Strategic Reserve as a Danish Capacity Remuneration Mechanism

The impact of strategic reserve remuneration for decentralised combined heat and power plants

Daniel Møller Sneum | Master's Thesis | Sustainable Energy Planning and Management | Aalborg University | 2013-2014

Aalborg University

M.Sc.(Eng.) in Sustainable Energy Planning and Management, 4th semester (thesis)

Project title

Strategic Reserve as a Danish Capacity Remuneration Mechanism
- The impact of strategic reserve remuneration for decentralised combined heat and power plants

Project period

September 2013 to January 2014

Author

Daniel Møller Sneum

Supervisor

Anders N. Andersen

Number of printed copies

3

Pages

101

Front page shows key terms and words applied in the project

Summary

This Master's thesis investigates strategic reserves (SR), a capacity remuneration mechanism, in a general energy economic perspective, and in a narrow perspective as a potential means to ensure maintained thermal capacity in the Danish transition to a renewable energy system by inclusion of decentralised combined heat and power plants (DCHP). Strategic reserves are investigated through interviews and literature reviews. In addition to this analysis, techno-economic analyses have been carried out on different types of equippings of a typical Danish DCHP, to determine the required level of SR remuneration. These analyses have been performed through modelling in the energyPRO software, and includes a reference scenario of 2013 with the current equipping of the DCHP. For 2020, equippings of business as usual, solar heating, heat pump and a new, more efficient engine has been modelled. The results show that requirements for remuneration varies among the scenarios, since their revenue from the spot market – the alternative to operating as strategic reserve – depends on the equipping of the DCHP. Furthermore, the analysis shows that under the given conditions, the only option under which the DCHP will be business economically better off than 2013, is if a heat pump is installed. Since none of the scenarios are better off entirely without electric production capacity, it is concluded that SR is not a necessary measure to maintain capacity from DCHP. However, SR might be relevant to apply, in case remuneration is at levels where reinvestment and overhaul of capacity becomes feasible.

Aalborg University
Department for Development and Planning
Vestre Havnepromenade 5
9000 Aalborg, Denmark
http://plan.aau.dk/

Preface

This Master's thesis was carried out by Daniel Møller Sneum during the 4th semester of the M.Sc. programme in Sustainable Energy Planning and Management at Aalborg University. The study has been carried out between September 2013 and January 2014.

The topic of the thesis is strategic reserves and the consequences of their application in the energy economy in general and for combined heat and power plants in particular. This topic has been chosen since the energy economy and the transition towards a sustainable energy system is fundamental to the Master's programme and of substantial scientific interest to the author.

The author lives in Copenhagen, and Anders N. Andersen has kindly hosted supervision sessions at EMD International A/S in Aalborg.

The energy consultancy Ea Energy Analyses have generously hosted the author during the studies in Copenhagen.

Referencing is carried out according to the Chicago Manual of Style (author, year) and the bibliography is found at the end of the report. The attached cd contains recordings of the interviews carried out during the study, and output sheets supplementing the techno-economic analysis performed in the modelling software energyPRO. Tables and figures are sequentially numbered, while the relatively few equations are not.

Many people have been helpful during this study and the author wishes to thank the following for their assistance:

- Alexander Chaplin, M.Sc. Eng.
- Anders Plejdrup Houmøller, CEO, Houmoller Consulting
- Jesper Koch, Manager, Green Energy
- John Tang, Head of section, Danish District Heating Association
- Jørgen Bukholt, Manager, Hvide Sande Fjernvarme
- Kim Clausen, Technical consultant, Green Energy
- Morten Sommer, Economist, Energinet.dk
- Nina Detlefsen, Senior consultant, Insero Energy
- Rasmus Lund, PhD, Aalborg University
- Simon Müller, Energy analyst, IEA
- The full staff of Ea Energy Analyses

A special appreciation goes to supervisor Anders N. Andersen, for providing generous hosting in Aalborg and for his constructive input during the study.

Tak, mor, far og familie for den vedholdende og gavmilde støtte I på alle tænkelige måder har givet mig gennem mine studier. Jeg håber at kunne give det videre.

The author wishes to extend his warm gratitude to Emma Andrés og Kapt. Chr. Emil Andrés Familielegat for support throughout the studies.

TABLE OF CONTENTS

1. Introduction

Two subjects are currently debated both publicly and in the corridors of the Danish energy sector. The first is a new way of restructuring the power market by introducing so-called capacity remuneration mechanisms (CRM). The second is the future of the Danish power system, where questions are raised about security of supply and poor power plant economy. These two subjects are interwoven, and this study brings them together in an analysis of how a CRM can influence the economy and operation of Danish decentralised combined heat and power plants (DCHP), and how such a mechanism will perform in a broader energy-economic perspective.

1.1. Problem Statement

Introducing increased amounts of renewable energy sources with variable production requires a resilient energy system in order to maintain technical stability. The Danish power system can be considered quite resilient. In fact, Denmark has been ranked first in class in regard to electricity grid flexibility (Chandler 2011). The Danish electricity sector is liberalised and based on an energy-only market[1], where energy is traded on the spot market. Furthermore, the Danish energy system is characterised by a significant deployment of variable renewable energy (VRE), as a consequence of political prioritisation and support-schemes the last decades. The development in capacity of central power plants, DCHPs and wind power is seen on Figure 1.

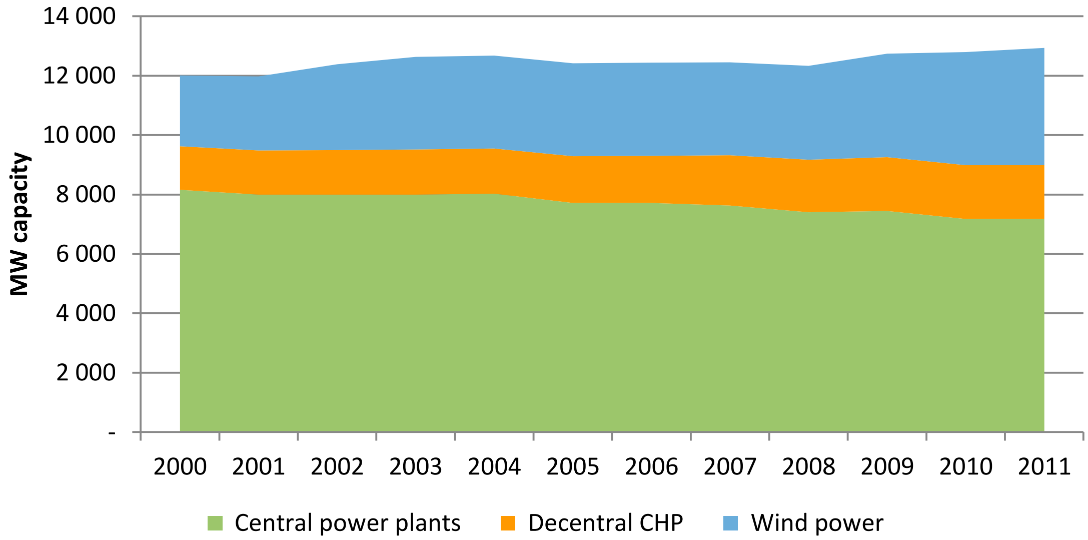


FIGURE 1 THE ELECTRICITY CAPACITY OF WIND POWER, DCHP AND CENTRAL POWER PLANTS IN DENMARK (DANISH ENERGY AGENCY 2012A)

The ambition in current Danish energy policy shows a continuation of this development: by 2020, the Danish ambition is to have 50 % of the electricity demand covered by wind power (Danish Ministry for Climate Energy and Building 2013a). Under these conditions, an important challenge has emerged, since adding subsidised VRE to the liberalised power market makes the investors and owners of thermal power plants[2] question the long-term profitability of their power plants as they are increasingly confronted with fewer operating hours and lower electricity prices. Among these plants are the DCHP which are distributed across Denmark. Official numbers set the amount of plants to 285, with a total installed capacity of 1811 MW_e in 2011, equalling roughly 30 % of the peak load and 20 % of the thermal electrical

[1] Further details on this in Chapter 3

[2] In this study defined as fuel-based power plants with the ability to cycle their production in on/off-mode, and to ramp output up and down on demand, within the technical boundaries.

capacity in Denmark (Danish Energy Agency 2012a). As is seen in Figure 2, there has been a general decline in the electricity production from DCHPs since 2000, while wind power production has increased[3] .

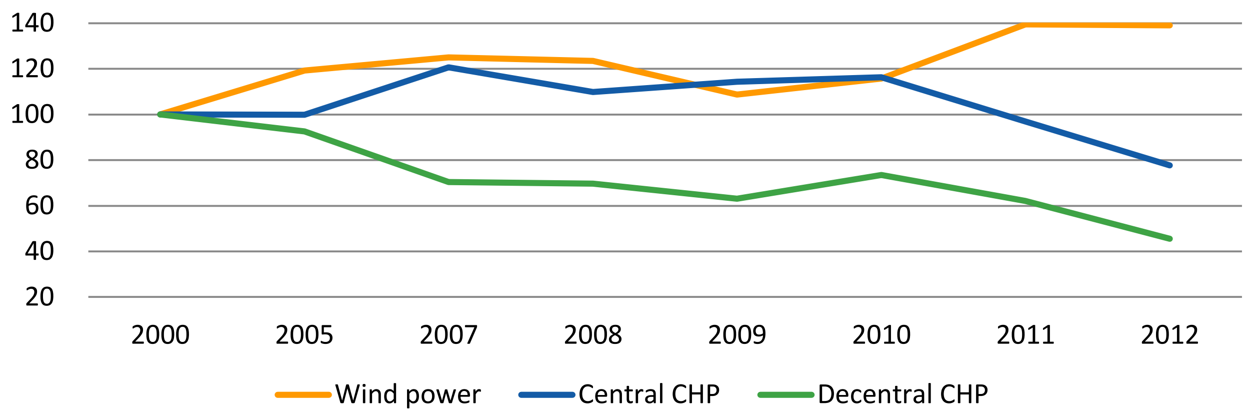


FIGURE 2 THE ANNUAL ELECTRICITY PRODUCTION FROM DCHP (GREEN ENERGY 2013A)

Figure 2 should not be interpreted as a conclusive argument for steadily decreasing production from DCHP in the years to come, since the price-setting of electricity is influenced by the surrounding countries through trade in the Nordic power market Nord Pool Spot[4] and on the German market. However, it does provide a framework for understanding the results of a recently conducted survey on Danish DCHP, where a majority of the plants either decided against, or were at least uncertain on whether to prolong the lifetime of their electricity generation when the fixed amount of operating hours on their engines and turbines have run out. See Figure 3.

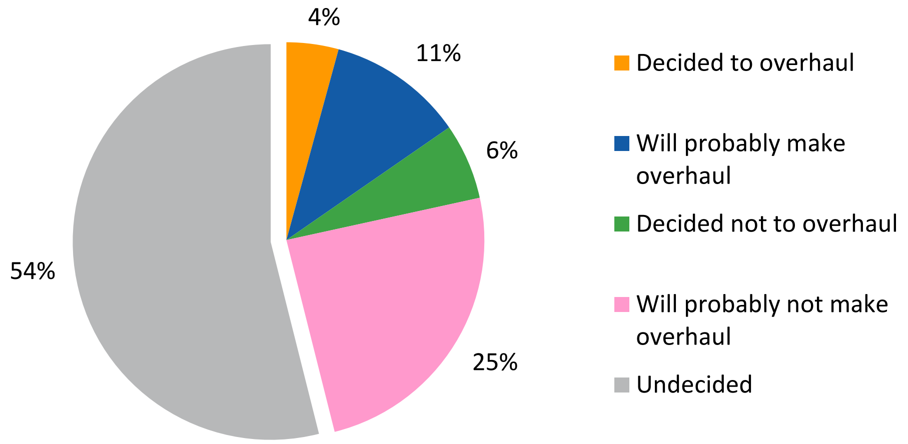


FIGURE 3 DCHP REPLIES ON THEIR PLANS FOR LIFE-EXTENSION OF THEIR ELECTRIC CAPACITY (GREEN ENERGY 2013B)

[3] IEA has shown that in order to achieve a carbon neutral Nordic energy system, the wind power share of electricity generation should go from the current 3 % to 25 % in 2050 (International Energy Agency and Nordic Energy Research 2013). While carbon neutrality can be achieved in many other ways, the numbers merely illustrate the potential order of magnitude of wind power deployment.

[4] Variations in annual electricity production are not uncommon and are associated with either dry, wet or normal years in which the Scandinavian production of hydropower either increases or decreases correspondingly.

The liberalisation of the Danish power sector enabled the participation of DCHP on the market. But at the same time, the output of both wind power and DCHP is favoured with special conditions on this market. In the case of DCHP, the plants get the so-called *production-independent payment*[5] (PIP), a capacity payment that guarantees the power plants a certain level of income in return for maintaining the availability of their electricity generating equipment on the market. According to a study conducted by Green Energy (2013b), the main reason for the rejection and uncertainty towards the life-extension of generation capacity, is the expiry of the production independent payment from 2019, as this is especially significant in the business economy of DCHPs during periods with low electricity production. The second most important parameter is the price of commodities since the majority of the DCHPs are required to use natural gas in their power production (Danish Ministry for Climate Energy and Building 2013b). Both these arguments essentially concern issues of profitability and competitiveness of the power plants. The concerns regarding future profitability of power plants extends beyond DCHPs; utilities such as German RWE and Swedish Vattenfall, Danish DONG and several other European power companies have, during the last three years, seen asset impairments on the generation-side and reductions in their installed thermal generation capacity (Dong Energy 2012; EY 2013). It is important to note that these matters are not only gaining attention from companies but also from the Danish authorities, who, simultaneously with this present study, are conducting analyses on matters such as, *How much capacity should the centralised power plants have?,* and *What role should the decentralised power plants play in the energy system?*[6] (Lidegaard 2013). On a similar note, the Ministry of Climate, Energy and Building (2013a) has raised the question how investment in capacity can be sufficiently incentivised in a future with more wind power. *The Economist* (2013) has summed up the list of challenges for the European power sector in the following way:

- Reduction in demand due to the recession
- A broken EU Emissions Trading System
- Cheap shale gas in the USA, leading to exports of American coal to EU, which makes coal-based plants outperform gas-based plants
- Increased amounts of subsidised renewable energy generators, and in turn low-cost electricity from these

Another approach to the explanation, but with a similar message, has been provided by IHS CERA (2013), illustrating the challenges as seen on Figure 4. In a Danish context, the combined cycle gas turbines could equally well be the natural gas-fired DCHPs.

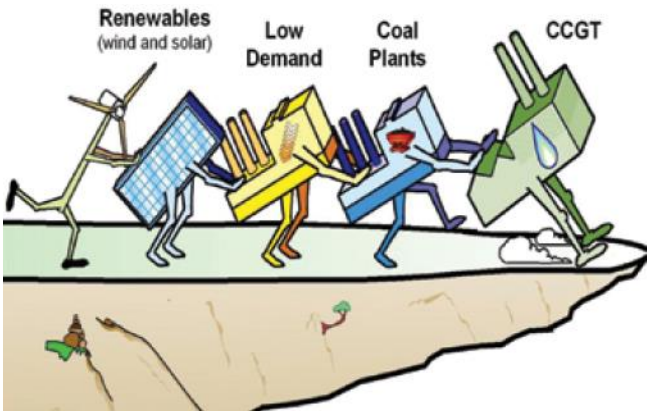


FIGURE 4 ILLUSTRATING THE CURRENT CHALLENGES IN THE EUROPEAN ENERGY SYSTEM

[5] Translated from its Danish name *produktionsuafhængigt tilskud* or *grundbeløb*. This will be described further in Chapter 5

[6] Translated from Danish: *Hvor stor kapacitet skal de decentrale kraftvarmeværker have?*, and *Hvilken rolle skal de decentrale værker spille i det samlede energisystem?*

In order to deal with these issues, and essentially to ensure a certain level of electricity generating capacity to provide a desired level of security of electricity supply, various types of CRM have been applied in different power systems. Such mechanisms are presently being debated in the EU, where actors such as the European Commission, the Agency for the Cooperation of Energy Regulators, the Italian transmission system operator TERNA, the Department of Energy and Climate Change in the UK and German regulators are engaged in studies of capacity mechanisms (IHS CERA 2013). The official Danish policy is generally critical towards capacity mechanisms, but it is argued that the potential need for additional capacity could be secured through procurement of strategic reserves (SR) (Danish Energy Agency 2013a; Montel Online 2013a). If a CRM was to be introduced in Denmark, SR appear as the most probable type, which is the reason for choosing this CRM for the study.

