, have been used in industry. The earlier versions were, among others,

vacuum tube diodes, and currently semiconductor diodes of different types and topology are widely in use in small and large industrial as well as domestic concepts. While three phase rectification is the most common in industry, single phase rectification is also in use, mainly in domestic equipments[1].
Due to lower cost of installation, passive rectification is the most widely used method. However, to fulfill the aim of reactive power compensation, the electrolyzer needs to be equipped with active rectification. In active rectification, the diodes are replaced with switches for the active control of current, the advantage of which, among others, is enhanced voltage regulation.
Figure 2.2 presents a general sketch of a rectifier's reactive power contribution to the grid.

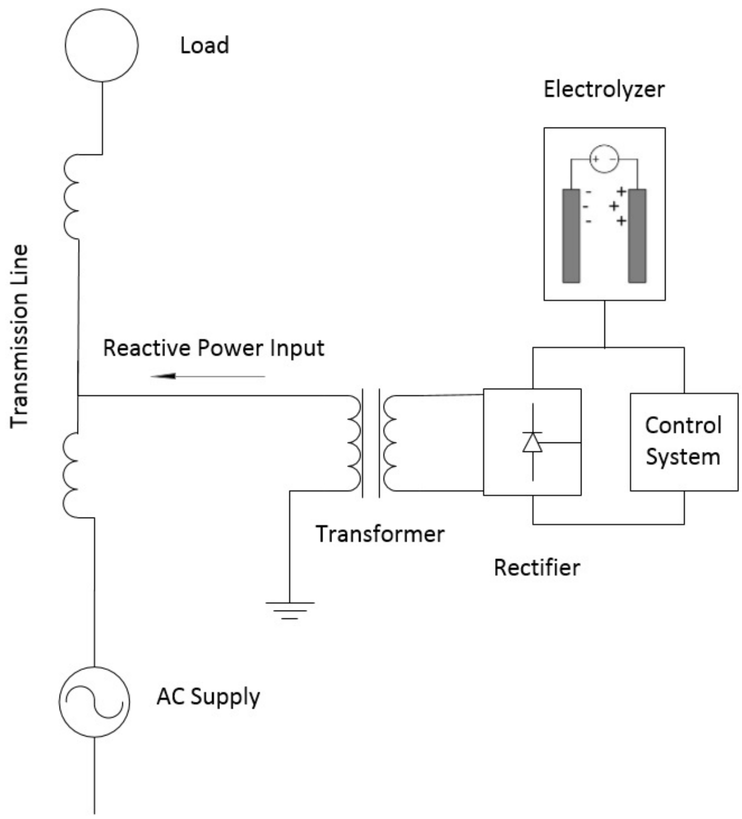


Figure 2.2: DC supply to electrolyzer and reactive power regulation with help of active rectifier(Inspired by [24] and [25]).

[1]It is probably needless to mention that within the present project it is three phase rectification that is intended.

To feed the electrolyser, the AC power is converted to DC via an active rectification process. A digital control system is implemented to take care of the rectifier, and a transformer is required to regulate the rectifier's voltage input.
Due to power factors close to unity, and a more efficient conversion performance, active rectifiers come in smaller less bulky sizes than passive ones. Nevertheless, it shall be noted that, despite their larger sizes and lower efficiency (with power factors between 0.65 to 0.95), passive rectifiers usually are the most cost-effective solution. Active rectification is more costly due to the increased complexity of the system and additional control requirements and, etc [26]and [27].

2.4.3 Hydrogen Storage

Hydrogen is versatile in both energy and power capacity. Energy density of hydrogen per unit mass is so high that one kilograms of hydrogen carries as much energy as three kilograms of gasoline [28], making hydrogen a convenient energy carrier and energy storage medium. This feature becomes important in times of wind curtailment where the excess electricity can be stored in form of hydrogen [29], [30]. The storage is done with different efficiency rates depending on the energy converting process and the storage medium [31]. Nevertheless, in a liberalized power market, it is essential to assess the use of hydrogen storage systems in terms of economic optimization especially with regard to their applications in maintaining load levels and contributing to the integration of more renewable and distributed generation and also the important role they could play in the development of Smart Grid concept [32].

2.4.4 Sabatier Reactor

The hydrogen produced from electrolysis and CO_2, usually coming from industrial processes, are combined together through the Sabatier reaction to produce different fuel products [18].
Equation (2.1) presents the Sabatier reaction for e-methane as

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + energy \tag{2.1}$$

where CH_4 is the product of the reaction. Likewise, the Sabatier reaction for e-methanol, CH_3OH, is stated by

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O + energy \tag{2.2}$$

where the end product is e-methanol in addition to water and some energy [33].

As it can be seen, the Sabatier reactions have no bi-product but water and some energy. This factor makes the technology quite interesting with regard to GHG emission issues and CO_2 mitigation programs.

Chapter 3

Method

As described in the previous chapter, AS cover a vast area of grid-related concepts. Three main areas have been the focus of this project. These areas are namely reactive power regulation, congestion management, and reserve services. The reason behind choosing these three areas lays in the nature of the investigated technology as well as the local characteristics of the studied country, i.e. Sweden. For the aim of this project, the most interesting and relevant part in EFP process is electrolysis where the power consumption for hydrogen generation is of importance with regard to congestion and congestion release services. Also, electrolyser is a potential reliable actor in regulating markets to provide reserve services as a large consumption utility in the grid. Furthermore, as a significant load, the electrolyser, with the help of modern power electronics, has the potential of providing reactive power services to the electricity network.

3.1 Reactive Power Regulation Services

Initially, a comparison of the total installation cost of rectifier with passive vs. active solutions has been performed. This is with the aim to identify the extent of differences in costs with the shift from passive rectification to active rectification. As described in Chapter 2, compared to passive rectification, active rectification is expensive yet required for reactive power compensation. The difference in costs is to be included in the total cost of reactive power regulation in terms of necessary investment enterprise for electrolyser as an acting utility in the power market. Subsequently, it is investigated how, for a constant active power supply, the installation costs for the increased size of rectifier vary. This increased size, as explained previously, is meant to be exploited for reactive power injection/absorption to/from the grid. It is thus

of value to compare the calculated costs with those of common reactive-power supply devices such as capacitors and reactors.
The required additional rectifier capacity to compensate for the reactive power that is to be supplied by the capacitor is calculated using the well-known relationship between apparent, active and reactive power. Adopting a certain value as the constant DC power (kW) to be supplied to the electrolyser, the required extra rectifier capacity needed to replace different values of capacitor have been calculated. The same calculations have been performed for shunt reactors. In a new approach, with the same cost assumptions for the year 2020, the perspective of changes in terms of the sensitivity of the investment to the economies of scale has been studied. Accordingly, four different cases have been looked at. In two of these cases, scaling factors other than the empirical 0.6 were picked and the impact of this change on the investment costs was studied. In the third and forth case, the effect of changes in power factor was investigated.

3.1.1 Data and Assumptions

The economical and technical data required for this section have been collected from different global or local industrial and administrative organizations, the details of which follows in this part.

Installation Costs

Reliable sources for pricing of rectifiers for power systems are difficult to find. However, [34] has suggested three time-based price values for power electronics where rectification is included as well. The suggested prices have been used in this project as the base to represent the costs for passive rectification in year 2015 while an increase of 30% is calculated to cover the higher costs associated with active rectification.
Moreover, the probable future changes in investment costs for rectifier are taken into account to study the impact on the initial results. For a scope of 5 years, a decrease in the investment costs is assumed, which is due to the expected technology enhancement and economic progress in near future [35]. Accordingly, the cost for passive rectification and the corresponding increased cost for active rectification are assumed to be lower by 2 EUR/kW and 10% respectively for the year 2020. The pricing method for year 2020 is based on [34] as well. The calculations assume an initial capacity value of 50-100 kW which is the common pilot scale for electrolysers.
The reference prices for capacitors are taken from [36], where the one time installation cost and the size cost of EUR per kVA are included. Capacitors

of input voltage of 20 kV have been considered in the calculations. For shunt reactors, the reference price has been considered based on the pricings in [37]. Moreover, an additional one-time installation cost has been assumed for the reactors based on [38], [39]. Though, the operating voltage for the reference reactor is 15 kV, its installation cost has been assumed to apply for a 20 kV reactor as well.

Economical Assumptions

Different capacity values for electrolyzer and the corresponding rectification costs have been calculated where the installation cost is assumed to be subject to the economies of scale. Hence, for estimating this cost the rule of six tenth factor has been applied. This method for cost estimation can be used if the cost of an initial size of an investment is known and the approximate increase of the cost with increasing size is desired to be known. Through empirical use, the method has proven reliable with producing valid results within an approximate range of $\mp$%20 [40], [41]. Equation (3.1) presents the described method as

$$\frac{C_{DF}}{C_{DF_0}} = \left(\frac{S_{DF}}{S_{DF_0}}\right)^n \tag{3.1}$$

where C_{DF} is the approximate cost (EUR) of the equipment with the corresponding size S_{DF} and C_{DF_0} is the known cost (EUR) of the equipment with the corresponding size S_{DF_0}. In this equation n is the scaling factor, which as proved liable through experience, is usually assumed 0.6 [42] [40]. Thus, 0.6 is used in this project as the standard case. However, to evaluate the impact of this factor on the results, scaling factors of lower and higher values are also considered in further calculations.

The same cost estimation method has been used in the installation cost calculations for capacitors and reactors.