1.2. Research Questions

> *The most important challenge for policy makers over the next decade will likely be the shift away from a supply-driven perspective, to one that recognises the need for systems integration* (IEA 2012, 10)

It is the assumption in this study that an improved focus on the integration and interaction of different parts of the energy system will become increasingly important. This challenge is what ties the elements in the problem statement together: the increase in VRE and the apparent decrease in the profitability of DCHPs need to be considered together. The underlying argument is that district heating systems could help in balancing variable and uncertain production from VRE. This can happen both through electricity-to-heat-options and by having fast and flexible capacity to fill in, when the VRE is not producing. Economic viability is usually determined by the ability to make sufficient profit on the longer term, and DCHPs are not considered any different in this regard. Hence, their incentive to establish, offer and maintain capacity is largely determined by the economic benefit of doing so. The production independent payment will be phased out from 2019 and from this point onwards, the DCHPs will be experience harder market conditions. Assuming that a CRM will be introduced in Denmark, this project analyses how such a mechanism can affect the operation and economy of a DCHP, now and in the future. The research questions are as follows:

- **What are the general energy-economic implications of strategic reserves as a capacity remuneration mechanism?**
- **What is the economic and operational performance of a Danish decentralised combined heat and power plant with various types of equipping under current- and 2020-conditions on the spot market?**
- **What should be the concrete remuneration from a strategic reserve to decentralised combined heat and power plants in current and future conditions, in order to provide a business-economic incentive for participating in a strategic reserve?**
- **Will such remuneration from SR contribute to maintaining electrical generation capacity among decentralised combined heat and power plants?**

The results of the analysis show economic and operational consequences for the Danish DCHPs. These results will contribute to an increased understanding of the future of the DCHP in Denmark if strategic reserves are introduced.

1.3. Analytical Framework

As defined in the research questions, this study deals with specific elements of a CRM and its effect on DCHP. While that subject is rather concrete, this section presents the more holistic perspective on how the study is approached, i.e. a bird's eye view on the framework under which the study is conducted.

Energy economy, in this study defined as satisfying energy needs in a world of scarce resources, is considered a key aspect of this study. Professor Frede Hvelplund (2013) has characterised the energy economist as the proverbial gardener, nurturing the societal soil, facilitating preferred (technical) solutions to grow from it. Applying this perspective on the many challenges associated with unfavourable externalities of the energy system, can provide part of the explanation why all these problems persist despite a multitude of technical solutions: the technical solutions might be present, while the economic framework is not. Hence, in this study the critical point is perceived to be making the transition to a sustainable energy system pay for both business and society. Such an approach is illustrated by Figure 5, where *Situation 1* on the left sees a discrepancy between the socio-economic optimum *Socio-Economy I* and the business economic optimum *Business Economy I*. By changes in the market *Market Economy I* and the public regulation *Public Regulation I*, a new optimum *Business Economy II* can be achieved in *Situation 2*, where also both societal and business priorities are satisfied.

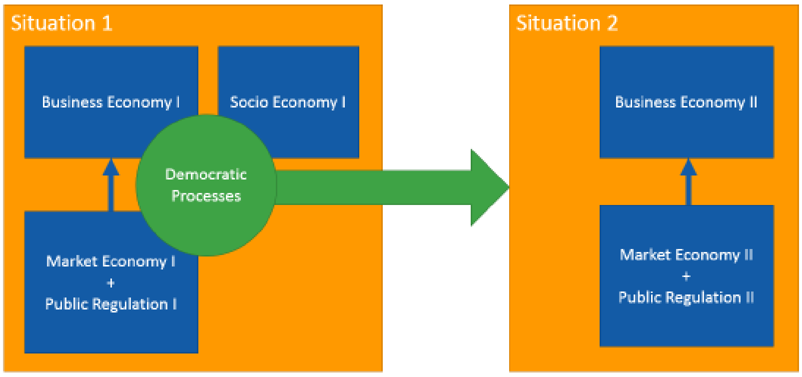


FIGURE 5 OBTAINING BUSINESS- AND SOCIO-ECONOMIC OPTIMAL SITUATIONS. FIGURE BASED ON LUND AND HVELPLUND (1998)

The author's personal experience indicates that such a perception is often seen as provocative, highly politicised and as an unnecessary intervention in the market. It is the perception in this study that such argumentation is countered by real life evidence, where energy markets are imperfect for reasons such as general externalities, inflexible demand and the commonplace political interventions in the regulation and the construction of markets. Thus, the perception in this study is that such regulation in the market economy and public regulation can and will happen in the future, in order to ensure socio-economically optimal solutions. In the context of this study, this means facilitating a business environment that motivates the supply of sufficient electricity generating capacity in order to avoid socio-economic costs due to shortages in electricity supply. Figure 6 illustrates the approach in this study.

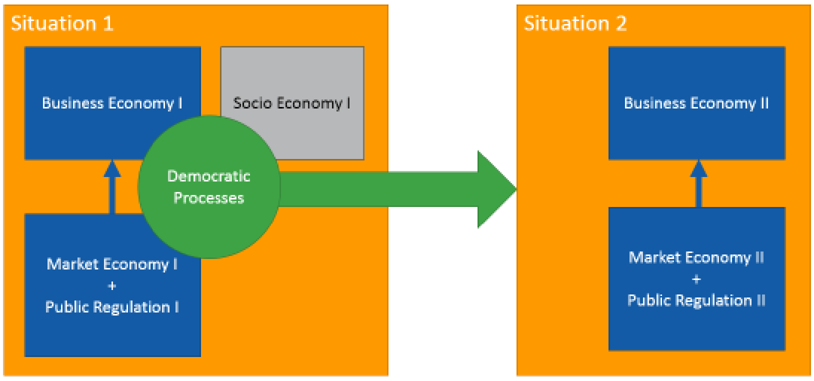


FIGURE 6 THE ANALYTICAL APPROACH IN THIS STUDY

As indicated in Figure 6, this study does not calculate specific socio-economic costs and benefits, but focuses on the current business-economic consequences of *Market Economy I + Public Regulation I*. By defining new conditions through the introduction of a strategic reserve in *Market Economy II + Public Regulation II*, the *Business Economy II* is then analysed for *Situation II*, to see what impact the strategic reserve mechanism can have on a DCHP.

1.4. Delimitation

Energy planning spans from detailed technical solutions to broad societal consequences. In order to focus on the analyses of this study, certain elements have been prioritised over others. This section provides an overview of the prioritisation.

- As indicated by Figure 6, socio-economic analysis is necessary to determine the full societal impact of markets and regulation. A full analysis of the consequences of introducing strategic reserves would thus entail further studies than the business-economic. Such analysis is considered outside the focus of the current project. Instead, this study can be considered as a part of a potentially larger analysis, spanning both business- and socio-economic aspects
- The application of CRM is likely to become a cross-border issue. However, this study does not apply a national or international energy system-perspective, since the focus is rather on the specific consequences for a single power plant. Additionally, the geographic focus is limited to the DK1 region, which covers Western Denmark. The reason for this delimitation is twofold: firstly, since the CHP in the case study is found here, secondly, due to the majority of Danish wind power being part of this region. The geographical limitation furthermore limits the study boundaries to the Nordic spot market
- Ancillary services are not included in the study, due to time limitation
- The time horizon dealt with is 2020, and, unless stated otherwise, events such as investments and refurbishments pre-2020 and post-2020 are not considered
- The aim of this study is not the design of a perfect market or a strategic reserve in particular. Instead, it is to establish a framework of such a market under which the analysis can be conducted. The study will, however, conclude on the consequences of the strategic reserve and thus also on the implications of this type of regulation
- Technological aspects related to the equipping of the plant are not addressed in detail, and certain simplifications are assumed for physical and technological characteristics of the energy conversion units. Examples are simple assumptions on the coefficient of performance and the heat sources for heat pumps, simple assumptions on the placement of solar heating arrays and simple assumptions on equipping an engine with improved efficiency
- The power system can be divided into three physical components: producers, consumers and the grid connecting them. Changes in either of these components are assumed to create impacts on the two others, but since the focus is put primarily on the producer-side, the grid and the demand-side[7] are not included. Furthermore, the techno-economic study is performed on a single plant, which is assumed representative for DCHPs

[7] One exception is the application of an electricity-consuming heat pump.

2. Methodology

This chapter provides an overview of the methods applied in the study. In addition to thorough desk research on the fundamentals of CRM, Danish CHP-regulation and energy economy, two main methods are applied in this project: interviews and modelling. The qualitative data made available through the interviews, provides empirical knowledge on capacity remuneration mechanisms and concrete data on the case study. The quantitative perspective of the study is provided by a model, which supplies concrete and quantifiable results for the analysis. The methodologies applied are outlined in Table 1, followed by elaborations in the ensuing sub-sections.

TABLE 1 THE METHODS APPLIED IN THE STUDY

Main method	Subdivision	Purpose
Desk studies		
	Legal documents, reports, books, scientific papers etc.	Establishing a fundamental understanding of energy economy, theories of- and experiences with CRM, terminology, Danish tax-structure pertaining to DCHP and legal framework etc.
Interviews		
	Morten Sommer, Energinet.dk	In-depth knowledge about matters on policy and legislation, hereunder TSO's perspective on CRM
	Jørgen Bukholt, Hvide Sande CHP	Qualitative and quantitative data on a single DCHP, providing input for the modelling
	Anders Houmøller, Houmøller Consulting	Knowledge on energy economy, markets and the potential consequences of a CRM, hereunder policy and legislation
Modelling		
	Techno-economic analysis in energyPRO	Showing the impacts of various equippings of a single power plant under different market conditions

2.1. Report Structure

Figure 7 depicts the structure of the report, where the issues identified in Introduction (Chapter 1) provide the framework of the entire study. Methodology (Chapter 2) defines the approach to the descriptive as well as the analytical aspects of the study. Power Systems and Their Economics (Chapter 3) lays out the foundation for understanding the concepts presented in Strategic Reserve (Chapter 4). Case Study: Hvide Sande CHP (Chapter 5) provides the framework for the model and a fundamental introduction to the context of Danish DCHPs. After establishing the overall framework of the analysis, the Techno-Economic Analysis (Chapter 6) is carried out, followed by the Sensitivity Analysis (Chapter 7). Finally, further perspectives are treated in the Discussion (Chapter 8), while the Conclusion (Chapter 9) completes the study.

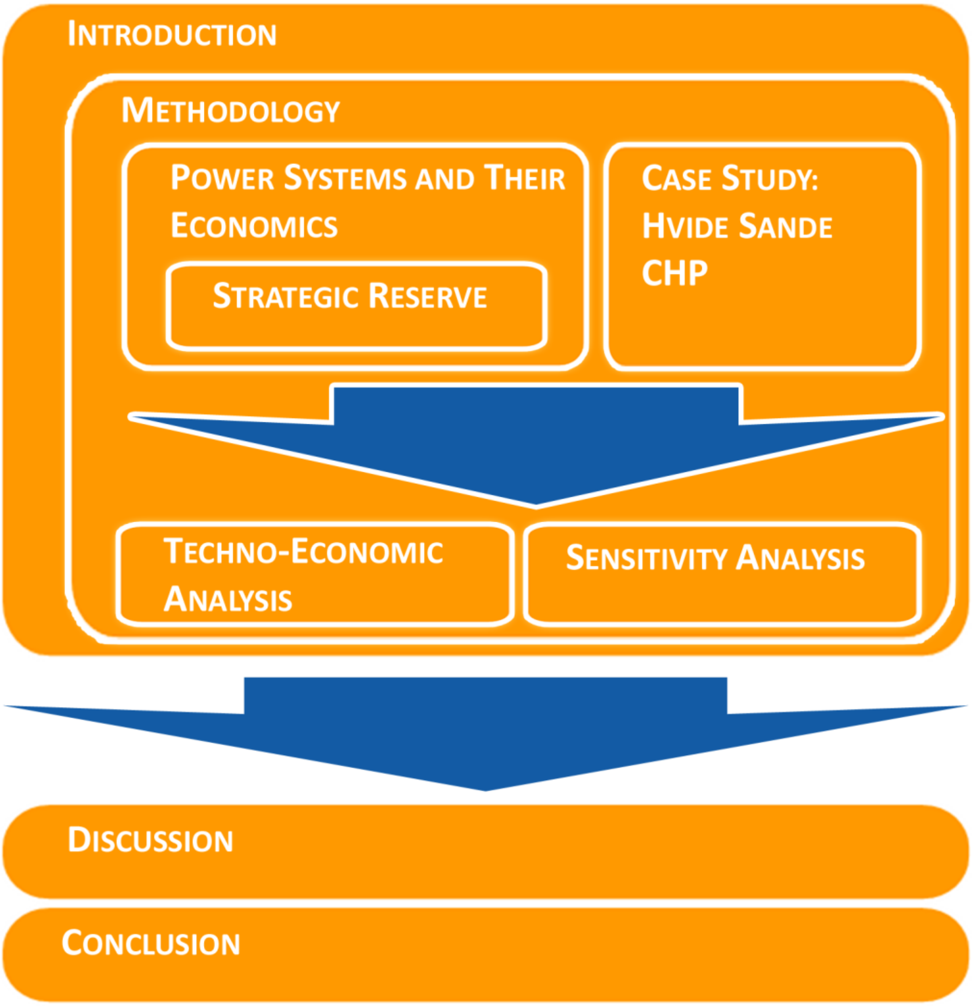


FIGURE 7 PROJECT STRUCTURE

2.2. Interviews

As seen in Table 1, three interviewees have provided input to this study. All interviews have been accomplished using a partly structured approach, as defined by Andersen (2008). This method has been chosen in order to strike a balance between obtaining the necessary information specified in a pre-defined question-guideline, and at the same time to provide an open framework for the informant, hereby opening for new information that might arise during the interview.

2.2.1. Morten Sommer, Energinet.dk

Morten Sommer, economist at Danish TSO Energinet.dk, deals with market-related issues, hereunder CRM, in Energinet.dk. The interview was carried out early in the study in order to obtain inputs on the general understanding of markets, CRM and on the views of Energinet.dk on CRMs. His views are his own and they do not represent the views of Energinet.dk.

2.2.2. Jørgen Bukholt, Hvide Sande CHP

Jørgen Bukholt, supervisor on Hvide Sande CHP. Bukholt has provided detailed information on the plant, ranging from technical and operational issues to economic details, including the participation on power markets and specific material on expenditure and revenue.

2.2.3. Anders Houmøller, Houmøller Consulting

Anders Houmøller, CEO in Houmøller Consulting, is an energy market specialist. The interview was carried out early in the study in order to gain inputs to the general understanding of markets and CRM, including Houmøller's own suggestion for the design of a CRM.

2.3. Modelling in energyPRO

One of the main purposes of this study is to analyse the techno-economic differences in operation, respectively on the spot market and under SR-regulation. The energy modelling software energyPRO was chosen for this study, since it specifically allows the analysis of a single plant under these conditions. energyPRO is an energy-modelling tool that allows analysis of local energy systems. It is a deterministic input/output model that provides techno-economic analysis of CHP plants and several other types of production- and consumption units. The calculations are in this case performed in steps of one hour over the duration of one year. Numerous economic and technical inputs are used as critical parameters in the model. These include the heat demand, the power markets, the equipping of the plant and meteorological data. The inputs utilised in this study are presented respectively in Chapter 5 on Hvide Sande CHP and in the techno-economic analysis in Chapter 6. The output from the model shows economic data for the plant, detailed in monthly and yearly cash flows, specified according to different sources of revenue and expenditure. Similarly, the operation is analysed through parameters such as operation hours, heat production and fuel consumption. Additionally, the model provides a visual representation of the operation, allowing a detailed analysis of individual weeks, days and hours. A selection of these outputs has been chosen to represent key parameters in the study. These are found in the techno-economic analysis in Chapter 6.

2.3.1. Operation in energyPRO

The model is a simplification of complex systems, where certain assumptions are needed in order to have manageable inputs, processing and outputs. In modelling the DCHP, the following definition is descriptive of the perspective applied:

> *The company is seen as a rational, profit-maximising entity […] that aims towards creating the largest possible profit for its owners.*[8] (Sornn-Friese 2007, 23)

Some conditions of this assumption do not apply perfectly in the real world. One important example in this case is the Hvide Sande CHP, bidding in on the spot market in a regular schedule, and in blocks of four hours. This means that the plant might not be winning all the bids at the spot market that it could have done. Another example is the fluctuation of the gas price in the real world, which in the model is assumed constant over the year. These differences make a precise calibration of the model impractical, since the operation of the real-world plant under some parameters is not as economically efficient as the model assumes, while the opposite is the case in other instances. Furthermore, the model cannot take into consideration that the staff of the plant might be performing more economically efficient on matters outside the scope of the model, than if they were to spend their time making detailed bids instead of block-bids. Bidding in on the spot market is determined by concrete techno-economic parameters that are explained in the following part, since bidding is crucial to the understanding of how Hvide Sande CHP and other Danish CHPs are participating on the spot market. Figure 8 illustrates the so-called balance price, i.e. the point where production on the CHP-unit is the same as in the gas boiler. In this example, the balance price between the engines[9] and Gas Boiler 2 is around 550 DKK/MWh_e.

[8] Author's translation. Original text: *Virksomheden opfattes som en rationel profitmaksimerende enhed […], der sigter mod at skabe så stor profit til sine ejere som muligt.*

[9] Both engines follow the same trajectory, and the orange line of Engine 1 is thus hidden behind the blue line of Engine 2

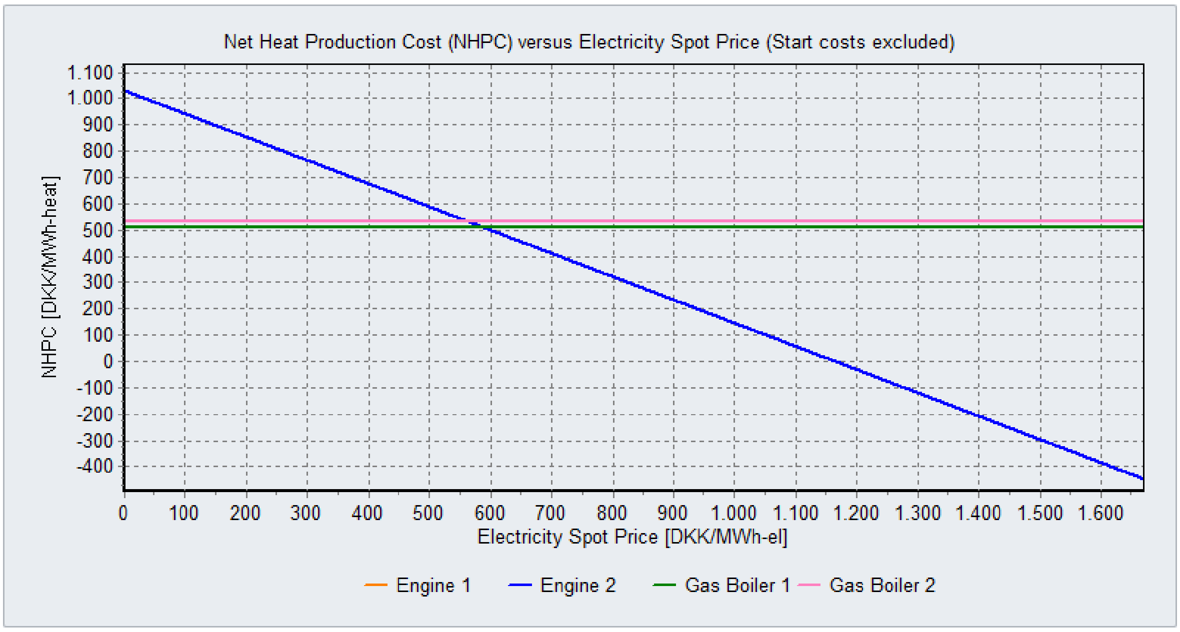


FIGURE 8 EXAMPLE OF BALANCE PRICE BETWEEN TWO ENGINES AND TWO BOILERS

The calculation is as follows

$$B = \frac{P_{eng} - P_{boi}}{\frac{O_e}{O_{th}}}$$

Where

B	: bidding price on the spot market per MWh_e, e.g. EUR/MWh
P_{eng}	: cost of producing one MWh_{th} on the engine
P_{boi}	: cost of producing one MWh_{th} on the boiler
O_e	: electricity output in MW_e
O_{th}	: heat output in MW_{th}

The equation shows that the higher the electricity efficiency becomes, relative to the heat efficiency, the lower the bidding price will be. Conversely, a CHP with relatively lower electricity to heat-ratio will have higher bidding prices, all things being equal.

2.4. Investment Calculation

Investment calculation is conducted in the techno-economic analysis in order to determine the value of adding a heat pump to the plant. The investment calculation is performed as explained here. It is assumed that the management of the plant will be interested in the solution where most money is available after a given period. Thus, it is assumed that the plant takes a loan for the investment in 2013, with an annual payment of interest, subtracted an annual amortisation. The annual amortisation is based on the nominal amount[10], which is saved on the plant because of the heat pump. The calculation illustrated below requires performing the steps for each period contained in n:

$$G_{n-1} * (1 + i) - S_{n-1} * (1 + I_n) = G_n$$

Where

G_{n-1}	: account balance in the previous period
n	: the given period of calculation
i	: interest rate
S_{n-1}	: amortisation in the previous period
I_n	: net price index in period n
G_n	: account balance in period n

The method is applied in the investment calculation in Chapter 6.

2.5. Case Study

The case study is a method which can encompass several other methods. Qualitative and quantitative approaches can be included, which is also the case in this study. The case study is applied in situations where there is a requirement for elaborate analysis of a single phenomenon[11] in a concrete context. The purpose is to identify the forces that influence the studied phenomenon in its given context. This does not mean that the results of the case study are solely applicable to the specific phenomenon, since the understanding provided by the case study can be applied in other, similar situations. If the case is indeed generic, the phenomenon can be regarded as a critical case, i.e. a case where the results not only apply to the given study, but possibly also to similar phenomena elsewhere (Flyvbjerg 1991). This study applies the case study method for an analysis of the impacts of different equippings and market-settings on the operation and economy of Hvide Sande CHP (HSCHP). The following section explains this choice in detail.

2.5.1. How Generic is Hvide Sande CHP?

HSCHP is chosen as case study based on its characteristics of fuel supply (natural gas), type of equipping (engines and boilers), year of construction (1994) and electrical production capacity (2*3.73 MW_e). Many Danish DCHPs have a similar set of characteristics, and the following figures compares HSCHP to the 2011-numbers of natural gas-fired, decentralised, engine-based CHPs. According to Danish Energy Agency (2012b), out of 286 DCHP, 223 of these are natural gas-fired, engine-based DCHPs, including HSCHP. All data in the figures is based on Danish Energy Agency (2012b).

[10] *Nominal* defines the amount of money saved in the given year. This means that if inflation in year n is x % different from 2013, then the saved amount in year n is adjusted accordingly to the inflation

[11] In this case *phenomenon* characterises Hvide Sande CHP and the results of the scenario analyses of this CHP

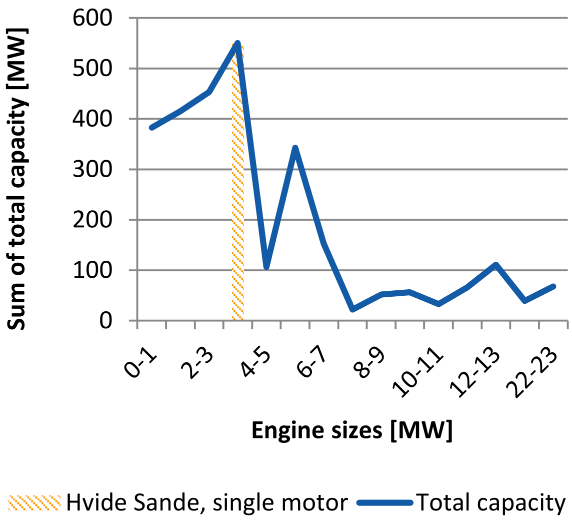


FIGURE 9 DISTRIBUTION OF MOTOR SIZES

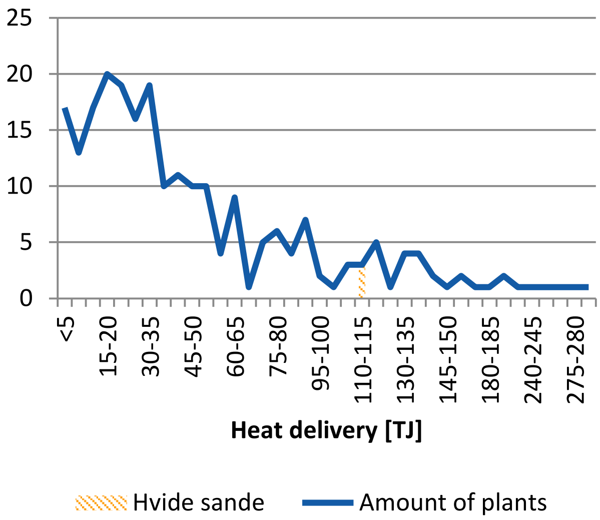


FIGURE 10 TOTAL AMOUNT OF HEAT DELIVERED FROM PLANTS

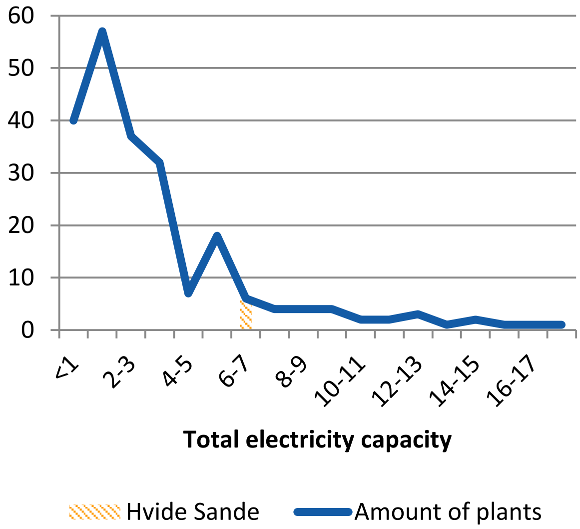


FIGURE 11 DISTRIBUTION BASED ON ELECTRICITY CAPACITY PER PLANT

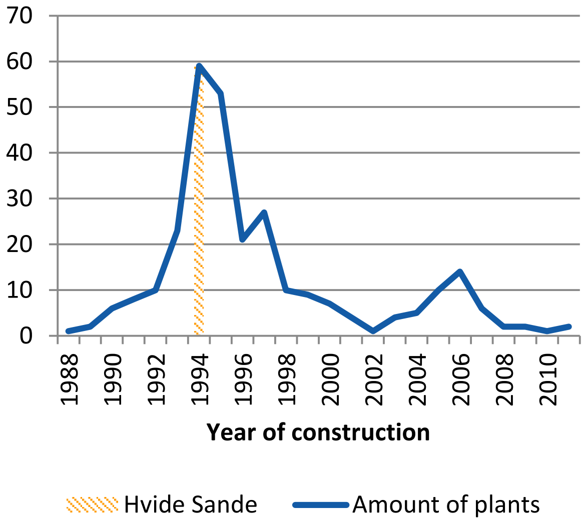


FIGURE 12 YEAR OF CONSTRUCTION

As the figures indicate, the characteristics of HSCHP are common regarding its engine size and its year of construction, while the total electrical capacity and heat delivery are larger than the norm. The latter points are expected to provide a relatively stronger impact of electricity-related prices and to provide a more stable economic foundation due to a larger demand. Neither of the two subjects will be analysed further in this study. Although HSCHP is not a perfectly average plant in all concerns, as the above tables show, the characteristics presented in this chapter are considered to make it a valid critical case for indicating the impacts of implementing strategic reserves.

2.5.2. Focus of the Case Study

While the study is a techno-economic analysis, at the same time it is a business-economic study in the way that a selected company, HSCHP, is analysed. The business-economic focus is specified by the following points, formulated by Sornn-Friese (2007, 10):

- On what should the company base its income?
- How should the company organise its activities?

- Which markets should the company focus on?

These focal points are addressed by the investigation of the possibility for introducing SR remuneration, by investigating different types of equipping and by examining the alternative to operation on the spot market. Jensen and Gaden (2007) describe such a micro-economic model as a magnifying glass that investigates a limited section of the socio-economy. As described in the theoretical framework in Chapter 1, the utilisation of energyPRO in this case study should be considered exactly this way: a smaller part of a whole. Therefore, no focus is put on the national- or socio-economy in this study, but certain elements will be discussed in the Chapter 8.

Another important distinction is the perspective of the analysis. As defined by Sornn-Friese (2007), Jensen and Gaden (2007), a normative approach provides directions on how something should be done in the ideal world to optimise profits, while the descriptive theory rather focuses on the understanding of complex phenomena of the practical actions in the company. This study is primarily normative in its modelling assumptions, and the plant is considered a rational, profit-optimising actor.

Regarding the time frame of the scenarios, the year 2020 is chosen for the analysis for the following reasons:

- 50 % of traditional electricity demand must be covered by wind in 2020, according to Danish policy. This is implied in the projected spot market price
- The production independent payment will be phased out from 1 January 2019. This takes away a significant source of income for the DCHPs
- 2020 is sufficiently far ahead to leave room for investment decisions, but sufficiently close to create a need for having these decisions – and possible political regulation – carried out soon

2.5.3. Why Scenario Analyses?

The establishing of scenarios have been chosen as an appropriate method to resolve the questions asked in the problem statement. The purpose is to establish a series of qualified estimates on the consequences on operation and economy under different conditions. Such an approach requires a fundamental assumption on the predictability of the future and on according planning, as described by Van der Heijden (1996):

> *[…] planning must be based on the assumption that something is predictable. If the future is 100% uncertain, planning is obviously a waste of time*.

Thus, it is acknowledged that the scenarios might not be full representations of the future, but on the other hand that they are qualified estimations on the development under the given conditions.

3. Power Systems and Their Economics

One of the four research questions targets the broader energy economic impact of strategic reserves. This question has three motives. Firstly, since it is assumed on a conceptual level that, when dealing with capacity remuneration mechanisms, one inevitably also deals with the subject of energy economy. Secondly, to address the energy economic aspects of capacity remuneration mechanisms on a theoretical level. Thirdly, to provide a concrete framework for understanding and evaluating the concept of strategic reserves, which is treated in Chapter 4. This present chapter is neither a comprehensive introduction to energy economy nor a simple glossary; instead, it provides a selective insight to subjects and terms that emerge in the span between energy economics and capacity remuneration mechanisms.

3.1. Fundamentals of Power System Economics

This section explains how CRM influences selected fundamental subjects of power system economics.

3.1.1. The Energy-Only Market

The market: *Any context in which the sale and purchase of goods and services takes place.* (Stoft 2002)

This section will present the energy-only market (EOM), a type of market where electric energy is traded, and the market in which the DCHP described in Chapter 5, makes its revenue. The Nordic power market is essentially an energy only market, but two of the TSOs[12] in the Nord Pool area additionally hold strategic reserves (Botterud and Doorman 2008). The EOM, also called a price-based approach, is usually supplemented with some form of procurement of reserve capacity (Cramton, Ockenfels, and Stoft 2013). In the Danish case, this includes frequency containment reserves, frequency restoration reserves and frequency replacement reserves[13]. EOM is a wholesale market, which in many ways functions similarly to the traditional understanding of a market, when prices are formed. As illustrated on Figure 13, the clearing price will arise in the point where supply meets demand. In the case of the day ahead spot market as seen in Nord Pool Spot, such a clearing price will be set for each hour during the following day (Houmoller 2013).

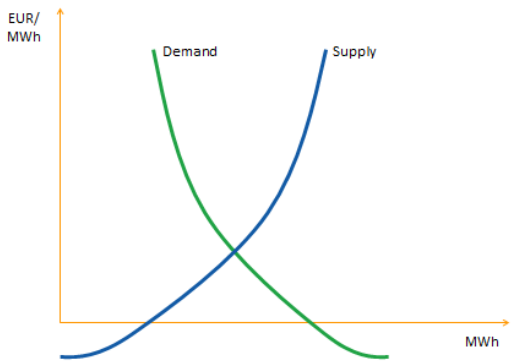


FIGURE 13 CLEARING PRICE ON THE EOM ILLUSTRATED BY SUPPLY- AND DEMAND CURVES

When identifying the clearing price in the spot market, certain assumptions apply when determining whether the given outcome of the market is also economically efficient. These have been defined by Hvelplund, Lund and Sukkomnoed (2007)

[12] Sweden and Finland

[13] These are known under several names, but is here presented under the present terminology (Elgaard 2013). Reserves and their markets are outside the scope of the study and thus not included in further analysis

- Many mutually independent suppliers of a product
- Many mutually independent buyers of a product
- Full information regarding quality and prices of producers available
- Agents in the market, acting with rational behaviour
- Sellers who maximize profits and buyers who maximise utility

Hogan (2013) states that the lack of participation from the demand side means that *this idealized version of an "energy-only" electricity market does not exist.* This central criticism of the EOM will be addressed along with other points in Section 3.2. According to economic theory, in a system with excess capacity, or in fact just as long as the market is efficient, competition among suppliers should drive the market clearing price to the marginal cost of the most expensive producer[14] (Stoft 2002; Hogan 2013). The principle for bidding prices in EOM is illustrated by the merit-order curve on Figure 14, where the different types of generators have different marginal production costs[15].

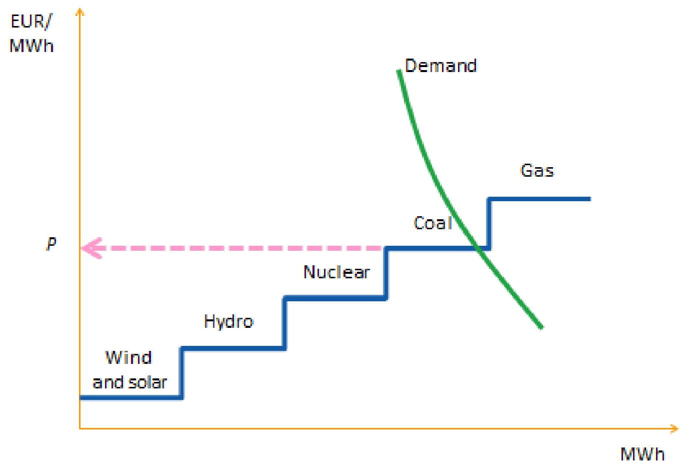


FIGURE 14 MERIT ORDER CURVE, THE MODEL FOR ELECTRICITY TRADE IN NORD POOL SPOT. SCALES ARE FOR ILLUSTRATIVE PURPOSES ONLY

As opposed to a pay-as-bid-market, in the merit order market all producers are paid the same as the winning marginal bid. This means that the generators, who win bids in the merit-order, would be paid the price *P* on Figure 14. Depending on demand and supply, the price for electricity can hence vary. The impacts of both these parameters will be discussed later in this chapter, since they each have significant influence on the functioning of the EOM.