3.2 Congestion Release Services

In order to study the potential of electrofuel production in providing congestion release services, a market model has been designed and simulated in GAMS. The model covers Sweden and represents the Swedish spot market. Since November 2011, Sweden has been divided into four different bidding areas with four different price levels. Such a system is an indicator of the constraints on transmission capacity in the power system. Accordingly, depending on the geographical location of a market actor, i.e. producer or consumer of electricity, the price they receive or pay for each power unit relatively differ [2]. Figure 3.1, which has been drawn based on the illustrations available in [2] and [43], illustrates the four Swedish bidding areas where the red lines represent the limits on transmission capacity which lead to the emergence of four different price areas. However, it shall be mentioned that such variations in prices do not exist all the time and are highly dependant on the demand load in the system in different time scales.

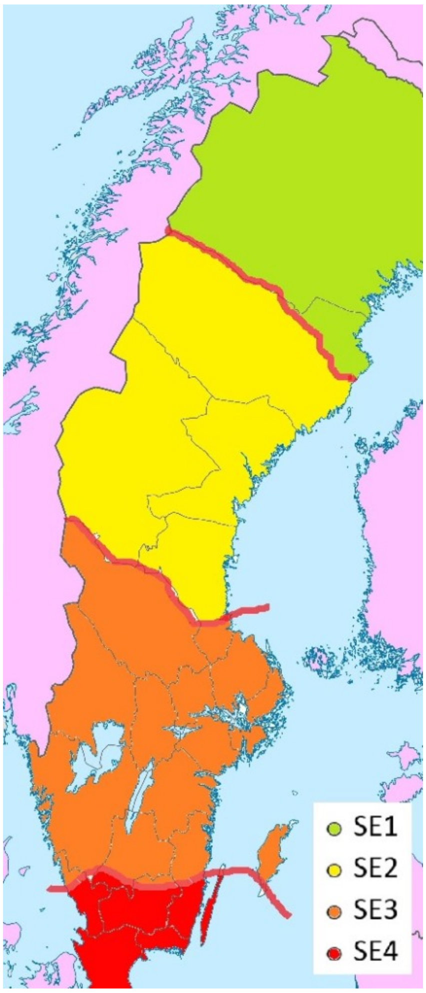


Figure 3.1: The four Swedish bidding areas, SE1, SE2, SE3, SE4. (based on [2], [43])

3.2.1 Simplifications and Assumptions

Transfer capacity

While between each two areas there are several transmission lines, the accumulate transmission capacity of these lines have been considered, regardless of the specific characteristics of each line such as its length, capacity, etc. Moreover, the maximum transmission capacity between each two areas differs from hour to hour and day to day, and this is caused by many different factors, a brief explanation of which was presented in Chapter 2. Hence, from the data provided by Nord Pool for the predicted transmission capacity for different hours of each day of a week, the minimum predicted value was taken into consideration [44].

Demand per area

The demand per area was taken from the historical data on Nord Pool for the year 2014, where the accumulated consumption for each hour of the year for all four Swedish price-areas is provided in MWh. The most demanding hour in this year occurred on the 4th of December at 17-18, where the demand in SE1, SE2, SE3, and SE4 was 1290, 2265, 13506, and 3989 MWh respectively [44]. These values are implemented in the model as the most extreme situation. EFP, as a major consuming party will contribute to the increase of demand in each of the areas individually.

Costs

Today, the installation of electrolyser costs something around 600 to 1500 EUR/kW. However, in this project, the investment cost of electrolyser has been assumed to be 400 EUR/kW, as a falling price for this technology is expected within the coming 10 years [14] [45].
Table 3.1 presents the cost of production for the power generation technologies included in this model[1]

[1]The currency conversions are based on the actual exchange rates on the day of calculations [46].

Table 3.1: Cost of generation for different technologies

Generation Technology	**Cost** (EUR/MW)
Nuclear [47]	22.10
Hydro [47]	10.00
Coal [47]	32.45
Wind [48], [46]	10.24
Gas [47]	47.23
Oil [49], [50], [51]	67.45
Bio [52], [46], [47]	24.10

The power generation costs from nuclear, hydro, coal, and gas technologies are mainly based on the data from the EIA's 2015 Annual Energy Outlook [47]. The wind generation pricing comes from the American NREL [48]. The cost of generation from oil combustion has been taken from IEA's Projected Costs of Generating Electricity 2010 edition [49]. However, since the oil prices has decreased comparatively since then, some calculations were made in order to identify a better value for oil generation cost based on the day's oil prices. The average price of oil in April 2010 was 85 USD a barrel [50], while in April 2015 the value had decreased to 60 USD a barrel [51]. Hence, a decrease of 70% was taken into account for calculating today's oil-based generation per MWh. For biomass generation, the cost of biomass fuel in Sweden has been taken into account [52], while the operation and management costs are based on IEA's report for solid biomass generation in the Netherlands [49]. The cost of generation from resembling power plants has been assumed to be constant for all the four price-regions. However, in reality these costs vary slightly depending on different, mainly technical, factors.

Supply Capacity

The main existing power plants in Sweden, namely, nuclear, hydro, wind, bio, and gas, have been included in the optimisation model. While other generation types, e.g. solar, have been dropped out because of small installed capacity and thus trivial impact on the total system, coal and oil plants have been included due to their high environmental and political impact. The installed capacity values for the mentioned power generation technologies, presented in table 3.2, are based on the data from Nord Pool and IEA's reports [49], [44].

Table 3.2: Supply capacity (MW) of different generation technologies installed in the four price areas [49], [44].

Price-area	Nuclear	Hydro	Coal	Wind	Gas	Oil	Bio
SE1	0	9044	0	500	0	0	282
SE2	0	5121	0	1710	0	0	586
SE3	9531	1571	0	1850	992	763	2499
SE4	0	414	130	1520	577	1005	0

3.2.2 A Model of the Swedish Power System

The model is designed for a time scale of one hour with the objective function being the minimization of the system's total generation cost. The constraining factors are the demand supply balance and the transmission limits. The mathematical formula of the model with all the necessary constraints are presented below[2].

The spot market model is cleared with the objective function to minimize the total cost of generation to supply the demand in the system. Equation (3.2) presents the objective function

$$Minimize \quad Cost = \sum_{i=1}^{4}\sum_{j=1}^{7}(PG_{i,j} * CG_{i,j}) \tag{3.2}$$

where $PG_{i,j}$ is the active power output of generator j at area i, and $CG_{i,j}$ is the production cost of generator j at area i.

The objective function 3.2 is subject to the following constraints:

[2]A visual illustration of this model is presented in figure **??** in Appendix **??**.

Taking the power transfer between the areas into consideration, (3.3) presents the Demand-Supply balance constraint,

$$\sum_{i=1}^{4}\sum_{j=1}^{7}(PG_{i,j}) - \sum_{i=1}^{4}\sum_{k=1}^{4}(NeT_{i,k}) = \sum_{i=1}^{4}(PD_i) \tag{3.3}$$

where $NeT_{i,k}$ is the net power transfer between area i and area k, and PD_i is the power demand in area i.

Each generator has a maximum amount of power to produce in one hour. The generation cannot exceed this maximum capacity. Equation (3.4) presents this constraint as

$$PG_{i,j} \leq PS_{i,j} \tag{3.4}$$

where $PS_{i,j}$ is the maximum active power capacity of generator j at area i.

The transferred power cannot exceed the maximum transmission capacity between each two areas. This constraint is presented in (3.5) as

$$NeT_{i,k} \leq TM_{i,k} \tag{3.5}$$

where $TM_{i,k}$ is the maximum transmission capacity between area i and area k:

The last constraint, presented in (3.6) as

$$NeT_{i,k} = NeT_{k,i} \tag{3.6}$$

indicates the equality of net power transfer in both directions (from i to k).

The above described linear optimisation program is modeled and simulated in GAMS.
The model simulation considers the changes in marginal price in each of the four price-areas with implementation of different capacity values for electrolyser, assuming the electrolyser to act as a major consumer utility, i.e. increasing the demand in the system. Since the aim is to investigate the

congestion release potential, the different values of increased demand are implemented in SE1, SE2 and SE3, in order to identify the most promising area for the final installation of the electrolyser of a certain capacity. Area SE4 is not included in this investigation, since this is the area where the more expensive power generation sources are located. The implementation of a large industrial load in this area is not only impractical but also it does not necessarily lead to congestion in the transmission lines. The main impact of such implantation is expected to be a drastic increase of electricity price in this area.

3.2.3 Compensating EFP Capacity

In 2014, while the SE1 and SE2 almost held similar marginal prices, there have been 185 hours when the spot price differed between SE3 and SE2. This indicates the existence of transmission constraint during these hours. With a case of increased demand in SE3, it is expected that the number of hours with congestion between SE2 and SE3 rises. Nevertheless, the price difference in more than 30 -out of 185- hours is less than 1 EUR/MWh. Hence, only a slight increase in the number of hours with grid congestion is considered in the case of increased demand due to electrolyzer installation. With the aim of congestion release, it is intended to identify the electrolyser's amount of power consumption that needs to be decreased in order to avoid grid congestion in times of high load. However, this decrease in power consumption means a decline in hydrogen generation and thus less electrofuel production. Accordingly, to avoid probable economical losses caused by reduction of electrofuel production, the electrolyser -and hydrogen storage- capacity shall be selected such that the congestion release service does not affect the electrolyser's capacity for hydrogen generation. The extra demand, caused by electrolyser, attributed to each congestion hour has been selected using a random distribution, taking the real market data trends into consideration.
In a comparable approach, with similar presuppositions and formulation as before, the Swedish power market is studied in a scenario where the nuclear power capacity will decrease. This factor is important partly because a drastic decrease of nuclear generation in future is highly likely to befall, and partly due to the fact that Vattenfall has declared a coming phase-out of 1730 MW of nuclear generation as a result of closing down Ringhals 1 and 2 between the years 2018 and 2020 [53]. This means a decrease from 9531 MW to 7801 MW of installed nuclear power capacity in Sweden.
Accordingly, the same capacity values of electrolyser have been tested for such a scenario, i.e. 1730 MW less nuclear capacity. The values were chosen mainly because at exactly these capacity values the marginal generation

technology shifts to a more expensive one resulting in a higher electricity price in the affected regions.

3.3 Reserve Services

In this section, the contribution of EFP in providing reserve services is investigated, where the historical data and literature review has been the main method of research. The economics of Demand-Response as a form of reserve service to be provided by electrolyser is the focus of this part of the project. The main factor deciding wither participation in balancing markets is profitable for an industrial utility is the energy intensity[3] of its processes [11] and [54]. EFP is indeed an energy intensive process, where the lion share of power consumption is ingrained in electrolysis. To act in the balancing market, the electrolyser, as a major electricity consumer, is to reduce its consumption when supply of reserve service is required. The service is called upon mainly during the market critical peaks.
In demand-response activities, what is important is the response time of the utility and also the time length of the actual shift, i.e. the number of hours or days a utility can shift its consumption. There might be even rare cases of the need for a demand response for longer periods of time, e.g. a month of little or no wind/sun. However, critical peaks usually occur in short time intervals limited to minutes or hours. Changing the consumption pattern for electrolyser and capitalizing on the high opportunity costs of load shifting could prove highly profitable for EFP processes. Principally, the electrolyser's compensation contribution shall correspond to actual load reduction. For electrolyser as an industrial customer, the value of each kWh of electricity is regarded as a part of the costs of producing the final product, i.e. hydrogen and eventually the final electrofuel. Thus, the value of electricity is evaluated with its correlation to the total production cost. Accordingly, as a market player, the electrolyser is to submit its activity plans and the eventual shift of power consumption to other times only when the compensation payment is worthwhile. Hence, in an ideal market, the electrolyser should demand payments above the average market price for providing reserve service. Having stated the general relevant theories, the method of investigating the balancing market participation potential for EFP might be stated as partly similar to the congestion release section, where the role of electrolyser in demand response is studied. For this purpose, the available historical data for balancing markets provided by Nord Pool has been used. The data is readily available for the years 2013, 2014 and 2015. The up-regulation volumes, in

[3] i.e. how much electricity is included in the final product.

case of occurrence, during each hour of each year have been considered to count for the actual possible volume to be regulated by electrolyser [55].
As such, the total up-regulation volumes and the number of hours of imbalance for each area have been used to calculate the required electrolyser capacity to compensate for the up-regulation volumes, as presented in (3.7)

$$Cap_{up} = \frac{Vol_{up}}{nH_{im}} \tag{3.7}$$

where Cap_{up}, Vol_{up}, and nH_{im} present the required up-regulation capacity(MW), total up-regulation volumes (MWh) and number of hours of imbalance respectively. The required electrolyser capacity values for each year and each price-area are calculated accordingly and presented in table (3.3).

Table 3.3: Required capacity (MW) to cover for the up-regulation volumes in each of the four price areas for the years 2013, 2014, and 2015 [55].

Price-area	**2013**	**2014**	**2015**
SE1	99	83	103
SE2	91	109	96
SE3	62	74	63
SE4	38	33	18

The associated market prices for each hour is also considered for the calculation of the potential revenues. Here as well, assuming 400 EUR/kW for investment cost of electrolyser, the payback period for the installation of the required extra electrolyser capacity has been calculated and presented in (3.8) as

$$PB_t = \frac{Cost_{cap}}{Rev_p} \tag{3.8}$$

where PB_t presents the payback period (years), $Cost_{cap}$, presents the installation cost of required up-regulation capacity(MEUR), and Rev_p presents the total potential revenues from demand balancing(MEUR).
The up and down regulation volumes and the corresponding prices for every hour of each year provide a vast range of data, making it possible to simulate a similar group of data for several more years. Using MATLAB[4], such simulation has been

[4]MATLAB's Statistics and Machine Learning Toolbox

performed reproducing data through random distribution for 20 years, roughly 175000 hours. In the simulation, the present general condition of the market has been assumed unchanged. This is done mainly with the aim to assess the reliability of the results based on historical data.

Chapter 4

Results

4.1 Reactive Power Regulation Services

With the described data from Chapter 3, the difference in cost with the shift from passive to active solution for rectification process was investigated.
Figure 4.1 illustrates the cost ratio curve for pricing years 2015 and 2020 with brown and orange colors respectively. The curves present the proportion of cost for passive vs. active rectifier for different sizes of electrolyser in an ascending order. In the calculation an initial investment cost for rectifier was included as well, where for the both pricing years the active solution is 50 percent more expensive than passive one.
The difference in cost between active rectification and passive rectification is highly dependant on the initial investment cost for each technology. The higher the initial cost difference the higher the ratio of cost. For the case illustrated in figure 4.1, for year 2015 passive rectification is less costly than active one within a range of 33% to 25%. This trend appears to rise upwards for larger sizes where a cost difference of roughly 20% is always expected. As for the year 2020, the ratio is not too high either, and the highest cost ratio between active and passive rectification remains around roughly 30%.

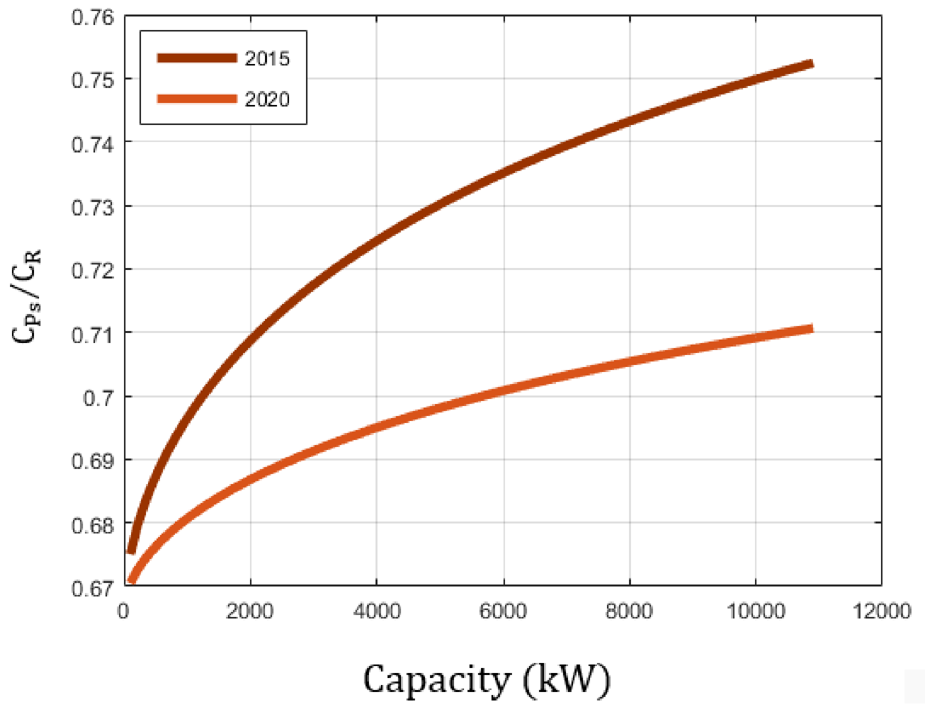


Figure 4.1: The difference in investment cost with switch from passive rectification to active rectification ($\frac{C_{Ps}}{C_{Ac}}$) where C_{Ps} represents the investment cost for passive rectifier and C_{Ac} for active rectifier for the related capacity value

As for the reactive power compensation[1], rectifier proves to be highly profitable compared to reactors and capacitors, where the revenues almost double as the capacity for reactive power compensation is increased. This is confirmed in the study of the relation between the marginal cost of rectifier and the total cost of capacitor and reactor with respect to the increasing capacity values of reactive power.

The results proved that in the most expensive cases, i.e. low capacity values, rectifier is more than 25% cheaper than reactors and capacitors of the same size. However, this ratio decreases considerably for higher capacity values leading to a situation where, for sizes larger than 1000 kVA, rectifier proves to be economically more favorable by 75% lower investment costs. Figure 4.2 illustrates the described

[1]Adopting a prospective approach, the active rectifier's cost based on the pricing year 2020 was considered for these calculations.

results. Furthermore, the correlation between the cost of rectifier against the cost of reactor and capacitor was individually calculated, the result of which are also presented in figure 4.2. In both cases, the trend takes a linear form after 1000 kVAr, where reactor is always more expensive than rectifier by a difference of 70%. As for the comparison with capacitor, though rectifier is 3 to 1.5 times more expensive for smaller sizes, with increased capacity the costs descend notably and for sizes over 2000 kVA the rectifier remains to be more expensive by a cost gap of roughly 20%.