3.1.2. Security of Supply

*Regardless of the electricity market design, from fully regulated monopolies to competitive electricity markets, the common objective of all these approaches is to find the set of rules and regulations that provides **the right amount** and **the right mix of resources**, affordably and reliably.* (Rautkivi 2013)

This quote rightly acknowledges the variety of objectives that are present in the design of the electricity market, and at the same time that these objectives are focused on two things: sizes and types of supply. Both these pertains to security of supply, which in this study is perceived as one of the key focal points in all actions that are carried out in order to regulate or de-regulate the power markets. The goal is not necessarily to achieve the highest possible level of security of supply, but rather to reach an optimal level of security of supply, based on political, economic and/or technological goals. Concrete measures for maintaining the security of supply are *reliability criteria*. CRM are entwined with reliability

[14] Chapter 4 applies the term *balance price*. The two terms are considered the same in this study, but since marginal cost is generally applied regarding markets and energy economics, this term is used in this section

[15] The distinction between marginal costs and capital costs is important, since the relationship is – roughly speaking – inverse to the marginal production cost curve

criteria, since the CRM framework, such as auctioning, is based on achieving sufficient supply to satisfy the reliability criteria (Joskow 2013). These are set in order to achieve a certain probability for maintained security of supply. From the administrative target, the criterion is changed into a concrete reserve margin in MW_e, to accommodate for uncertainties in the demand and availability of power generation capacity (Joskow 2013). Security of supply can be expressed as a sum of system adequacy and system security, where the difference between the two is temporal (CREG 2013).

$$System\ adequacy + System\ security = Security\ of\ supply$$

System adequacy[16] implies the long-term ability of the system to deliver the required resources for sufficient electricity supply. System security concerns the short term ability to balance the system during sudden disturbances (CREG 2012). According to Hogan (2013), the reliability planning standards that drive system adequacy policies are usually not derived from cost benefit analyses. Instead, they appear to be driven by rules of thumb, such as the standard for 1-event-in-10-years. The alternative would be to base the requirements on value estimates of lost loads[17] and on cost benefit analyses. This would mean that scarcity pricing would represent the consequences and the probability, i.e. monetisation of the risk. (Hogan 2013)

Security of Supply in the Danish Context

Article 22 in the European Electricity Market Directive requires the Member States, through their TSOs, to monitor the security of supply and system adequacy. This happens through the Member States' annually executed ten-year network development plans that are submitted to the European regulatory authority. The reporting must include *reasonable assumptions about the evolution of the generation, supply, consumption and exchanges with other countries, taking into account investment plans* (European Union 2009). When the liberalisation of the Nordic power market began in the early 1990's, reserve margins[18] were quite high. In 1995, the Nord Pool region had a reserve margin of 41 %. Part of the explanation is that hydropower, a large share of the Nord Pool capacity, traditionally was dimensioned with spare capacity to deal with the variable inflow. (Botterud and Doorman 2008) In the Nordic system as a whole, this relatively large reserve margin is still present (Andreasen 2013), and serves as critical argument in the present Danish debate between the proponents of interconnection, and the advocates for a larger degree of Danish self-supply. In Denmark, there is no officially defined margin for maintaining security of supply. Instead, it is targeted to maintain the current level of electricity supply, i.e. power supply, 99.996 % of the time (Sommer 2013). Other power systems have defined limits such as one day every 10 years in some power systems in the US, 3 to 16 hours per year in various European countries or a 10 % margin to peak load in Spain (Cramton, Ockenfels, and Stoft 2013; Andreasen 2013).

Value of Lost Load

Value of lost load (VOLL) is a term used for describing the cost of involuntary load curtailment (Stoft 2002). The concept can be utilised when determining the economically optimal amount of load shed during scarcity situations, i.e. the opportunity cost of serving load versus the opportunity cost of load curtailment. Thus, VOLL can aid in measuring whether it pays to increase security of supply, or to compensate the demand-side for load curtailment. In essence, this

[16] ISO New England (2013) use the term *resource adequacy*. Here it is described as *the ability of a bulk electric power system to supply the aggregate electrical demand and energy requirements (i.e., the electrical loads of all the customers plus external transaction sales to other areas) at all times, taking into account scheduled and reasonably expected unscheduled outages of system devices (e.g., generators, transformers, circuits, circuit breakers, or bus sections).* The only, but important, difference from the above definition is ISO New England's inclusion of system security in the term, essentially making it similar to this study's definition of security of supply

[17] See Value of Lost Load

[18] Reserve margin is here defined as the margin between peak load and installed firm capacity

is a way of quantifying the amount of reliability that the consumer is willing to pay for. The Council of European Energy Regulators has earlier pointed out that

> *In order for NRAs*[19] *to be able to implement reliable financial incentives regarding continuity of supply, it is of great importance that sufficient knowledge about customers' real costs and their willingness to pay and willingness to accept is available in order to introduce or to improve such regulations.* (CEER 2010)

One caveat when applying VOLL is that it usually is applied as an average of all consumers' VOLL. This homogenous approach can mean that some consumers are forced to buy more reliability than they need and others less. In practice, determining VOLL can be difficult, as the demand side currently takes few actions concerning reliability. A further step in the consideration on VOLL leads to a realisation where the economic motivation of CRM is not necessarily the total avoidance of black- or brownouts, but rather *just a matter of minimizing the total cost to consumers of generation and blackouts*. (Cramton, Ockenfels, and Stoft 2013) This relates to the application of security of supply explained in Section 3.1.2. This economic concept of optimising security of supply/VOLL against the amount of generating capacity is illustrated by Figure 15. Where

C_o	: total social cost of outages
C_g	: social cost of generation capacity
Q^*	: economically optimal amount of outages and generation capacity
$C_o + C_g$	: sum of total social cost of outages and social cost of generation capacity

In the real world, adjusting security of supply to an economic optimal level might meet resistance among politicians and from the demand-side, in case this adjustment would reduce the security of supply compared to the present level.

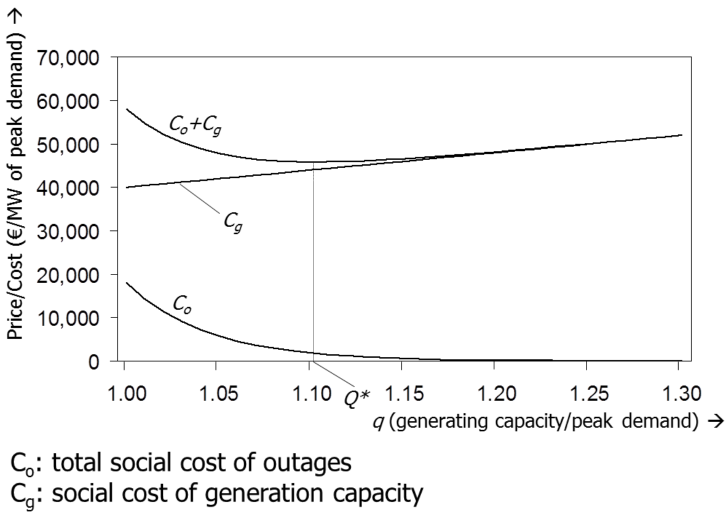


FIGURE 15 THE SOCIAL COST OF GENERATION CAPACITY AND OUTAGES. FIGURE BASED ON DE VRIES (2013)

3.2. Present Challenges in Energy Economy

The current debate on the need for CRM is spurred by the apparent shortcomings of the EOM. While Adam Smith's invisible hand, in theory, coordinates efficient redistribution in the EOM, several other – more or less visible – hands are

[19] National energy regulatory authorities

influencing this market in reality. This section describes the challenges that the EOM is facing, and elaborates on the challenges presented in Chapter 1.

3.2.1. Inflexible Demand

The assumption of full information and agents acting rationally on the market, described in Section 3.1.1, are both challenged by the inflexibility of demand that is seen in power markets. As pointed out by Boisseleau (2004), elasticity of demand is generally considered to be low in power markets, due to the high importance given to the product and its low substitutability. Real-time price information could be added, since the majority of consumers usually have no information on the price of electricity of at a given hour[20]. Due to the inflexibility on the consumption-side, EOM come with a risk of price spikes and shortages. In theory, this should be possible to avoid, by *allowing customers to determine for themselves the level of reliability they are willing to pay for* (Spees, Newell, and Pfeifenberger 2013, 13). Willingness to pay is a central issue when discussing demand-response (DR)[21] in power markets, since the consumption side currently only actively participates in the market to a limited extent. This makes consumers and political regulators sensitive towards extreme prices and it leads to intervention from authorities to reduce the level and frequency of price spikes (Montel Online 2013h; L. J. De Vries 2013). This sensitivity is not unique to power markets, but to pricing policy in general, as stated by Baumol and Blinder (2004, 285).

> *It is not easy to accept the notion that higher prices can serve the public interest better than lower ones. Politicians who voice this view are in the position of the proverbial parent who, before spanking a child, announces, "This is going to hurt me much more than it hurts you!" Because advocacy of higher prices courts political disaster, the political system often rejects the market solution when resources suddenly become scarcer.*

One way of approaching this subject, and perhaps reducing the size and frequency of extreme prices, is by increasing demand-response. DR resources have proven to take up a rather significant share of the capacity market in the US power system PJM and in the SR in Sweden (Spees, Newell, and Pfeifenberger 2013; Näringsdepartementet 2010a). Since the contribution from demand-side resources is to abstain from using electricity, they need to be measured against a benchmark of what they would have consumed, had they not contributed to the mechanism. Additionally, the reduction of consumption is rewarded by not paying for the electricity. Both issues should be dealt with, when considering the inclusion of DR (Cramton, Ockenfels, and Stoft 2013).

Market Power, Scarcity Rent and Price Caps

Market power, scarcity rent and price caps are interwoven subjects that all pertain to the price formation in the EOM. From a general perspective on price caps, some economists argue that politically induced price caps are unjustifiable in an EOM where price solely should be determined by market forces (Spees, Newell, and Pfeifenberger 2013). This is counter-argued by others, pointing out that price caps are necessary in a market where almost all consumers are non-elastic (Hogan 2013). In such a situation, the market would set a wrong price, and the non-elastic consumers could risk paying more than their VOLL, simply due to their lack of information and inflexibility (Cramton, Ockenfels, and Stoft 2013). Another function of price caps is to mitigate problematic issues with market power, where generators withhold capacity in scarcity situations to drive up prices. Stoft (2002) argues that having price caps builds on the expectation that generators will withhold capacity under scarcity periods. In such situations, the presence of market power contradicts the assumption on the free market's many mutually independent suppliers. Green (2006) describes market power the following way:

[20] This is expected to change in the Danish context, where all meters are required to be remotely read on an hourly basis by 2020 (Danish Energy Agency 2013c)

[21] Here defined as electricity consumers who can alter their consumption

At peak times, the margin of spare capacity on most electric systems will generally be less than the size of the largest generating company. This means that the largest company will be ''pivotal'' at those times, for demand cannot be met without using some of its plants. It can ask any legal price that it wishes for the output from those plants, and the grid operator will be forced to pay that price or cut off some consumers.

Green further notes that a sufficiently small margin of spare capacity can mean that even small players can become pivotal, but still do not necessarily reach the market shares that are associated with dominance in European law. Green's definition is not comprehensive, since excessive market power can be exercised and mitigated in different ways[22]. During the execution of this study, the price cap in Nord Pool Spot was raised from 2 000 EUR/MWh to 3 000 EUR/MWh, see Table 2. This happened as a consequence of the North-Western Europe price-coupling project. The boundaries are allegedly based on VOLL and historical clearing prices (Nord Pool Spot 2013a).

TABLE 2 THE CURRENT AND PREVIOUS PRICE CAPS ON THE NORD POOL SPOT IN EUR/MWH

	Old boundary	New boundary
Lower	-200 EUR/MWh	EUR -300 EUR/MWh
Higher	2 000 EUR/MWh	EUR 3 000 EUR/MWh

Some economists argue that price caps contradict the theoretical ability of energy-only markets to recover long-term costs of producers, by the so-called scarcity rent (Stoft 2002; Spees, Newell, and Pfeifenberger 2013)[23]. Scarcity rent is defined as revenue minus variable cost obtained by peak producers during periods of electricity shortage, i.e. when the supply and demand curves do not cross (Stoft 2002). In the case of the Nord Pool Spot market, different measures are taken in order to make the supply and demand meet, thereby creating a clearing price. These steps include dispatch of Swedish and Finnish strategic reserves, which is further explained in Chapter 4. In case there is no solution, the purchase bids are evenly curtailed and the price is increased to the maximum, i.e. the price cap in Nord Pool Spot (Nord Pool Spot 2013). The principle is illustrated in Figure 16, where the dotted top-down line illustrates the curtailed load.

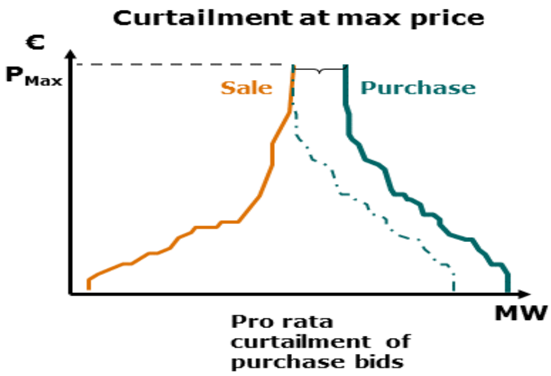


FIGURE 16 THE PRINCIPLE OF RAISING THE SPOT PRICE TO THE PRICE CAP, AND CURTAILING DEMAND. FIGURE FROM NORD POOL SPOT (2013)

Joskow (2013) argues that *the fundamental challenge for dealing with the revenue adequacy problem is to achieve appropriate scarcity pricing*. In the current energy-only markets, the market has no, or only limited information on the final consumers' willingness to pay. This results in a lacking ability to ration the supply efficiently through proper scarcity pricing, in a situation with limited provision of capacity (European Energy Exchange AG 2013). It could be argued that

---

[22] Stoft (2002) simply defines market power as *the ability to alter profitably prices away from competitive levels*. See Spees, Newell and Pfeifenberger (2013) for examples of market power

[23] In economics also referred to as *inframarginal rent*

higher prices provide an incentive for consumers to become more flexible, a statement that leaves an interesting case of catch-22. From an economic perspective, the attempt to transform the demand-side from being less flexible to more flexible can be seen as an attempt towards increased marketization of the security of supply of the electricity consumers.[24] This increased participation in the market from the demand side would change the serving of demand into being a question of opportunity costs of the consumer, i.e. choosing to have one's demand served or not, depending on economic priority or capability. This brings up the politically sensitive issue of whether electricity is a kind of public good, or simply a product traded on a market.

3.2.2. The Merit-Order Effect and Other Impacts on the Wholesale Market

In a European context, the energy only market has been described as an anachronism, which is challenged as long as pricing of carbon emissions is low, gas prices are high and coal prices are low (Montel Online 2013b). This section will treat these issues, along with the merit-order effect. The merit-order effect is described as the reduction in revenue for power plants, as a consequence of the introduction of low-cost energy generators[25] (Cochran et al. 2012, 96).

> […] *the "merit-order effect" (i.e., whereby conventional power plants are pushed down the order in which plants are used).*

Along with other challenges, the merit-order effect is illustrated in Figure 17. *More RE* illustrates the introduction of low cost generation which can displace the marginal producer out of the demand curve. Displacing more expensive marginal producers leads to a general reduction in electricity prices, since winning bids are from producers with smaller marginal costs (Rautkivi and Kruisdijk 2013; EY 2013).