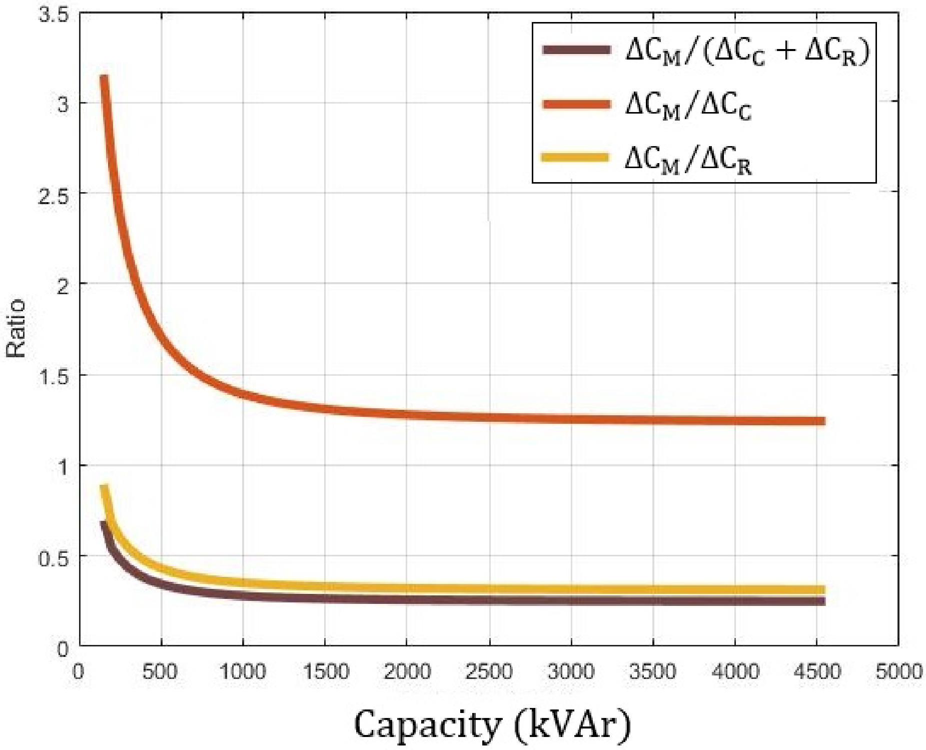


Figure 4.2: The ratio of rectifier's marginal cost of investment against the investment cost of reactor, capacitor, and reactor plus capacitor, indicated in yellow, orange, and brown respectively

4.2 Congestion Release Services

4.2.1 Simulation Results

Base Case

The simulation of the Swedish power market, for the situation described earlier in chapter 3 divides Sweden into two main areas, where the marginal price of electricity for SE1 and SE2 is 10 EUR/MWh and for SE3 and SE4 is 22 EUR/MWh, indicating a limited transmission capacity between SE2 and SE3. This situation brings about a total system cost of 297 000 EUR for that hour.

SE1

4970 MW of increased demand, i.e. installed electrolyser, in SE1 leads to the use of all hydro to full capacity and activates wind generation in this area leading to the spot price of 10.24 EUR/MWh in SE1 and SE2, and 22 EUR/MWh in SE3 and SE4. Despite the roughly 5000 MW demand increase the increase in the total cost of the system is not effusive. 7180 MW of electrolyser, increases the generation in nuclear plants, after using wind and hydro to full capacity in all the 4 areas. Inherently, the marginal cost of electricity is 22 for all the regions. The total cost of the system increases by only 22 000 EUR compared to the 5000 MW case.

SE2

Installing 1000 MW of electrolyser in SE2 increases the marginal cost only in this area from 10 to 10.24 EUR/MWh. The total cost of the system increases slightly by a difference of 10000 EUR compared to the original situation. This increase in the SE2 load runs hydro generation in this area to full capacity and also activates the wind generation in this area It is expected that with an installation of 2000 MW the marginal cost in this area does not change (10.24). However, installation of 2067 MW or more leads to reaching full capacity of wind in this area and thereby increasing the marginal cost of electricity to 22 EUR/MWh which is the cost of nuclear power generation in SE3. The installation of 4757 MW and/or more in SE2 activates bio generation in SE3 and accordingly increases the marginal cost in the last three areas to 24.

SE3

Installing 1000 MW of electrolyser at SE3 does not change the marginal cost of electricity in any of the areas of the base case. More nuclear power is generated and the system cost is increased by slightly more than 20 000 EUR. This double increase of system cost in comparison to 1000 MW installation in **SE2** is due to the increased nuclear generation which is twice more expensive than wind power.

Installing 2691 MW or more of electrolyser at SE3 increases the marginal cost in SE3 and SE4 from 22 to 24 EUR/MWh, i.e. the activation of bio generation in SE4. The marginal electricity price in SE1 and SE2 remains unchanged, i.e. 10 EUR/MWh. The total system cost in this case is 356024.8, which is partly due to the increase in demand and partly because of more expensive generation.

Concluding Remarks

SE1 region is the most flexible location in terms of total cost for the system. While it proves feasible to have more than 7 GW of installed electrolyser operating in SE1, the total system cost remains small and the system maintains a marginal price of 22 for all the four regions, meaning the operation of nuclear plants at margin and no serious constraints on transmission. This region is thus not a suitable location for the purpose of congestion release service, as even very high demand values does not impose a constraint on transmission. SE2 as well has a similar situation where the increase in the system total cost is hardly due to transmission constraints. The higher costs are mainly because of higher demand rather than the limited transfer capacity. On the other hand, SE3 price-area is home to the most considerable changes in terms of system total cost, and changes in marginal generation cost. See figure 4.3, where the green curve presents the changes in the system total cost for price-area SE3. Higher capacity values result in activation of fossil-fuel plants with higher generation costs and thus highest marginal electricity cost. SE1 curve starts from 1000 MW mainly because lower capacity values do not change the curve's slope and the cost increases linearly. SE2 curve stops at 6000 MW due to transmission constraints. However, this constraint is not significant as it does not lead to a different marginal cost for SE2 because this area mainly uses its hydro and wind plants to full capacity. The braced angles in SE2 and SE3 curves indicate the changes in the production mix.

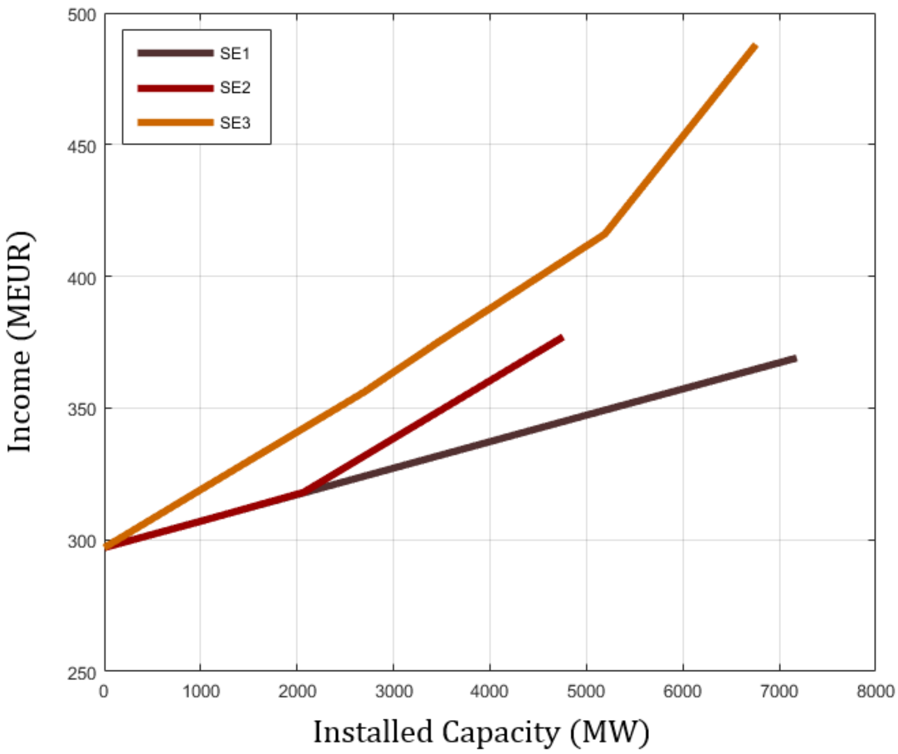


Figure 4.3: Increase in income[2]with increased electrolyser capacity in SE1, SE2, SE3.

The latest indicates a constraint on transmission from SE2 to SE3. This provides a potential for congestion release service where the electrolyser could act as a flexible load to be curtailed in times of high pressure on the transmission grid, especially considering the flexibility of the technology in quick response to down regulation.

Compensating EFP Capacity

For a case of 2691 MW of increased demand in SE3, it is expected that the number of hours with congestion between SE2 and SE3 rises slightly. As such, it has been tried to use the correlation between the increase in demand and the increase in hours of congestion observed in historical data, in order to assume a certain increase of congestion hours for the 2691 MW of increased demand. Accordingly, roughly,

[2]The increase of income for electrolyser is equal to the increase in system cost for TSO/ISO.

200 hours with different levels of congestion in the grid has been considered. The demand values were distributed randomly among these 200 hours. This random distribution is needed because the different levels of congestion in the grid last for different time periods, while some last in some minutes only, others last for an hour or longer. E.g. there might be 2 MW of imbalance lasting for one hour in a cold winter night, or 10 MW of imbalance lasting for 10 minutes in a mild spring day. And since the price levels are different from time to time, use of random distribution seems to be the fairest way of seeing through the situation. Accordingly, the calculations yielded a total demand of 159 GWh was calculated. This is the demand of electrolyser in the times of grid congestion. Moreover, 6 hours of non-operation adds about 16 GWh to this value. To compensate for this demand on other hours of the year around 20.5 MW extra capacity is needed. This would be a total required capacity of roughly 2711 MW with an investment cost of roughly 8.2 million Euros.
Curtailing the extra load caused by electrolyser during these hours and thereby releasing the transmission constraint saves the system a total sum of slightly less than 3 million Euros per year. Hence, the curtailment as an ancillary service brings about a net cash flow of about 3 million Euros (2.9 MEUR) for the investor, which means a payback period of less than 3 (2.8) years for the required extra capacity.

Nuclear Phase-Out

SE1

Even in a case of nuclear-phase-out the increased demand in SE1 does not put any constraint on transmission capacity mainly because of redundant hydro generation sources in the area, not to mention the expected increased installation of wind turbines in this area in near future [56].

SE2

For 1730 MW less nuclear power availability, the simulation for 1000 MW of installed electrolyser in SE2 maintains the same values as in the base case. This is because even in this scenario, the nuclear generation does not reach its full capacity. 3028 MW in this case activates bio generation in SE3 as the nuclear capacity is fully used. The marginal cost of bio generation, 24 EUR/MWh, decides the electricity price in the last three areas. Increasing the demand (higher electrolyser capacity) in SE2 activates the more expensive power plants in SE3 and SE4 and changes the electricity price in the last 3 areas in correspondence to the actual marginal generation cost, starting from coal and ending with oil and gas.

SE3

For 2691 MW of electrolyser capacity in SE3, bio generation is increased to full capacity resulting in marginal costs of 10 EUR/MWh in SE1 and SE2, and 24 EUR/MWh in SE3 and SE4. Installing 3461 MW and more of electrolyser in SE3 successively activates coal, gas and oil generation in SE4 resulting in corresponding marginal electricity prices in SE3 and SE4.

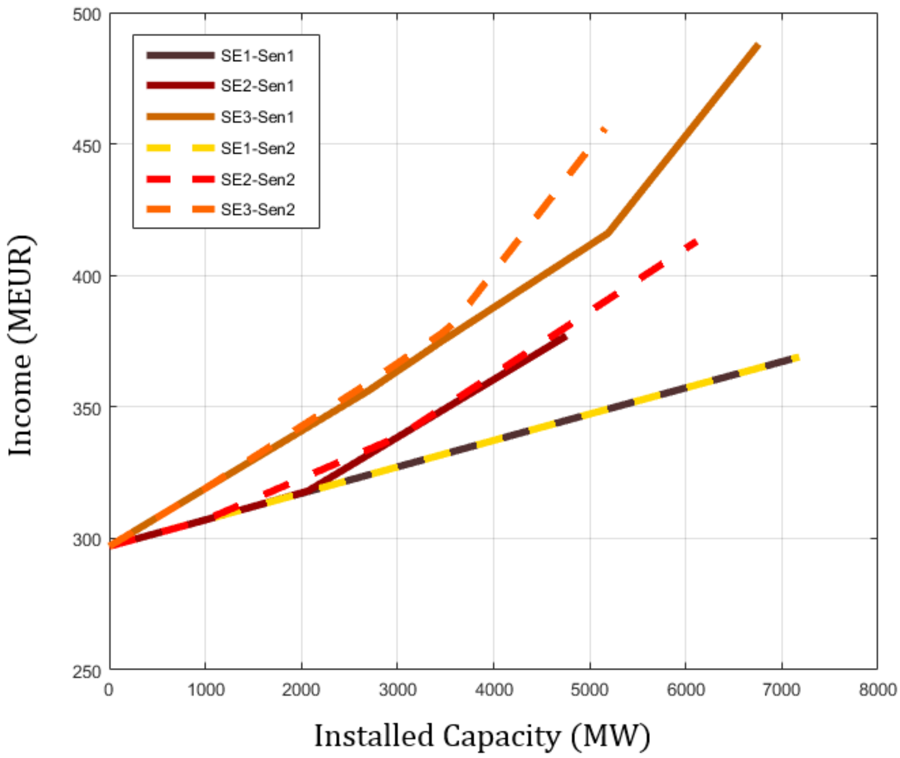


Figure 4.4: Increase in income[3]with increased electrolyser capacity in SE1, SE2, SE3 for two different scenarios.

For larger sizes of electrolyser the changes in marginal electricity cost are highest for SE3 price-area[4]. So are the changes in the system total cost. Figure 4.4 illustrates the changes in the system cost in the three price-areas with increasing the electrolyser size for a scenario with less nuclear generation compared to the

[3]See figure 4.3.

[4]Higher capacity values result in activation of fossil-fuel plants with higher generation costs

base case described in Chapter 3. A value of 3500 MW of installed capacity leads to a major shift in total system cost which is mainly due to a shift to more expensive generation caused by deficiency of low cost nuclear generation in this area as well as the limits on transmission grid. This result confirms what was concluded for the base case. A large-scale implementation of electrolyser system in SE3 imposes a constraint on transmission capacity from SE2 to SE3, indicating the potential of electrolyser, as a part of electrofuel production system, to provide congestion release service to the grid.
In addition, similar to the base case, different demand values- ranging from 3500 MW to 0.1 MW, were attributed to the congestion hours through random distribution. However, considering the decreased nuclear capacity and increased electrolyser demand, the number of hours were increased to 210 hours plus 6 off hours for maintenance work. The new situation brings about a total demand of 201 GWh to be curtailed. Meaning a need to increase the capacity by 24 MW, costing the investor more than 9 million Euros. However, due to activation of expensive generation, the cost for system and thus the net cash flow for the electrolyser is estimated to be around 3.4 million Euros. The investment payback period for the case of nuclear phase-out is estimated to be around 2.7 years, i.e. a decrease of roughly 4% compared to the base case.

4.3 Reserve Service

As has been discussed previously, the market price for up and down regulation is similar in all the four Swedish price areas. The results prove a possibility for electrolyser to be an active player in regulating market by immediate response to up-regulation demands in the system. Figure 4.5 illustrates the potential income for electrolyzer using the historical data [55]. The calculations have been based on the assumption of providing the total up-regulation demand in the system through demand-response where the electrolyser is paid the actual market price for each hour of the year. In the figure, black, brown, copper and beige columns represent the potential income from installations in SE1, SE2, SE3, and SE4 respectively.

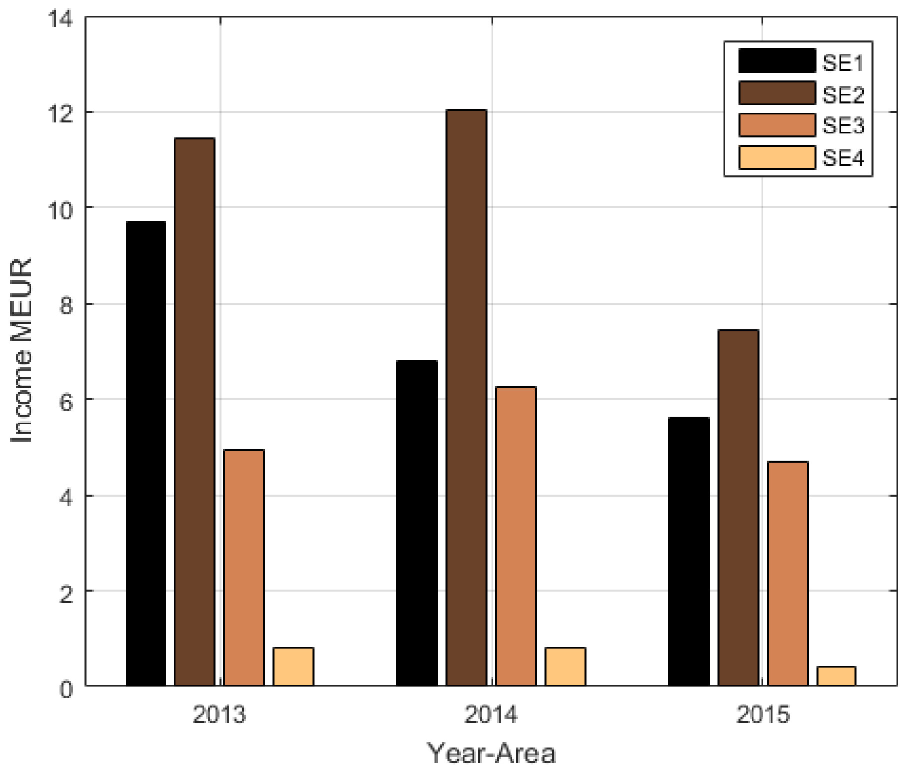


Figure 4.5: Potential income from demand-balance services in SE1, SE2, SE3, and SE4

It is though of importance to remark that such results are largely dependant on the number of hours of imbalance in the system for each area. A fact which is deliberately presented in figure 4.6. Yet, another considerable fact presented in this figure is the comparative similarity in the occurrence of imbalance for all the three years while the income shown in figure 4.5 is notably lower for year 2015. Now this could have roots in several reasons needing thorough investigation of the case taking into account numerous system-dependant factors. The immediate cause to hit the mind can however be summarised as the actual market prices which depend on the actual marginal power generator utility in the system in addition to other technical factors such as transmission constraints and the status of import and export from other regions. In general, there is little or no reason at all to justify that demand-response cannot be a potential source of income for electrolyser.