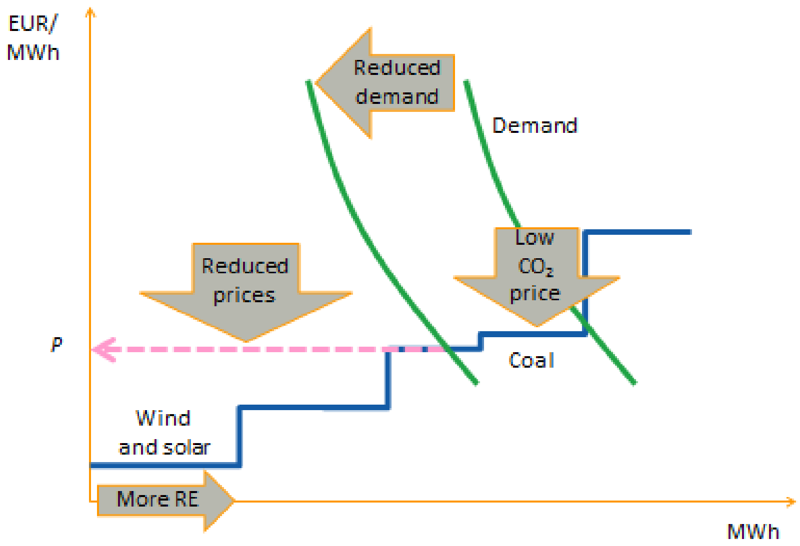


FIGURE 17 IMPACTS ON THE MERIT ORDER-BASED EOM

Figure 17 additionally displays two other impacts on the price of electricity in EOM, which in turn have impact on the revenue generated by conventional plants. The first is the low CO_2-prices, e.g. in form of European Emission Allowances (EUA) traded in the European Emissions Trading System (EU ETS). Their low price essentially means that external costs caused by the combustion of fossil fuels is valued rather low in the market, facilitating the use of otherwise high-emitting resources like coal (L. de Vries 2011; CREG 2013). Reduction in demand is the second impact treated here. It can be

[24] Lauge Pedersen (2013) has argued that security of supply is currently a (partially) public good

[25] Importantly, it should be noted that this effect is assumed to be the case with any low-cost electricity producer, and is often, but not always, related to RES per se

caused by e.g. increased energy efficiency or by a financial crisis. The consequence for the EOM is that the demand-curve is displaced to the left, potentially moving towards lower bid-levels and leaving some generators, to the right of the demand curve, outside the merit-order. As the theory illustrates, this bundle of existing generator market-challenges have consequences for the income of existing generators on the market. The important question is whether, despite the challenges, current generators stay in the market, if they put aside, or even decommission their capacity. No matter what the result, it is assumed that Spees, Newell and Pfeifenberger (2013) have a relevant point when they argue

> […] *wholesale power markets—with or without capacity constructs—will never work "perfectly" in how they function, given how they have to balance various policy objectives.*

3.2.3. Investment and Risk: The Missing Money-Problem

The prior sections have dealt with challenges in the energy economy, and in maintaining capacity in the EOM in particular. This section describes the impacts which these challenges have on the incentive to invest in capacity and related assets, the so-called *missing money-problem*. Risk and investment incentives are relevant to cover since the argument for introducing CRM often is to create better incentives for investment, thereby maintaining system adequacy and security of supply.

Investment Fundamentals

The EU Electricity Market Directive states the following regarding investments in the power market:

> *A well-functioning internal market in electricity should provide producers with the appropriate incentives for investing in new power generation* (European Union 2009)
>
> *Market prices should give the right incentives for* […] *investing in new electricity generation.* (European Union 2009)

How the market concretely provides this incentive is suggested by Lévêque (2007), who categorises the incentives for investment in power plants as follows:

- Capacity scarcity can make market prices rise. This signals profitability, and thereby makes investment in new capacity attractive for the investor, i.e. when the investor believes that the energy price will be sufficient for long enough to provide return on investment
  - This is founded in the assumption that short term price signals provided by the spot market incentivise investments in the longer term (Houmøller 2013a)
- Some of the existing capacity is obsolete and must be replaced
- Low efficiency of existing capacity makes it profitable to exchange this with new and more efficient capacity

In the EOM, the revenue of the producers is based on sales of electrical energy[26], but the efficacy of the EOM in creating investments, is currently being questioned, as described in Chapter 1.

The Missing Money Problem

While this section will not attempt answering the question of the ability of the EOM to provide sufficient incentives for investment in capacity, it will provide an overview of the risk-related parameters that characterise the investment in generation capacity. Joskow (2013) frames the challenge this way

> *The revenue adequacy or "missing money" problem arises when the expected net revenues from sales of energy and ancillary services at market prices provide inadequate incentives for merchant investors in new generating*

[26] There is also revenue from ancillary services, but these are not included in this study

capacity or equivalent demand-side resources to invest in sufficient new capacity to match administrative reliability criteria.

Hogan (2013) and Spees, Newell and Pfeifenberger (2013) take one step further by attributing the causes to administrative actions that limit increases in the market price. These include price caps and out-of-market calls, and, on a more general scale, that capacity scarcity is not reflected in the electricity prices. While the section Investment Fundamentals presented the assumption that spot market prices should provide the incentive for long-term investments, the following quote from De Vries (2011) points towards a weakness in this assumption:

> *In current electricity markets, relatively much power is traded through contracts with a short duration in comparison to the time horizon that an investor in electricity generation capacity needs to contend with.*

De Vries summarises one of the fundamental risks that the investor faces: uncertain revenue. This and other types of financial risk in generation investment can be summarised the following way, based on Botterud and Doorman (2008) and De Vries (2011):

- High volatility in electricity prices, especially for plants with a low capacity factor[27]
- Lifetime and amount of the investment is usually relatively large, resulting in a need for certainty about the long-term profitability
- Regulatory risks are also to be considered, since changes in policy, such as new environmental or market regulations, might impede the power plants' ability to achieve short term goals[28]
    - The degree of intervention in the market is often discussed as a part of the CRM topic. Views differ, where De Vries (2011) argues that the level of intervention already exists to such an extent, that the notion of a free market is somewhat an exaggeration and that additional adjustments to the design are acceptable. CREG (2013) challenges this point by advocating that further regulation of the markets, such as CRM, will create distortion. Sharing this perspective is Energinet.dk, which according to Sommer (2013), argues that CRM should be avoided and that market forces, hereunder the increased size of markets through interconnection, should be able to manage the development in the energy system to a large degree.

Unless the yield is significant, such risks can make investors more risk-averse, i.e. hesitant to investing in new generation capacity. This yield, or risk premium, can be high prices during production or remuneration for available capacity. This study perceives risk in regulated liberalised power markets to be distributed in the span between suppliers and consumers. In this dichotomous span, risk can be shifted by regulation, for instance by redistributing more risk to the consumers through CRM, and thereby decreasing risks for the suppliers. It can be argued that such a redistribution of risk towards consumers can be necessary in case the investors are too risk-averse to build or maintain capacity. Conversely, it can also be argued that such a redistribution of wealth from the consumers to the producers is an unfair insurance premium to levy on the consumers. No matter the perspective, this is what capacity remuneration mechanisms attempts to do. While CRM can address the suppliers' risk of volatile or low electricity prices, the matter of fuel price volatility is left unaddressed, and hence shows that risks for suppliers can still be present in power systems with CRM (Sommer 2013). Additionally, depending on the design of the CRM, capacity prices can be volatile as well, re-substantialising the element of risk (Spees, Newell, and Pfeifenberger 2013). Spees, Newell and Pfeifenberger (2013) points towards three categories that should be considered, when addressing and mitigating risks in CRM:

[27] *Capacity factor* describes the ratio of actual delivered energy in a period relative to its theoretical maximum amount of energy delivered of the same period

[28] Regulation risk is addressed in Article 3 the Electricity Supply Directive, but merely as a guideline, since this regulation is difficult to prohibit or regulate with other regulation

- Market fundamentals
    - Minimise administrative interventions in price formation
- Rule changes
    - Minimise changes in market design
- Administrative parameters
    - Minimise change in administrative parameters

As argued in Section 3.1.2, the market might reach an economically efficient level of system adequacy. This can happen at the point of time when the market is below the reliability requirement, since the economically optimal system adequacy is not necessarily the same as the politically preferred system adequacy. Striving towards a politically defined higher level of reliability might therefore reduce the profitability for producers, as is illustrated in Figure 18 (Spees, Newell, and Pfeifenberger 2013). Here simulations of the energy system of Texas illustrate the impact of increased reserve margin on revenue from a gas turbine (CT).

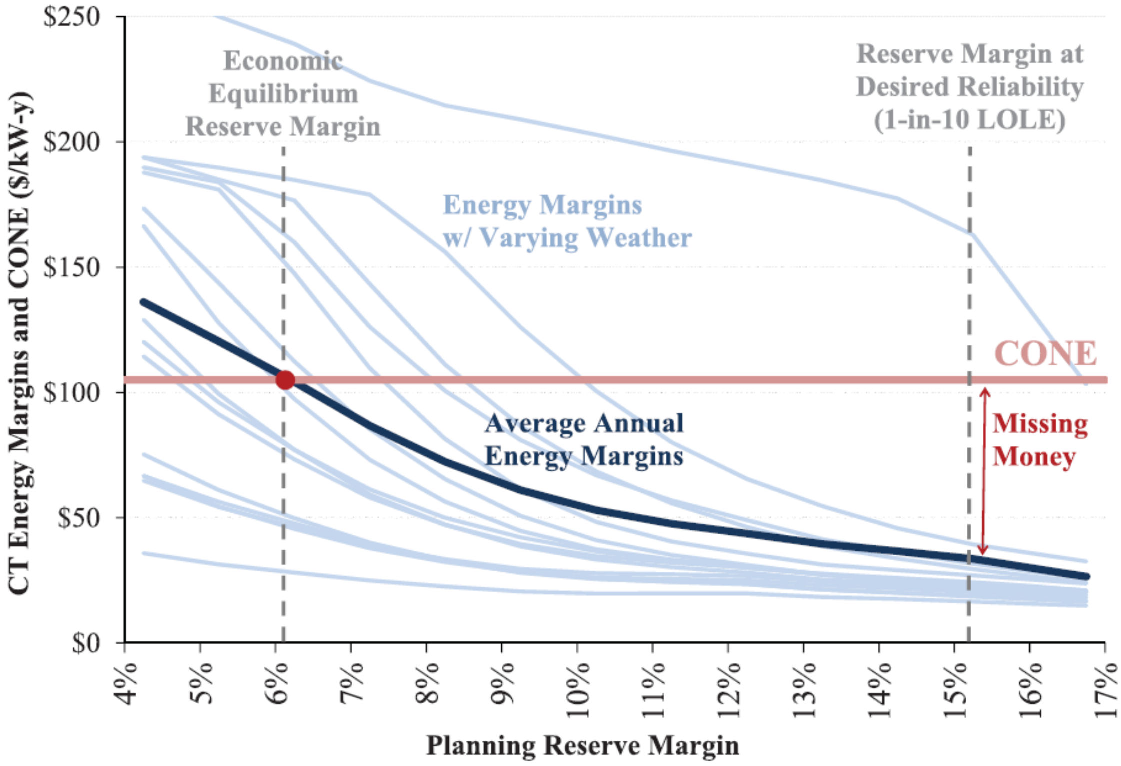


FIGURE 18 MISSING MONEY PROBLEM IN THE ENERGY-ONLY MARKET OF ERCOT. FIGURE FROM SPEES, NEWELL AND PFEIFENBERGER (2013)

The y-axis illustrates the marginal revenue from the gas turbine under varying weather conditions, while the x-axis denotes the planning reserve margin, i.e. how much spare capacity the system has. Increasing the reserve margin, i.e. increasing the amount of available capacity, also increases the competition among the generators, leading to a reduction in prices to somewhere below the cost of new entry (CONE). CONE defines the price level, where operating profits of a new producer would reach an equilibrium with the fixed operating- and capital costs (Spees, Newell, and Pfeifenberger 2013). This means that while determining the optimal volume of capacity can be a combination of economic and political priorities, determining the amount of missing money, i.e. the price for capacity, is a different matter. In the case of addressing this in a CRM with the purpose of attracting new capacity, the equilibrium value of the capacity product should be equal to the size of the missing money in that market. This equilibrium should provide the same revenue as potentially generated by long run marginal cost (LRMC) for supplying the required level of capacity. While different from LRMC, the net cost of new entry (net CONE) is applicable in this regard. Net CONE is *equal to the* *annualized fixed cost of new capacity* […] *minus the operating profits that a new entrant can expect to earn in the energy and ancillary services markets.* (Spees, Newell, and Pfeifenberger 2013, 13). In other words, net CONE can be considered the difference between short run marginal costs and LRMC.

3.3. Addressing Challenges Through Capacity Remuneration Mechanisms

Skov and Petersen (2007) argue that the Danish energy policy mainly focused on security of supply in the beginning of the 1980's, while this focus was shifted to environmental issues towards the end of the decade. It can be argued that these focal points have now converged into a combined desire for an environmentally friendly power system with sufficient security of supply – in a liberalised context. This touch upon the core purpose of discussing CRM, and the challenges which CRM pose, is put into structure in this final section of the chapter. The economic framework of power systems can be divided into two timescales: planning and operation[29]. Planning concerns investments on the longer term, which in this chapter is characterised by the missing money problem. Operation concerns the way in which existing resources are used, and relates to the preservation of existing capacity in the market. Due to the unbundling of actors on the power market, investment decisions happen in individual entities, meaning that there is no central investment-planning happening in such markets. The discrepancy between public interests, and hereunder public regulation, and the liberalised market, leads to certain challenges regarding both the planning and operation scale. The causes and effects of these challenges are presented on Figure 19.

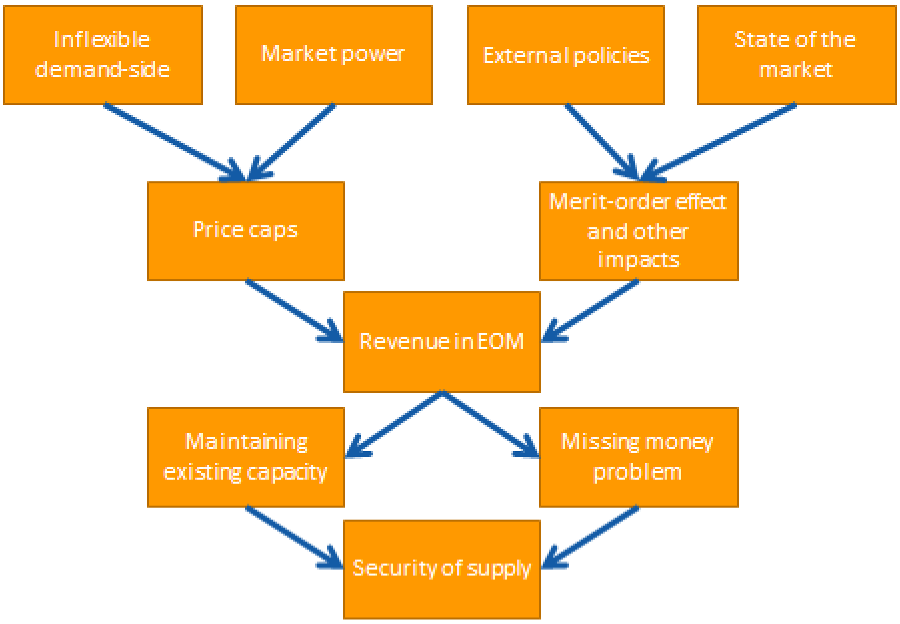


FIGURE 19 STRUCTURE OF THE CHALLENGES AND THEIR CAUSALITY IN THE EOM

It is seen that the inflexibility of demand and risk of market power can lead to the application of price caps. These impact the revenue for generators in EOM, since they effectively limits the size of the bids that the generators can make. External policies denote political priorities and regulation, which are imposed on the EOM. Together with the state of the market, e.g. a financial crisis, it creates the merit-order effect and other impacts. It is important to note that these are all external conditions and not necessarily market failures per se[30]. This could lead to an argument for two rather

[29] This distinction is based on yet unpublished material from the IEA study Grid Integration of Variable Renewables. For more details, see http://www.iea.org/topics/renewables/givar/

[30] The discussion whether to define this as market – or regulation failures, is not pursued in this study

different solutions: deregulating or re-regulating the market. The latter is where CRM appears. Essentially, the link between CRM and EOM can be said to be *net revenues*[31]. In this perspective, if the EOM does not generate sufficient revenue for incentivising investments in new generation or preserving existing capacity, the CRM will equilibrate between the EOM and the missing revenue, in order to provide sufficient revenue to cover the annualised fixed costs, hereunder the investment. Table 3 sums up the elements identified in this chapter, supplemented with elements from Brunekreeft et al. (2011), which are relevant as parameters for a CRM to address. The table and its parameters are in Chapter 4 used for evaluation of the CRM in focus: the strategic reserve.

TABLE 3 EVALUATION PARAMETERS WITH WHICH A CRM CAN BE EVALUATED

Parameter
Administration
Contracting mechanism
Technology neutrality, hereunder participation of demand-side
Relation to market power
Sensitivity to the state of the market
Impact on EOM
Sensitivity to reduction in demand
Sensitivity to increase in low-cost generation
Sensitivity to CO_2-prices
Incentive to preserve capacity in power system
Investment incentive
Revocability
Complexity
Compatibility with surrounding markets
Controllability of costs
Stabilisation of electricity prices

Regarding all the challenges addressed in this chapter, there is an important consideration to be made, namely if the challenges in question are in fact a consequence of a malfunctioning market, if they are just temporary, or if they are the natural consequence of the market functioning as it should, essentially by getting rid of a surplus of generators.[32] O'Briain (2013, 6) phrases it this way: *Distinguish generation adequacy concerns from profitability concerns (take into account overcapacity and economic crisis)*. This distinction between missing revenue and missing capacity illustrates the core of the problem: the former is the concern in the power sector, and the latter the concern of the consumers[33]. This study analyses the consequence of introducing SR as a way to satisfy both these needs, and the following chapter, Chapter 4, will address exactly how SR performs according to the parameters defined in this present chapter.

[31] *net* ensures that the revenue from the energy market is deducted from the capacity revenues

[32] This matter will not be discussed further, but it is important to be aware that established actors have vested interests. This matter permeates to the discussion of CRM, where money are transferred from consumers to generators

[33] And in the Danish case the TSO, since Energinet.dk is the responsible actor in Denmark for security of supply

4. Strategic Reserves

As stated in the research questions, it is sought to identify which implications strategic reserves can have in an energy economic perspective. In order to answer this question, the chapter at hand introduces the fundamental concepts of capacity remuneration mechanisms, and investigates the details of the CRM in focus: the strategic reserve. This is done through literature reviews and interviews, in order to provide an overview of the basic concepts of, experiences with, and stakeholder perceptions on SR. Furthermore, while Chapter 3 introduced key energy economic concepts for understanding SR, the focus in this chapter is to define the concrete characteristics of SR that will be used in the modelling in Chapter 6.

4.1. Introduction to Capacity Remuneration Mechanisms

Market failures are what Cramton, Ockenfels and Stoft (2013) sum up as the reason for introducing capacity markets. This understanding is expanded in this study to encompass CRM in general. Several of the direct consequences of market failures have been presented in Chapter 1, while their theoretical background has been supplied in Chapter 2. There are several types of mechanisms, which can be implemented in order to address these market failures by providing the amount of desired capacity. Common for those mechanisms is that some kind of remuneration is provided as an incentive for providing capacity, hence the term *capacity remuneration mechanism*. CRM is in this study used as a collective name for initiatives intended to provide electricity generation capacity which would otherwise not be maintained, developed or introduced in the energy system. The European Energy Exchange (2013, 1) defines a CRM as *supplementary market rules creating an artificial demand for a guaranteed capacity which would not evolve on its own*. While this definition fits some types of CRM, it provides the notion that the CRM is introduced on market terms; something which is not necessarily the case, as is seen in the following overview of CRM. Figure 20 depicts an array of solutions and the categorisation of the CRM in focus: the SR. The list is not exhaustive, but introduces the different concepts applied as CRM.

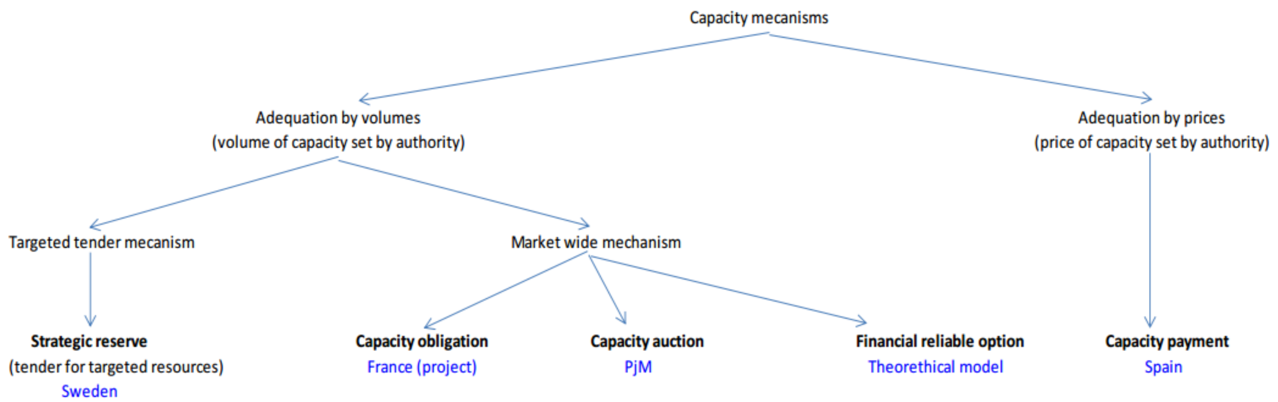


FIGURE 20 CATEGORISATION OF DIFFERENT TYPES OF CRM. FIGURE BY CREG (2012)

It is challenging to provide a satisfactory description of the mechanisms presented on Figure 20 in the format of a short summary, since many of these are complex structures that require detailed description. Such in-depth accounts of different CRMs is not the purpose of this study, but can be found in other studies, such as Baritaud (2012), Energinet.dk (2012) and CREG (2012). The CRMs are summarised from top-down in Figure 20. The first level is:

- Capacity mechanisms
    - The equivalent of the more precise term utilised in this study, capacity remuneration mechanisms

Second level presents two different categories:

- Adequation by volumes
  - Describes CRM where the volume of capacity, i.e. the concrete amount of MW_e required for maintaining security of supply, is determined by authorities
- Adequation by prices
  - Describes CRM where the price of capacity, e.g. in EUR/MW_e is determined by authorities

Third level sees two different categories, each under *Adequation by volumes:*

- Targeted tender mechanism
  - Describes CRM where the tender for resources is based on certain requirements where the amount of targeted actors is limited
- Market-wide mechanism
  - Describes CRM where multiple types of capacity can participate

It has been argued that a CRM should be technology neutral, since this is assumed to create the most economically optimal solutions on the market (European Energy Exchange AG 2013; Spees, Newell, and Pfeifenberger 2013). However, technology neutrality is not always the case, since CRMs can vary in the types of supply and demand that are allowed to participate in the mechanisms. The types of actors involved in CRM include power plants and actors on the demand side. Variations exist in different CRM designs, where the distinction can be on the inclusion of DR, whether the capacity is new or old and whether capacity will be built or already exists. Having a technology neutral market for capacity is assumed to produce the most economically optimal solutions, but can be difficult to obtain in case secondary goals are also pursued through the CRM (European Energy Exchange AG 2013). Abandoning the requirement for technology neutrality, De Vries (2011) argues that a differentiated, technology-specific capacity market would be necessary, in order to encompass the inclusion of the whole power system, also including VRE.

Fourth level under *Targeted tender mechanism* contains a single CRM:

- Strategic reserve
  - Describes a mechanism where certain types of capacity are remunerated for being available as an out-of-market reserve. Both Sweden and Finland have SR, and the more elaborate description of SR found later in this chapter is largely based on these countries[34]

Fourth level under *Market-wide mechanism* describes three CRMs:

- Capacity obligation
  - A mechanism where the suppliers are obliged to contract predefined amounts of capacity with generators, at prices negotiated bilaterally (CREG 2012). The capacity obligation can thus be categorised as a decentralised CRM, opposite to centrally tendered CRM (Baritaud 2012). The latter can be the case in capacity auctions/markets, described below. These obligations can be defined for the short-term or for several years ahead
- Capacity auction
  - The primary motivation for capacity markets is to meet administratively set targets for resource adequacy in liberalised markets (Spees, Newell, and Pfeifenberger 2013). For capacity markets, the stability-requirement is forecasted for the planning period ahead of the delivery. This forecast, along with a certain margin to cover uncertainty, provides the amount of capacity resources needed. In an optimal capacity market, the equilibrium value of the capacity product should be equal to the size of the missing money in that market
- Financial reliability option

[34] SR is also deployed in Poland, but not treated further in this report (NEPP 2011)

- ♦ A market where reliability contracts are auctioned as call options, i.e. options for capacity that may be called upon if needed. Such a construction hedges the consumer against high market prices, and maintains a market-based approach. Contrary to the other CRM, the call option is a physical and financial instrument that allows the consumer to cap the purchase price of electricity. (Baritaud 2012) In a situation where the spot price exceeds a certain amount on the market, i.e. the strike price in the reliability option, the generator must have its capacity available for the system operator. If not, the generator pays a fee according to the deficit in production capacity. (CREG 2012)

Fourth level under *Adequation by prices* describes a single CRM:

- ❖ Capacity payments
  - ♦ Contrary to a market-based CRM, the size of the capacity payment is defined centrally, according to the available amount of capacity. The system responsible party provides the capacity payment to the participants as an addition to the income gained on the energy market. This lowers the volatility of prices and provides a more stable and predictable income for the producers. The purpose with this is to provide sufficient incentive for investments in new capacity and to maintain existing capacity in the system. (Botterud and Doorman 2008)

It is important to be aware that the choice between a price-based approach (Adequation by prices) and a capacity-based approach (Adequation by volumes) is not a choice between a market approach and a regulated approach, since both can be carried out by tenders. Additionally, both approaches can solve the adequacy problem. Hence, the choice lies in the other aspects, including issues of risk and market power. Summarising on CRM: if a high cap on the price is not wanted in EOM, CRM might be the solution. (Cramton, Ockenfels, and Stoft 2013)

4.2. The Concept of Strategic Reserves

SR, also called peak load reserves, ring-fenced reserves or mothball reserves[35], are reserves that are called into the market, when the spot market does not clear. Participating actors usually consist of demand response resources and of plants that would otherwise be decommissioned, e.g. old plants (Spees, Newell, and Pfeifenberger 2013; Baritaud 2012). In the definition of DECC (2011, 30 Suppl 4:73):

> *A Strategic Reserve is an amount of reliable capacity which is held outside the electricity market apart from under certain, exceptional conditions.*

This definition will be expanded in the chapter at hand, since there are different designs and different views of the effect of SR. Energinet.dk (2012) points out that SR works as a physical precaution against load curtailment. In other words it emulates demand response by entering the market at a certain strike price, just as demand would exit the market at a given strike price. As indicated, SR does not have to be based on production capacity, but can equally well be based on demand response which is deployed in emergency situations, e.g. as in Texas (Spees, Newell, and Pfeifenberger 2013). Figure 21 illustrates the fundamental concept of SR. Here, the reserve is remunerated by a central actor, e.g. the TSO, and is kept outside the market unless it is required in order to deliver sufficient capacity in the system. Energinet.dk (2012) notes that the amount of hours where SR is dispatched in such a way is a good measure for how well the market functions.

[35] In case it is directed towards plants that would otherwise have been dismantled (Brunekreeft et al. 2011)

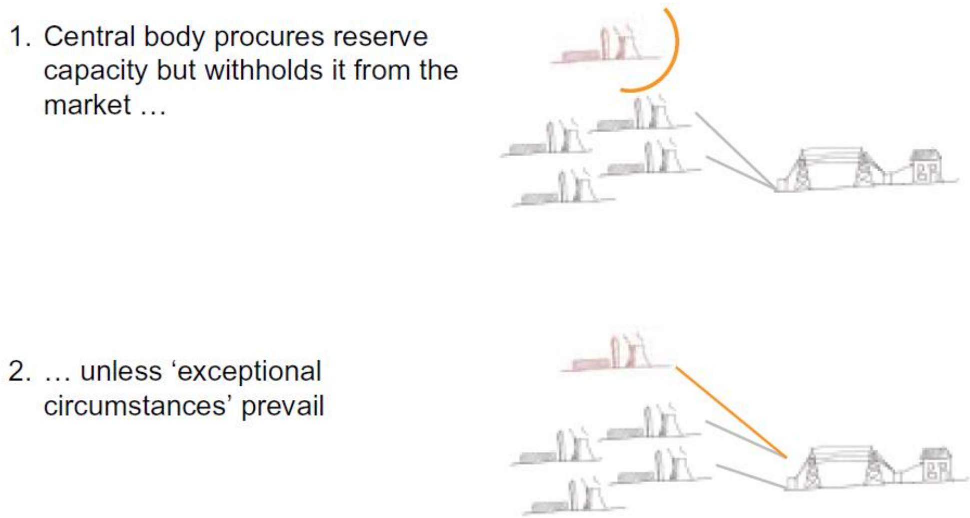


FIGURE 21 THE PRINCIPLE OF PARTICIPATION OF STRATEGIC RESERVES. FIGURE BY DECC (2011)

SR as a scheme is relatively easy to introduce and to revoke (Sommer 2013; Baritaud 2012; Brunekreeft et al. 2011). In relation to this, CREG (2012) argues that the life time of the mechanism should be determined *according to the date the RES would be able to enter the market without subsidy* (CREG 2012, 09:49). This flexibility of the mechanism is important, since Denmark and the neighbouring countries are in a transition-phase, where the introduction of RE means that adjustments to the power markets are likely to be needed along the way. Furthermore, SR is considered as robust against initiatives in surrounding countries, since the purpose of SR is solely to provide sufficient national capacity in the event of lacking regional market clearance. Finally, the mechanism is generally considered to be relatively uncomplicated in its design and with controllable costs (Finon and Roques 2012; Brunekreeft et al. 2011; Sommer 2013). This is relevant when considering different alternatives of CRM, hereunder the CRMs presented in Section 4.1.

4.2.1. No Participation on the Spot Market

In the case of Sweden, Finland and Germany, the plants under SR-regulation do not participate on the spot market. The reason can be found in regulation against anti-competitive actions. The EU directives 2009/72/EC (2009) on the internal market in electricity[36] and the Electricity Supply Directive 2005/89/EC (2006) regulate this matter. Here it is stated that tendering procedures are allowed in the case that current supply is deemed insufficient and given that the measure is not in competition with producers on the free market. This means that TSOs tendering for SR in the form of subsidies for investments in new plants, and the following participation of these plants on an otherwise well-functioning spot market, will probably not be allowed according to EU competition rules. The SR, as described for Sweden and Finland, is on the other hand allowed since these plants are not participating on the spot market on a regular basis (Energinet.dk 2012; Brunekreeft et al. 2011). Usually, the contract for strategic reserves defines a fixed annual payment, independent of the output, a so-called option-payment. The revenues from sales of energy depend on the contract design. Energinet.dk (2012) and Brunekreeft et al. (2011) describe two options:

a) Where the TSO has the right of disposal of both energy and capacity. The energy price paid from the TSO to the reserve can be defined as the marginal costs of the plant or the spot price

[36] Sub-clause 4 states: *In invitations to tender for the requisite generating capacity, consideration must also be given to electricity supply offers with long-term guarantees from existing generating units, provided that additional requirements can be met in this way.*

b) Where the TSO only has the right of disposal over capacity. The reserve is obliged to bid in its capacity on the spot- or regulating power market, and directly receive payment from the market. This solution is similar to the regulating power market seen in Denmark

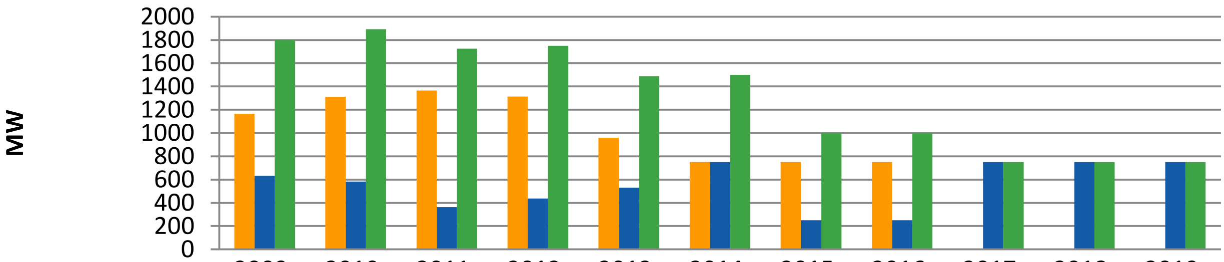
Both Sweden and Finland use designs similar to a). Furthermore, bids from plants participating as SR cannot be below the marginal price of the plants. This is relevant since one country should not have costs of supplying SR to the neighbouring market in another country. (Energinet.dk 2012) The design of SR in the three countries means that a SR, when correctly designed, is compatible with the European market model (Brunekreeft et al. 2011).

4.3. Experiences With Strategic Reserves

After the brief introduction to SR in Section 4.2, this section adds to the picture by drawing on the experiences made with SR in Sweden, Finland and Germany.

4.3.1. Swedish and Finnish Strategic Reserves

Since 2003 Swedish and Finnish TSO's have procured SR through annual tenders (Baritaud 2012). Initially, the Swedish SR was introduced as a consequence of the widespread use of electric heating and as a measure of mitigating shortages during periods of low capacity in hydro reservoirs (Sommer 2013; Baritaud 2012). This became especially pertinent after the liberalisation, when producers began decommissioning oil-powered plants that had been used for backup. The Swedish SR was meant as a temporary solution for five years, but has been extended to 2020 (Näringsdepartementet 2010b). Production and DR capacity within the SR must be offered on the frequency replacement reserves market[37] in the full duration of the period of agreement, unless the reserve is activated on the spot market or out of order[38]. The requirement for DR is the ability to reduce with a minimum of 5 MW_e, while production resources are required to have a minimum capacity of 10 MW_e (Svenska Kraftnät 2012). The latter is assumed to be founded in the requirement for frequency replacement reserves, which similarly has a minimum requirement of 10 MW_e (Svenska Kraftnät 2010). In 2012, the contracted capacity was 1 726 MW_e, equivalent to 4.8 % of the total Swedish generating capacity (CREG 2012). In Sweden, the share of DR participating as SR was 25 % in 2012. As seen on Figure 22, this will gradually be increased to 100 % for the period of 2017 to 2020.



	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
Production MW	1166	1309	1364	1312,5	958	750	750	750	0	0	0
Reduction MW	633	582	362	437,5	531	750	250	250	750	750	750
Total MW	1799	1891	1726	1750	1489	1500	1000	1000	750	750	750

FIGURE 22 SWEDISH SR ALLOCATED ON PRODUCTION AND DR (SVENSKA KRAFTNÄT 2012; SVENSKA KRAFTNÄT 2013A)

[37] In Swedish termed *tertiärreglering* or *reglerkraftmarknaden*, which is similar to a term used for the same subject in Denmark, the *regulerkraftmarked*.