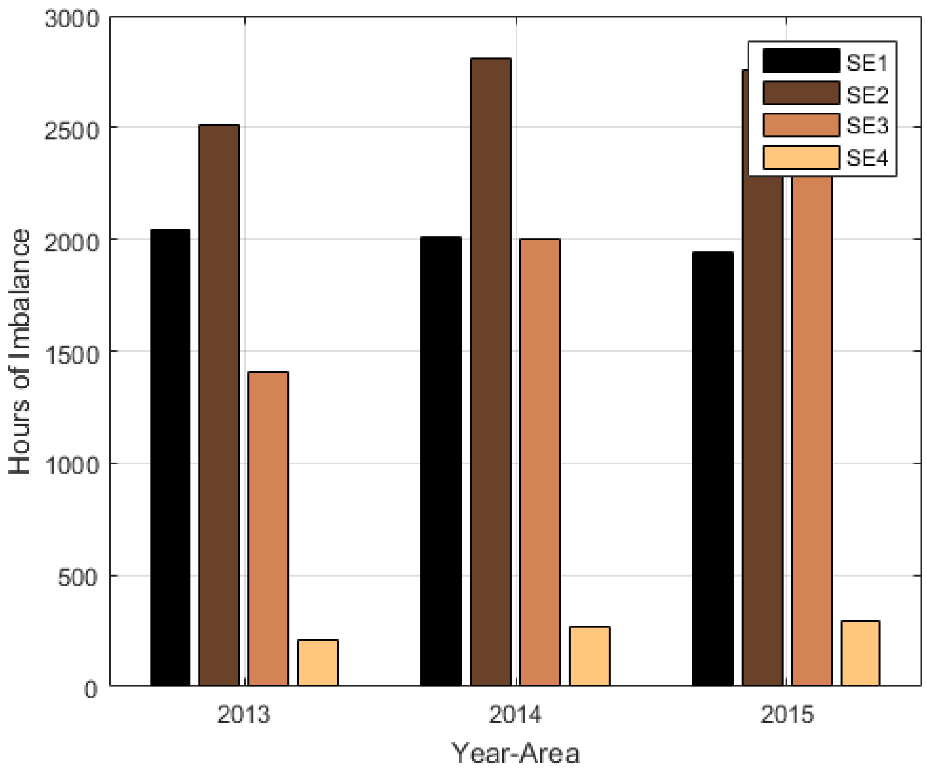


Figure 4.6: Hours of Imbalance in SE1, SE2, SE3, and SE4 in the three studied years

The comparison between the four areas with respect to the revenues indicates a rather consistent trend for area SE3 where the changes in number of imbalance have insignificant effect on the revenues gained through demand-response service in this area. This conclusion is even approved by the pay-back time of investment, if any shall occur, in either of the four areas. In figure 4.7, the corresponding payback periods for each of the three years is illustrated. The required extra electrolyser capacity and the corresponding revenues from supply of reserve service have been considered for the calculation of payback time. SE3 proves a consistency even in this regard which indicates the viability of investment in this area even when the system profile goes through some changes during the years, a comment which can not be likewise made for the other 3 areas but for area SE2 to some extent. In the later, while the number of imbalance hours from year 2014 to 2015 remains almost the same, the income decreases notably with a lengthened payback period for year 2015.

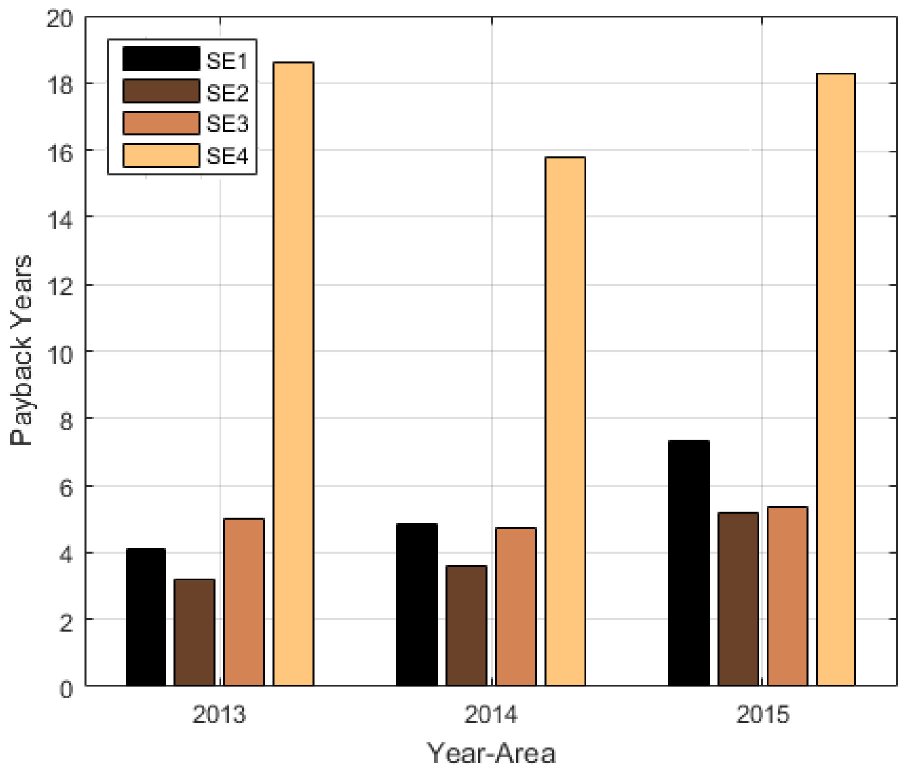


Figure 4.7: Payback time (years) for installation of the required capacity in SE1, SE2, SE3, and SE4

Once again, SE3 is a favorable area in terms of investments in EFP and in particular electrolyser. As such, this area was selected to be looked upon for a sensitivity analysis. The average values for the potential income, payback period and number of hours of imbalance were calculated. The results are presented in figures 4.8, 4.9, and 4.10. The average values indicate the consistency of the results gained in section 4.3, where the income remains at around 5 million Euros, with roughly consistent payback time of 5 years.

Concluding Remarks

In general, in the simulated data for hours of imbalance in SE3, as well as the other areas but SE1, an increasing trend can be observed, indicating an increase in the unpredictability of the market, and perhaps an increasing necessity for establishment of conditions where demand-response takes a more active role. This changes the system profile considerably, a factor missing in the data simulation in this section. It shall thus be stated that in such conditions, the chances for boosted revenues for electrolyser are not expected to be low.

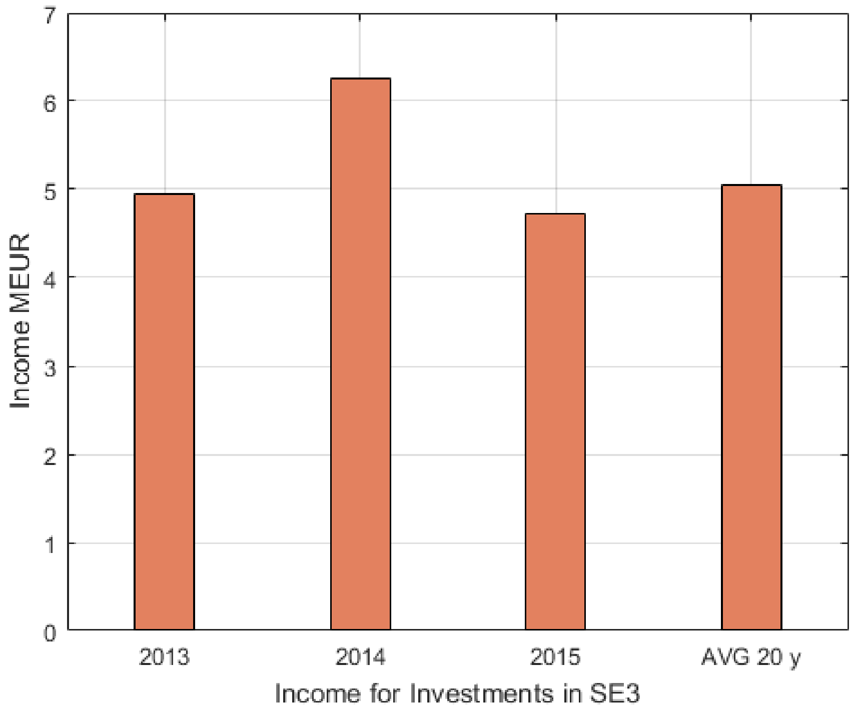


Figure 4.8: Income from Demand-Response Service Provided by Electrolyser in SE3 for the years 2013, 2014, 2015, and an average of 20 years of simulated data

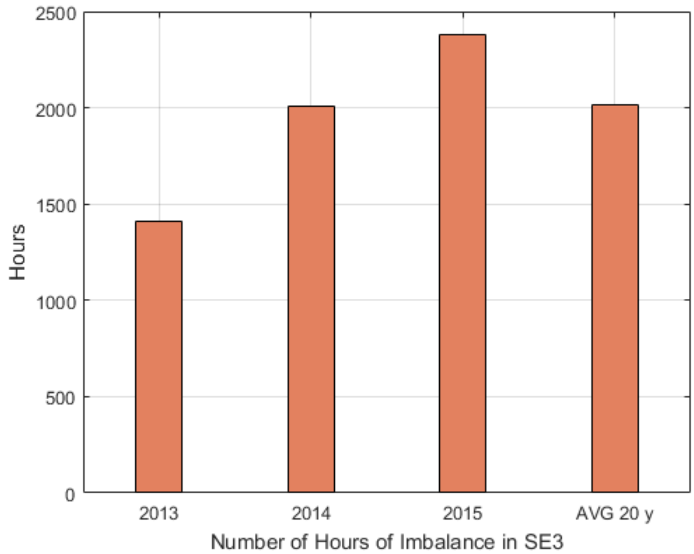


Figure 4.9: Hours of imbalance in SE3 for the years 2013, 2014, 2015, and an average of 20 years based on simulated data

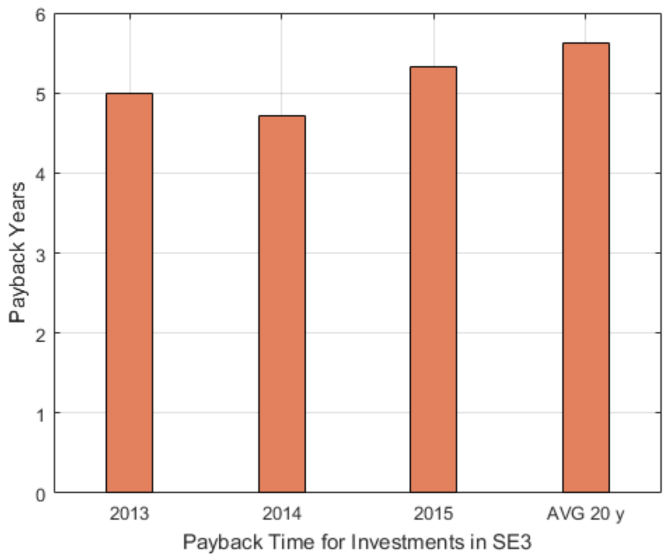


Figure 4.10: Corresponding payback time for installations in SE3 based on the data from 2013, 2014, 2015 and the simulated data for 20 years

Chapter 5

Discussion

In addition to the investigated factors within the three studied areas, there are some more points that need to be clarified or further explained.