[38] Note that production resources can be categorised as DR, in case they are installed with the purpose of replacing supply from the grid during shortages. In other words, DR can in some cases mean that served demand is transferred from the grid to a local generator physically present in, or near the place of load

Contrary to the participating supply, DR is allowed to participate in the spot market. This is partly due to the priority for further development of DR, in accordance with the ambitions of an increased share of DR in the SR. An additional reason is that prices during the winters around 2009-2010 got so high that rather small amounts of capacity would have large influence on the price[39]; this made it reasonable to reduce these prices through introduction of DR. Furthermore, the potential for DR will be present, also without a SR. The same is not the case for the supply-side, where the plants would otherwise be decommissioned. (Brunekreeft et al. 2011) The SR is dispatched to 0.1 EUR above the spot price (i.e. n+0.1 EUR/MWh), when the market does not clear[40]. Figure 23 illustrates the concrete procedure of participation of the SR in Nord Pool Spot. The step-wise approach is in line with the traditional price-formation on the day-ahead spot market, but also indicates that the method is developed for slow-starting plants that need ample notice before the hour of operation (Sommer 2013).

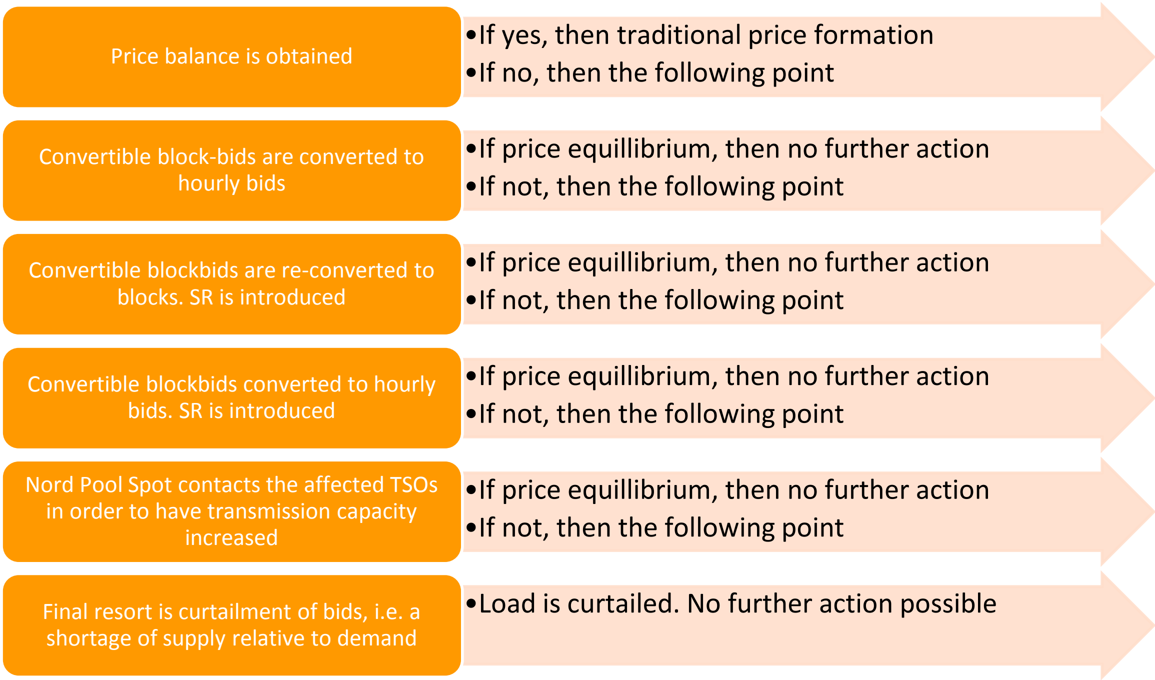
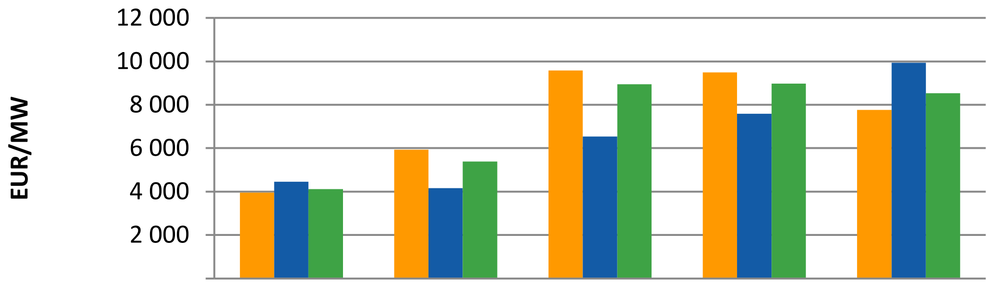


FIGURE 23 PROCEDURE OF PRICE FORMATION WITH SR IN THE SPOT MARKET (ENERGINET.DK 2012; SVENSKA KRAFTNÄT AND FINGRID 2008)

The SR remuneration has varied in Finland, as indicated by the prices from 2009 and 2010 that amounted to 22 500 EUR/MW_e/year and 2 500 EUR/MW_e/year respectively (Baritaud 2012). The cost for the SR in Sweden is financed through levies on the parties responsible for the balance, at a level of 0.5 EUR/MWh during daytime in the winter season (Brunekreeft et al. 2011). Cost of capacity since 2009 is seen in Figure 24, where the increase in cost of DR (Reduction) is explained by increased requirements for the resource-owner regarding bidding on the frequency replacement reserves market. The variations in production prices can be explained by the variations in the electricity prices, where higher prices on the spot market will mean higher prices for SR and vice versa (Svenska Kraftnät 2013b).

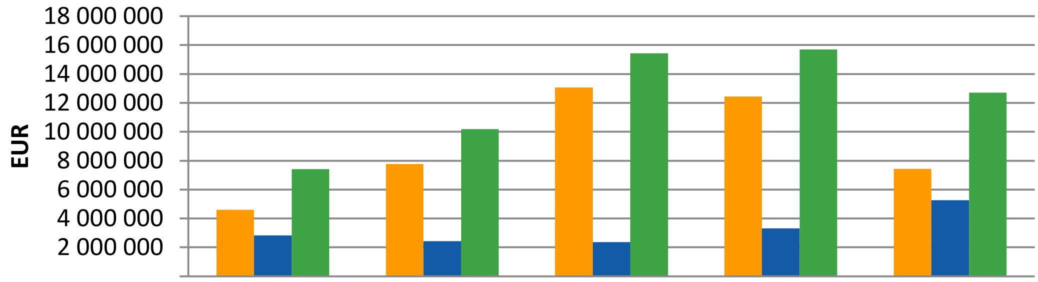
[39] This matter is pertinent to the discussion of market power, where withholding capacity can influence prices
[40] The Nord Pool Spot limit of EUR 3 000/MWh is still the overall price cap



	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014
Production	3 948	5 931	9 581	9 486	7 766
Reduction	4 459	4 158	6 533	7 580	9 934
Weighted total	4 117	5 385	8 942	8 972	8 539

FIGURE 24 COST OF CAPACITY IN THE SWEDISH SR (SVENSKA KRAFTNÄT 2013B)

The rise in cost of DR becomes apparent when calculating the total annual cost of each type of SR resource, as seen in Figure 25. The reduction in procurement of production capacity is also reflected in the total price. Moreover, it is important to be aware of the effects of electricity prices.



	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014
Production	4 603 852	7 763 343	13 068 602	12 450 356	7 439 610
Reduction	2 822 321	2 420 214	2 365 125	3 316 322	5 274 919
Total	7 406 075	10 182 200	15 433 770	15 700 127	12 714 421

FIGURE 25 COST OF CAPACITY, SUMMED FOR PRODUCTION AND DR RESOURCES (SVENSKA KRAFTNÄT 2013A; SVENSKA KRAFTNÄT 2013B)

A final note to address regarding the Nordic SR is an effect seen in the Swedish and Finnish markets, where downwards regulation has been deployed to a significant extent[41], simultaneously with the SR being activated. This might be explained by preventive actions by market actors, where producers will have a tendency to be over-supplied and consumers will reduce demand, both in order to avoid costs associated with shortages (Energinet.dk 2012). Sommer (2013) points out that the Danish context is different from the Swedish, where the deployment of electric heating is minimal. In the Danish case, it might be more optimal to have plants under SR operating in a cycle-mode, continuously running on a minimum standby-mode, thus enabling the plants to react faster.

4.3.2. German Grid Reserve

In 2013 Germany introduced the grid reserve[42], to compensate for transmission constraints (Baritaud 2012; European Energy Exchange AG 2013). As in Sweden, it allows contracting with production capacity in order to ensure security of

[41] E.g. in Sweden, where 40 MW_e was activated as SR, but 900 MW_e of downwards regulation was seen simultaneously (Energinet.dk 2012)

[42] In German: *Netzreserve*

supply. Furthermore, it opens up for the construction of new plants, in case the need for capacity becomes critical. The participating plants are not allowed to operate on the spot market until 2017, when the facilitating law expires. Furthermore, they must be considered critical to the security of supply, in order to participate in the reserve. This is evaluated by the TSO. The contracting period can be 24 months or more and remuneration includes operating costs. (Bundesministerium der Justiz 2013) Apart from being a technical solution to bottlenecks in the grid, Sommer (2013) notes that the grid reserve is additionally, and perhaps equally important, politically determined. In other words, the political sensitivity towards rising prices for the industrial sector, in particular in consumption-heavy southern Germany, might be larger than the actual technical need for capacity in the system. For the winter 2013-2014, the procured capacity under the grid reserve is 2 540 MW_e (Bundesnetzagentur 2013). The concept is otherwise the same as in Sweden and Finland, where plants are called in when the market does not clear (Sommer 2013).

4.4. Review of Perceptions on Strategic Reserves

In order to gauge the performance of - and perception on SR from a more general perspective than the focus on Sweden, Finland and Germany, this section reviews the political standpoints towards CRM and the performance of SR in an energy economic perspective, especially how a SR is assumed to address issues identified in Chapter 3.

4.4.1. Political Perception of CRM

The Danish Energy Association and the Danish District Heating Association have advocated for CRM during 2013 (Stenvei 2013; Montel Online 2013c). The European Commission has stated that any payments for capacity should happen on a competitive basis across Europe, and that national solutions are undesirable (Montel Online 2013b). This position has been backed by the European Agency for the Cooperation of Energy Regulators, Belgian energy regulator CREG, European Energy Exchange and UK energy regulator Ofgem (Montel Online 2013d; Montel Online 2013h; European Energy Exchange AG 2013; Montel Online 2013g). According to EU energy commissioner Günther Oettinger, capacity remuneration mechanisms might be a legal issue for the EC, since such mechanisms are likely to be subject to state aid control under the EU internal market rules (Montel Online 2013i). ACER has pointed out that capacity remuneration mechanisms might lead to short term impacts on energy prices, investment decisions and neighbouring markets (Montel Online 2013h). Additionally, the option for rolling back capacity remuneration mechanisms has been questioned by ACER and Danish TSO Energinet.dk (Østermark Andreasen 2013; Montel Online 2013h). As described in Chapter 1, the official Danish policy is against capacity markets. Instead, it is argued that any potential need for additional capacity could be secured through procurement of strategic reserves (Danish Energy Agency 2013a; Montel Online 2013a). Despite this generally unreceptive attitude towards CRM, the introductory remarks in the Electricity Supply Directive (2006) provide a rather wide opening for several kinds of CRM:

> *Measures which may be used to ensure that appropriate levels of generation reserve capacity are maintained should be market-based and non-discriminatory and could include measures such as contractual guarantees and arrangements, capacity options or capacity obligations. These measures could also be supplemented by other non-discriminatory instruments such as capacity payments.*

4.4.2. Economic Efficiency

For CRM in general, EEX (2013) and Houmøller (2013a) argue that intervention in the market should only happen when other, less intrusive elements, have already been applied. The rationale is that the use of resources in the case of the SR is inefficient, since plants under SR would have otherwise bid into the spot market. As seen in Sweden, this can be difficult to achieve, since plants under SR would perhaps otherwise be decommissioned (Cramton, Ockenfels, and Stoft 2013). Another aspect of economic efficiency is the matter of dispatch, when SR can be dispatched at a too low price, or not be dispatched at all. Regarding the latter, a situation could arise where the SR-plant is not dispatched although spot prices have risen above the marginal production costs of the plant. This can happen since the SR is only supposed to be dispatched in case of lacking price formation on the market (Brunekreeft et al. 2011).

4.4.3. Technology Neutrality

Technology neutrality is often seen as the preferred solution among economists for capacity mechanisms, since this in theory will supply the technology with the lowest cost to solve the demand. While there potentially is some room for competition when applying for participation in SR, the types of capacity are usually chosen prior to the tender, i.e. older and uncompetitive plants of a certain capacity and demand response resources (Baritaud 2012). This goes against the preference for technology neutrality, but since the initial approach in SR is to address market failures by maintaining non-competitive plants on the market, the notion of letting the market find the optimal plant is abandoned from the outset.

4.4.4. Finding the Right Amount of Capacity

SR does not address the issue of optimising the transfer of wealth from consumers to producers; something which can be said to be aggravated by the additional costs for the payment of SR (Brunekreeft et al. 2011). On this subject, EEX points out the difficulty in determining the adequate amount of capacity needed, potentially leading to over- or underinsurance (European Energy Exchange AG 2013). This is a fundamental schism when creating capacity mechanisms, since striking the right balance can be difficult. A CRM that leads to over-capacity in the market will be expensive for consumers, since they will pay for it in the end. On the other hand, a CRM that provides insufficient capacity can be detrimental to the security of supply.

4.4.5. Slippery Slope-Effect

The so called slippery slope-effect is another point of criticism (Houmøller 2013a; CREG 2012; Finon and Roques 2012). This describes a situation, where plants increasingly will tend to apply for remuneration from SR, since they are unprofitable on the EOM. An argument against this is that price formation in the spot market will reflect scarcity, resulting in a balance where SR will not result in a full shift from the spot market to SR (Sommer 2013).

4.4.6. Incentive for Investment

Investment risks and price volatility are still present in a market with SR (Brunekreeft et al. 2011; CREG 2012). It has been argued that existing SRs are ruining the wholesale market (Montel Online 2013e), that they do not provide a long-term investment signal and hence do not attract new capacity (Finon and Roques 2012; Brunekreeft et al. 2011; Energinet.dk 2012). The criticism regarding the ability of SR to attract investments is valid, since there is no real change in the incentives for investments in the mechanism itself. It is hence still up to the EOM to provide this incentive, and, depending on the strike price of SR, the scarcity rent can additionally become lower, increasing investor risk. If the dual purpose of the SR is to maintain investment incentives from the EOM, while ensuring backup capacity, then the criticism against SR regarding investments is justified, in case the design follows the pattern of the Swedish and Finnish SR. The SR-design of these two countries is expected to have an influence on the spot market, since the reserves are deployed with a price of 0.1 EUR/MWh above the spot market price. The impact on the spot market is due to the fact that the spot market during shortages will hit the strike price + EUR 0.1/MWh, instead of e.g. the 3 000 EUR/MWh price cap of the market. It can thus be argued that the Nordic approach takes away the scarcity rent[43] during shortages. In other words, power plants participating on the spot market earn a smaller scarcity rent in case the 0.1 EUR/MWh above spot price is far from the peak price that would otherwise emerge (Energinet.dk 2012; Cramton and Ockenfels 2011). Disruption of market prices will on the other hand not be a consequence, if the dispatch happens on the level of an existing price cap and/or VOLL (Cramton, Ockenfels, and Stoft 2013; Brunekreeft et al. 2011; CREG 2012). The consequence of the Nordic SR design is exemplified in Figure 26, depicting a situation where demand and supply do not meet, at the level of 1 000 EUR/MWh. The orange bar illustrates the spot price on the market, the green bar (enlarged for illustrative purposes) illustrates the market price where SR-capacity is dispatched and the blue bar depicts the

[43] See Chapter 3 for an introduction to scarcity rent

potentially lost revenue due to the price cap from SR. A similar example of market interference is when SR is bidding in on the day-ahead market at a fixed price, which effectively acts as a price cap (CREG 2012).