A switch from passive to active rectification could prove viable if certain technical and cost conditions are fulfilled. Economies of scale is a very important factor in this concept where sizes larger than 500 kW appear to be the most cost-efficient options for active rectification. With regard to a comparison between active rectifier and other reactive power utilities, it shall be noted that reactors in particular are drastically costly compared to capacitors with a cost roughly three times as expensive as that of capacitor. Thus, reactor installation cost has the major contribution to the calculations which result in high revenues for rectifier as a power market actor. When the comparison is done individually, rectifier is not an absolute winner against capacitor, though reactors still remain to be the most expensive of the three. There might be no need of comparing capacitors and reactors, as these devices solve different problems. However, from an investor point of view it is important to know the economical potentials for the services they could provide and where lies the most profitable market for their services. Nevertheless, it shall be taken into consideration that perhaps one of the most convenient advantages with rectifiers is the possibility they provide for continuous control of reactive power, a feature which reactors and/or capacitors are devoid of.

All in all, reactive power regulation through active rectification could become a source of income for the whole process of electrofuel production. Especially with taking into account the flexibility of active rectification technology in comparison to other reactive power regulating devices, this technology could not only serve to provide for the investor's duty to the grid, as an actor in the market, but also gain revenues through providing this service on behalf of other market participants.

As for the congestion release service, it is evident that large scale implementation of electrolyser in the power market as a major power consumer, creates a unique opportunity for the investor to play the significant role of congestion release provider in the times of peak demand and leads to shortened payback time for investment. This aspect is particularly highlighted under the prospective disappearance of nuclear generation from the Swedish power market interface. The same aspects apply to supply of reserve service in form of demand response. For the later case, it shall be added that the calculated revenues in the results are based on the actual electricity market prices for each hour of compensation. In a real life case, the prices could/will be higher than the mere cost of electricity, bringing in even higher revenues.

Environmental and Ethical Aspects

It shall be discussed that apart from the revenues for the investor and the lower total system costs, which mainly is of interest to the grid owner, the benefit of large scale installation of electrolyser in the northern part of the country, i.e., SE1 and SE2 is of course the abundance of cheap and clean electricity. In these areas, GHG emissions from generation are close to zero. Moreover, the otherwise curtailed wind power can be efficiently utilized through hydrogen generation and storage.

In the middle part of Sweden, SE3, the possible increase of emissions due to the increased demand is expected to be trivial. It is because of the fact that even large scale electrolyser implementation in this area, after utilizing the nuclear generation to full capacity, activates only the abundant bio generation. Due to the commonly accepted opinion that bio-generation enjoys a closed-carbon-cycle characteristic, the technology is considered an environmentally friendly technology. Although, there are always some fractions of emissions associated with this type of generation source, mainly with regard to the processes before and after power generation, i.e. harvest, transportation, etc.

On the other hand, in a not-inconceivable case of total nuclear phase-out in Sweden, such predictions may not thoroughly hold as the majority of nuclear power plants are located in the southern areas. Nevertheless, with the role of Swedish legislation in support of renewable generation development and the progressively rigorous European standards for decarbonization of Europe, the increase in emissions might never become an actual problem for the case of Sweden.

Last but not least is the expanding integration of renewable energy sources in the power system along with the gradual disappearance of nuclear generated power. Such changes will inevitably lead to increased imbalance and unpredictability in the market, highlighting the perspective for active demand-response role play for electrolyser in the regulating market as well. To all appearances, EFP has the advantage of addressing ethical and environmental aspects of energy production and consumption. It does not necessarily compromise nature's resources, on the contrary it promotes perseverance of green energy technologies and preserving natural resources. The latest is realised through putting a halt on intensive fossil fuel extractions as well as acting as a major carbon dioxide sink and hence releasing the limits on Eco-sphere's assimilation capacity[1].

Concluding Remarks

As yet, an important factor which makes SE3 an interesting investment location is the fact that it is the most populated price-area in Sweden. This factor might be the very first to be considered with regard to the potential market for electrofuels as a green substitute to fossil fuels. An investment as large as, at least, 3700 MW in electrolyser to be installed in SE3 could be considered as ideal if congestion release service is intended to become a source of income for the investor.

In the long run, utilization of EFP for supply of ancillary services might come in different forms. While functioning as a major demand, EFP is able to supply the electric power network with voltage regulation, reactive power, and congestion management. Most possibly, same services and more can be provided by EFP while functioning as a major power producer or a large scale storage facility.

[1]Assimilation capacity is the ability of nature -or a part of nature- to degrade and incorporate substances into the natural cyclic flows of substances. When this capacity is exceeded pollution occurs [57] and [58]

Chapter 6

Conclusion

Large scale investment in electrolyser appears to have a promising perspective. The potential for participating in the electricity market as a market player is high for this technology. Through this study it has been found that, although passive rectification is a more economical option, but the possibility of extra gains through active rectification, and reactive power supply, could cover for and even beyond the 20%-30% cost gap between the two solutions.
Likewise, large scale implementation of electrolyser for congestion release procurement is found to be prosperous. The study showed that providing congestion release service in SE3 could generate revenues as high as 3 million Euros per year, leading to investment payback period of less than 3 years.
Furthermore, investment in large sizes of electrolyser with the possibility of active participation in power regulating market could generate an average income of five million Euros for the investor where the investment will be fully paid back within 4-6 years.

Future Work

EFP is a complicated multi-divisional technology. This study has covered only a small part of the wide concept of ancillary services shedding light mainly on electrolyser and its potential with regard to AS. There are more areas to be investigated where EFP could be an active AS provider. In this context, the most interesting EFP divisions, among others, might be namely hydrogen storage, sabatier reactor, and probably combustion turbines, if any is to be installed.
Hydrogen storage, as well as electrofuel storage, is mainly important due to the opportunity it provides for storing of energy and utilizing the volatile and low/no cost energy sources. Energy storage, along with combustion facilities, is an important resource for supply of ancillary services such as congestion release and reserve service as well as system restore capacity etc. Detailed investigation of each of these areas contribute to acquisition of a deeper knowledge about the prospects

of EFP and its strengths, weaknesses, and opportunities as an ancillary service provider. While strengths and weaknesses concern the features and properties of EF technology as AS provider, hence requiring thorough study of the technology, the opportunities, and probably even threats, of employment of EFP as AS provider are features dependent to the power market. Thus, a detailed study of different power markets, with their different features and properties, where EFP is included as a demand or supply side, shall be a priority, as a better understanding of the power market could open up for new opportunities in this concept.
In a smaller context, a test case study to give forth an analogy with the present project would be of interest. Moreover, the mathematical optimisation model of the power market could be expanded to include a wider area, e.g. Nordic region. Similar approach could be applied to the investigation of regulating power market where a more expansive market can enhance the validity of the results and open up for the study of numerous geographical and technical factors which do not necessarily exist in the Swedish context where the power system profile is rather consistent compared to other European markets.
Furthermore, detailed and precise investigation of future scenarios where considerable alterations to the current market interface are included could as well yield interesting and valuable results.

Bibliography

[1] Regeringskansliet, "Fossiloberoende fordonsflotta - ett steg på vägen mot nettonollutsläpp av växthusgaser." http://www.regeringen.se/rattsdokument/kommittedirektiv/2012/07/dir.-201278/, 2012 (accessed Dec 03, 2015).

[2] Nord Pool Spot, "Nord pool spot /about us." http://www.nordpoolspot.com/About-us/, 2012 (accessed March 24, 2015).

[3] Dr. Anh Tuan Le, *Lecture notes and compendium for the course EEK201 Power Market Management*. Sweden: Chalmers University of Technology, Nov. 2014.

[4] J. C. Galvis and A. P. Feltrin, *Power System Ancillary Services*, pp. 555–579. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.

[5] Techopedia, "Congestion." https://www.techopedia.com/definition/18506/congestion-networks, 2015 (accessed February 03, 2016).

[6] Office of Electricity Delivery & Energy Reliability, "National electric transmission congestion studies." http://energy.gov/oe/services/electricity-policy-coordination-and-implementation/transmission-planning/national, 2015 (accessed January 10, 2016).

[7] T. Le, K. Bhattacharya, and J. E. Daalder, "Review of congestion management methods in deregulated power markets," in *7th IASTED International Conference on Power and Energy Systems (PES 2004), Florida, USA, November 28 - December 1, 2004*, pp. 204–212, 2004.

[8] E. Ela, M. Milligan, and B. Kirby, "Operating reserves and variable generation." http://apps1.eere.energy.gov/wind/newsletter/pdfs/51978.pdf, 2011 (accessed March 19, 2015).

[9] C. Bang, F. Fock, M. Togeby, "The existing nordic regulating power market." http://www.ea-energianalyse.dk/reports/1027_the_existing_nordic_regulating_power_market.pdf, 2012 (accessed December 08, 2015).

[10] SVK, "Svenska kraftnät (swedish national grid)." http://www.svk.se/Om-oss/, 2013 (accessed March 26, 2015).

[11] U. Hammarstedt and M. Nilsson, "Demand response in the strategic reserve - the case of sweden." http://www.elforsk.se/Documents/Market%20Design/projects/ER_14_29.pdf, 2012 (accessed December 10, 2015).

[12] Sveriges Riksdag, "Lag (2003:436) om effektreserv." http://www.riksdagen.se/sv/Dokument-Lagar/Lagar/Svenskforfattningssamling/sfs_sfs-2003-436/, 2003 (accessed Nov 28, 2015).

[13] E. Agneholm, "The restoration process following a major breakdown in a power system." http://webfiles.portal.chalmers.se/et/Lic/AgneholmEvertLic.pdf, 1996 (accessed March 7, 2015).

[14] M. Grahn, M. Taljegård, J. Ehnberg, and S. Karlsson, *Utilising excess power: the case of electrofuels for transport*, pp. 128–137. 2014.

[15] CRI, "Carbon recycling international, power to methanol technology." http://www.carbonrecycling.is/, 2012 (accessed March 24, 2015).

[16] M. Sterner, *Bioenergy and Renewable Power Methane In Integrated 100% Renewable Energy Systems: Limiting Global Warming By Transforming Energy Systems*. Kassel, Germany: kassel university press GmbH, 2009.

[17] S. Schiebahn, T. Grube, M. Robinius, V. Tietze, B. Kumar, and D. Stolten, "Power to gas: Technological overview, systems analysis and economic assessment for a case study in germany," *International Journal of Hydrogen Energy*, vol. 40, no. 12, pp. 4285 – 4294, 2015.

[18] A. Jonatan and L. Emil, "Integration of power-to-gas in gasendal and gobigas," 2013. 56.

[19] B. Kruse, S. Grinna, and C. Buch, "Bellona rapport 2002." http://bellona.org/filearchive/fil_Hydrogen_6-2002.pdf, 2002 (accessed December 7, 2014).

[20] M. Jentsch, T. Trost, and M. Sterner, "Optimal use of power-to-gas energy storage systems in an 85% renewable energy scenario," *Energy Procedia*, vol. 46, no. 0, pp. 254 – 261, 2014. 8th International Renewable Energy Storage Conference and Exhibition (IRES 2013).

[21] All Free Download, "Free vector." http://all-free-download.com/free-vector/download/environmental_and_green_energy_icons_310655_download.html, 2015 (accessed February 18, 2016).

[22] David W. Oxtoby et al, *Principles of modern chemistry, 7th ed.* Portland, USA: Brooks/Cole Publishing, 2011.

[23] F. Senftle, J. Grant, and F. Senftle, "Low-voltage dc/ac electrolysis of water using porous graphite electrodes," *Electrochimica Acta*, vol. 55, no. 18, pp. 5148 – 5153, 2010.

[24] E. Mainz, "Technical data about the energiepark." http://energiepark-mainz.de/, 2015 (accessed October 07, 2015).

[25] Z. H. Ryszard Klempka and Y. Varetsky, "Bank harmonic filters operation in power supply system cases studies." http://www.intechopen.com/books/power-quality-issues/bank-harmonic-filters-operation-in-power-supply-system-cases-studies, 2013 (accessed February 18, 2016).

[26] P. Bulent Sarlioglu, "Comparison of power quality solutions using active and passive rectification for more electric aircraft." http://icas.org/ICAS_ARCHIVE/ICAS2006/PAPERS/571.PDF, 2006 (accessed November 03, 2015).

[27] A. Prasad, P. Ziogas, and S. Manias, "An active power factor correction technique for three-phase diode rectifiers," *Power Electronics, IEEE Transactions on*, vol. 6, pp. 83–92, Jan 1991.

[28] C. Azcrate, R. Blanco, F. Mallor, R. Garde, and M. Aguado, "Peaking strategies for the management of wind-h2 energy systems," *Renewable Energy*, vol. 47, no. 0, pp. 103 – 111, 2012.

[29] J. Andrews and B. Shabani, "Re-envisioning the role of hydrogen in a sustainable energy economy," *International Journal of Hydrogen Energy*, vol. 37, no. 2, pp. 1184 – 1203, 2012. 10th International Conference on Clean Energy 2010.

[30] Energy Storage Association (ESA), "Energy storage technologies." http://energystorage.org/energy-storage/energy-storage-technologies, 2015 (accessed March 19, 2015).

[31] P. Medina, A. Bizuayehu, J. Catalao, E. Rodrigues, and J. Contreras, "Electrical energy storage systems: Technologies' state-of-the-art, techno-economic benefits and applications analysis," in *System Sciences (HICSS), 2014 47th Hawaii International Conference on*, pp. 2295–2304, Jan 2014.

[32] J. Michaelis, F. Genoese, and M. Wietschel, "Evaluation of large-scale hydrogen storage systems in the german energy sector," *Fuel Cells*, vol. 14, no. 3, pp. 517–524, 2014.

[33] J. Ralston, "The sabatier reaction, possible solution to co2 emissions." http://www.pennenergy.com/articles/pennenergy/2010/03/the-sabatier-reaction.html, 2010 (accessed December 22, 2015).

[34] Susan Rogers, U.S. Department of Energy, "Advanced power electronics and electric motors R & D." http://energy.gov/sites/prod/files/2014/03/f13/ape00a_rogers_2013_o.pdf, 2015 (accessed October 19, 2015).

[35] L. D. Sloan, “Economic outlook: survey reveals optimism among specialty manufacturers about future economic growth,” *Chimica Oggi-Chemistry Today*, vol. 33, p. 3, 2015.

[36] Energimarknadsinspektionen (EI), “Normvardeslista elnåt 2016-2019.” http://ei.se/Documents/Forhandsreglering_el/2016-2019/Dokument/Normvardeslista_elnat_2016-2019.pdf, 2015 (accessed October 29, 2015).

[37] Toshiba, “2011 Industrial Catalog: Drives, pac, PLCs.” http://www.esrmotors.com/Literature/Toshiba/VFDs/Catalogs/2011%20Industrial%20ASD%20PAC%20Pricebook_Apr-25-2011-small.pdf, 2011 (accessed November 19, 2015).

[38] J. Thorn. Private Communication, 2015.

[39] Haefely Test AG, Switzerland , “Automatic resonating inductor for use with midas system.” https://update.haefely.com/Midas2880/_private/Instructions%20Manual%20MIDAS%20288x.pdf, 2012 (accessed November 19, 2015).

[40] P. Randall W. Whitesides, “Process equipment cost estimating by ratio and proportion.” http://www.pdhonline.org/courses/g127/g127content.pdfs, 2012 (accessed November 05, 2015).

[41] J. Sweeting, *Project Cost Estimating: Principles and Practice*. Engineering management, Institution of Chemical Engineers, 1997.

[42] B. Amigun and H. von Blottnitz, “Capacity-cost and location-cost analyses for biogas plants in africa,” *Resources, Conservation and Recycling*, vol. 55, no. 1, pp. 63 – 73, 2010.

[43] Simple maps, “Free svg maps — resources.” http://simplemaps.com/resources/svg-maps, 2015 (accessed November 03, 2015).

[44] Nordpool, “Prognosis for trading capacities.” http://wwwdynamic.nordpoolspot.com/marketinfo/transmission/show-transmission.cgi, 2015 (accessed April 23, 2015).

[45] J. Lagorse, M. G. Simoes, A. Miraoui, and P. Costerg, “Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications,” *International journal of hydrogen energy*, vol. 33, no. 12, pp. 2871–2879, 2008.

[46] www.xe.com, “Xe currency converter.” http://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR, 2015 (accessed April 22, 2015).

[47] U. S. Energy Information Administration (EIA), “Annual energy outlook 2015.” http://www.eia.gov/forecasts/aeo/electricity_generation.cfm, 2015 (accessed April 22, 2015).

[48] S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe, "National renewable energy laboratory." http://www.nrel.gov/docs/fy13osti/56266.pdf, 2011 (accessed April 22, 2015).

[49] International Energy Agency, Nuclear Energy Agency, Organisation for Economic Cooperation and Development, "Projected costs of generating electricity 2010 edition." https://www.iea.org/publications/freepublications/publication/projected_costs.pdf, 2010 (accessed April 27, 2015).

[50] C. Baldwin, "Oil price to average 80.22 usd a barrel in 2010." http://uk.reuters.com/article/2010/05/25/energy-price-poll-idUKLNE64O01A20100525, 2010 (accessed April 23, 2015).

[51] Trading Economics, "Brent crude oil 1970-2015 data." http://www.tradingeconomics.com/commodity/brent-crude-oil, 2015 (accessed April 27, 2015).

[52] Skogsstyrelsen, "Skogsstatistisk årsbok 2014." http://www.skogsstyrelsen.se/Myndigheten/Statistik/Skogsstatistisk-Arsbok/Skogsstatistiska-arsbocker/, 2014 (accessed April 22, 2015).

[53] Vattenfall, "Vattenfall changes direction for operational lifetimes of ringhals 1 and 2." http://corporate.vattenfall.com/news-and-media/press-releases/2015/vattenfall-changes-direction-for-operational-lifetimes-of-ringhals-1-and-2/, 2015 (accessed April 22, 2015).

[54] M. Paulus and F. Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in germany," *Applied Energy*, vol. 88, no. 2, pp. 432 – 441, 2011. The 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, held in Dubrovnik September/October 2009.

[55] Nord Pool, "Historical market data." http://www.nordpoolspot.com/historical-market-data/, 2015 (accessed January 03, 2016).

[56] Svensk Vindenergi, "Vindkraftstatistik och prognos." http://www.vindkraftsbranschen.se/wp-content/uploads/2015/11/Statistik-och-prognos-vindkraft-20151104.pdf, Kvartal 3 2015 (accessed November 06, 2015).

[57] Encyclopedia.com, "Assimilative capacity." http://www.encyclopedia.com/article-1G2-3404800126/assimilative-capacity.html, 2016 (accessed March 05, 2016).

[58] S. Karlsson, *Man and Materials flows / Towards sustainable materials management.* the Baltic University Programme, Ditt Tryckeri, Uppsala 1997, 1997.

List of Figures

List of Tables