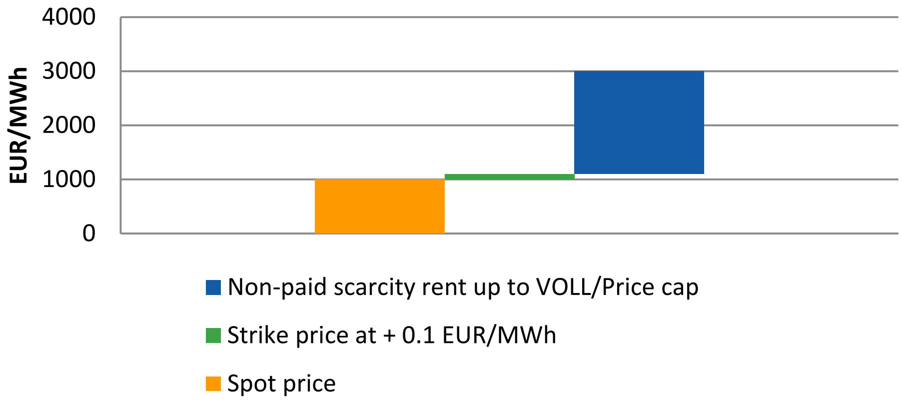


FIGURE 26 ILLUSTRATING THE LOST REVENUE FROM SCARCITY RENT AT A STRIKE PRICE OF 0.1 EUR/MWH ABOVE SPOT PRICE

Related to the issue of the strike price in SR, the following example from Finland shows that the market conditions are highly relevant, when setting the strike price: power markets are usually structured with a certain degree of segregation between producers and consumers, but the Finnish experience shows how this is not always the case. When SR was introduced in Finland, it happened when large industrial consumers were also owners of electricity production capacity. Since these consumers preferred a low market price, they advocated for the introduction of SR with a low activation-price. The result was an initial strike-price, and essentially a price cap for spot prices, at €500/MWh. (Sommer 2013)

4.4.7. SR Not a Flexible Resource

CREG (2012) argues that SR are not ideal for the backup of RES, since participating units are usually old and slow, and will be used often. While this might often have been the case previously, today it can be assumed that fast plants could be remunerated equally well as slow plants. This is already seen with gas-fired plants in Germany. Such reasoning enables participation of DCHP, which are smaller and more flexible than the capacities used in Finland and Sweden.

4.4.8. Market Power

As can be seen in Sweden, small margins in supply capacity can result in rather large changes in spot prices. To some degree, SR can address market power by introducing DR as a mitigation measure against market power enforced by the generator side. Challenges persist with market power, since generators can threaten to withdraw capacity from the market in order to receive SR remuneration. (Brunekreeft et al. 2011; Energinet.dk 2012)

4.5. Determining SR Remuneration

Based on the characteristics of SR identified in this chapter, a method for calculating the SR remuneration for a power plant is defined in this section. Like in the cases of Sweden, Finland and Germany, it is assumed that the plant cannot participate in the spot market as well as the SR, since this would go against the legislation on anti-competitiveness in EU-regulation, and since the preference is to reduce the impact on the spot market. Furthermore, it is assumed that a plant will have no incentive to move from the spot market to SR or vice versa, if this does not pay off. This might seem self-evident, but it is a pivotal point. Under this assumption, it can be inferred that if the total operational income from either the spot market or the SR are the same, that balance will be the marginal bidding price of the plant for participation in a potential SR. In other words, this method identifies the size of SR remuneration. In the scenarios presented in Chapter 6, the level of remuneration from the SR is found by this difference between participation and non-participation on the spot market.

$$SR = I_{Spot} - I_{SR}$$

Where:

> SR: The difference between total operation income on and off the spot market, i.e. the level of remuneration needed under SR-regulation to reach the break-even point with spot market operation
> I_{Spot}: The operational income with spot market participation
> I_{SR}: The operational income without spot market participation

The concept is exemplified in Figure 27, where the blue bar in the middle *Remuneration from SR* illustrates the difference between the operational income[44] on the spot market and off the spot market. Note that the operational income will be negative and that this negative amount will determine the heat price for the consumers. A better operational income thus means lower heat prices, the latter being the main objective for most DCHPs.

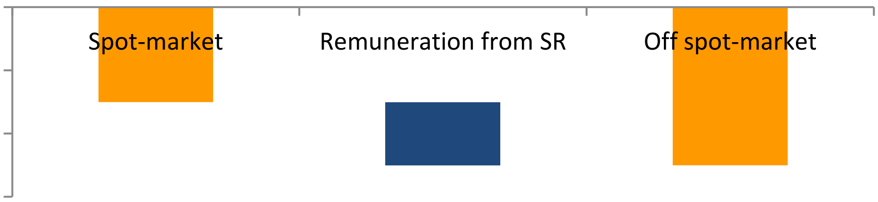


FIGURE 27 CONCEPT OF DETERMINING THE LEVEL OF SR REMUNERATION. NOTE THAT COLUMNS REPRESENT NEGATIVE VALUES

Remuneration from SR, represented by the patterned bar in Figure 27, can be interpreted in different ways, depending on assumptions:

- A potential Danish SR is based on competitive bids, and thus not constructed with special attention to the DCHPs
  - The DCHPs will be on equal footing with all other actors, and hence cannot expect any privileges. This means that the size of SR (the blue bar) will be the bidding-price or the marginal price of capacity on the plant
- A potential Danish SR is constructed with special attention to the DCHPs
  - The DCHPs will enjoy special privileges in the SR, where the size of the SR is the minimum size of remuneration paid by SR that would incentivise the DCHPs to participate in the SR

Although the above points have no influence on the techno-economic analysis in Chapter 6, the distinction is relevant for understanding the size and concrete configuration of the SR remuneration.

4.6. Partial Conclusion

The chapter has presented a CRM, which is already applied in different countries, and has been so for several years. This study asks which general energy economic consequences are implied in a SR. By reviewing experiences in Sweden, Finland and Germany and experiences from supplemental policy-maker perceptions on SR, the following conclusions can be drawn on the subject of energy economy[45].

[44] The term *operation income* is in this study applied as the term for total expenditure subtracted by total revenue
[45] This evaluation is directed towards the large-scale energy economic consequences, while the generator-specific consequences will be treated in Chapter 6

TABLE 4 EVALUATION OF THE ENERGY ECONOMIC IMPACTS OF SR

Parameter	Evaluation
Administration	TSO
Contracting mechanism	Tender
Technology neutrality, hereunder participation of demand-side	Limited amount of selected plants and demand response
Relation to market power	Robust, but generators can threaten to decommission plants. Can to some degree mitigate market power through DR
Sensitivity to state of the market	Low. The amount of contracted reserves can be adjusted from year to year
Impact on EOM	If the strike price is lower than the price cap, then high. Additionally, there might be situations where capacity is withheld despite spot prices over marginal cost of plants
Sensitivity to reduction in demand	Low. Assuming that the demand is reduced, SR can be adjusted downwards accordingly the next year
Sensitivity to increase in low-cost generation	Low. Assuming that SR capacity is contracted through bids among selected plants and assuming that the low-cost generation causes spot market prices to fall, bids for the SR are assumed to decrease as a result
Sensitivity to CO_2-prices	Low-medium. Assuming a Danish context where participating plants would be relatively efficient, relative profitability towards German capacity might increase if CO_2-prices increase. This would lead to increased costs of remuneration in SR
Incentive to preserve capacity in power system	High. This is the purpose of remunerating generators in SR
Investment incentive	None, still up to EOM
Revocability	Straightforward
Complexity	Low
Compatibility with surrounding markets	Can be implemented directly
Controllability of costs	Yes, since they are largely determined by the size of SR
Stabilisation of electricity prices	If dispatch at 0.1 EUR/MWh above spot price, then yes

A final conclusion to draw is that, with the exception of De Vries (2011), the treatment of a comprehensive regulation of the energy market has not been encountered in the literature on CRM and SR reviewed for this study. Instead, most perspectives on CRM appears to have a somewhat narrow focus on securing sufficient capacity, but not as a part of a wide-ranging analysis of the needs and opportunities of the energy system.

5. Case Study: Hvide Sande CHP

This chapter describes the combined heat and power plant in the town of Hvide Sande and its Danish context. The purpose of studying HSCHP is to have a somewhat generic plant, which is similar to many other plants, i.e. a critical case. Furthermore, the purpose of this chapter is to lay out the concrete foundation for the modelling by identifying the technological characteristics, taxes, subsidies and additional costs. All information specific to HSCHP in this chapter is provided by supervisor Jørgen Bukholt, unless otherwise specified.

5.1. The Danish Energy System: A Brief Introduction

The utilisation of CHP has in Denmark taken place for more than 100 years, but it is within the last 30 years that the DCHP has emerged, with the first Danish DCHP established in 1983 in the town Ullerslev (Skov and Petersen 2007). Figure 28 and Figure 29 illustrates the development, where the year 1985 on Figure 28 is significant, since it is one year before the Danish CHP agreement of 1986, where it was decided to implement an obligation for the deployment of 450 MW_e of DCHP across Denmark (Danish Energy Agency 2005).

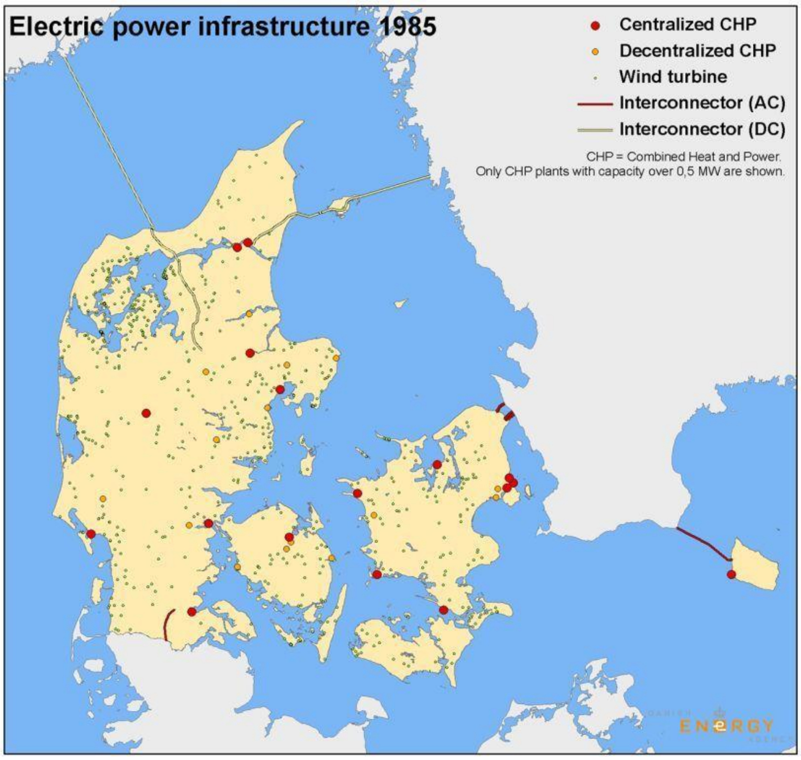


FIGURE 28 THE EARLY, MORE CENTRALISED ENERGY SYSTEM (DANISH ENERGY AGENCY 2013)

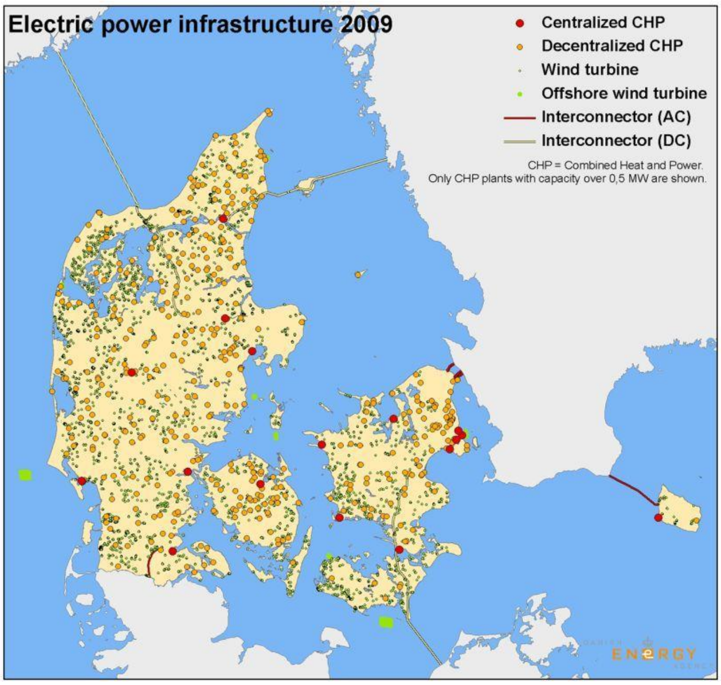


FIGURE 29 THE INCREASINGLY DECENTRALISED ENERGY SYSTEM (DANISH ENERGY AGENCY 2013)

The deployment of increased DCHP has several reasons, but can be attributed particularly to the political ambition to increase energy efficiency, which emerged after the oil crises of the 1970's (Skov and Petersen 2007; Danish Energy Agency 2005). The development is displayed in an annual interpretation in Figure 30, where the tendencies of the deployment of wind power, DCHP and central power plants are seen. Where the development of electric capacity of DCHP levelled out in the end of the 1990's, wind power has continued its increase up until now.

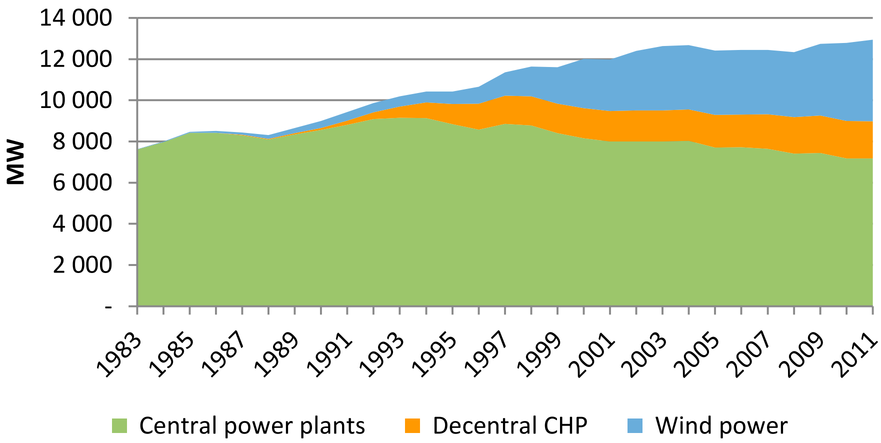


FIGURE 30 DEVELOPMENT OF INSTALLED CAPACITY OF WIND, DCHP AND CENTRAL POWER PLANTS IN DENMARK (DANISH ENERGY AGENCY 2012A)

As seen on Figure 31 and Figure 32, the western part of Denmark (DK1) is part of the synchronous system called Regional Group Continental Europe, while the eastern part of Denmark (DK2) is part of Regional Group Nordic. Although this means that Western Denmark is in synchronous connection all the way down to the countries bordering the Mediterranean Sea, the system cannot be balanced as one. This is due to bottlenecks, i.e. constraints in the grid that limit the transmission capacity within the system. An example of such balancing areas is seen in Figure 32, where several balancing areas are found within the same market.

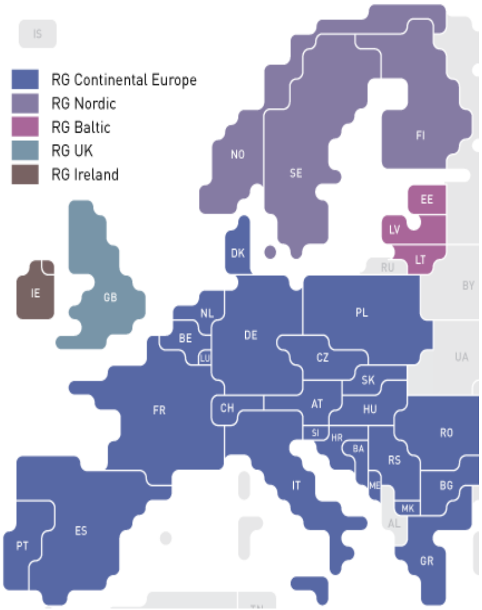


FIGURE 31 ENTSO-E'S GROUPING OF SYNCHRONOUS POWER SYSTEMS (ENTSO-E 2013)

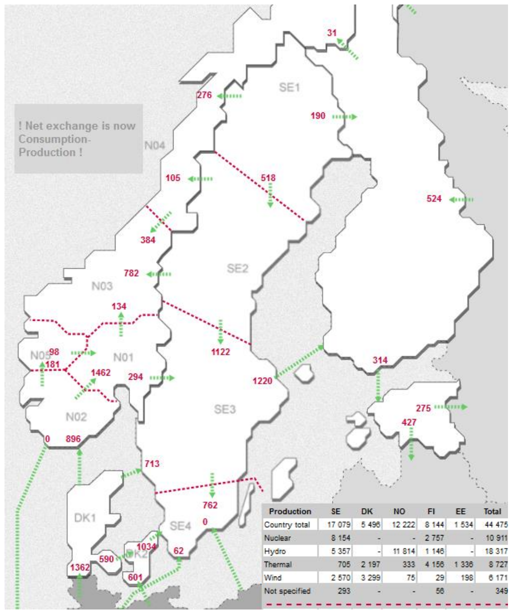


FIGURE 32 THE NORDIC DIVISION IN REGIONAL BIDDING AREAS (ENERGINET.DK 2013A)

Since the first Danish interconnection in 1915, Denmark has been part of a larger power grid. Despite the grouping of different synchronous systems, power can be traded freely across the borders (Lauge Pedersen 2013).

5.2. Hvide Sande CHP

As illustrated on Figure 33, HSCHP is placed in the westernmost part of Denmark, and is part of the RG Continental Europe and DK1. The town of Hvide Sande has 3 077 inhabitants per 2013 and is mainly characterised by fishery, tourism and public services (Den Store Danske 2013; Danmarks Statistik 2013). The town stretches north-south over a supply area of seven km. (Bukholt 2013). Average heat consumption between 2009 and 2013 has been 30 731 MWh, and the amount of consumers has been increasing throughout the years to 1 511 in 2013 (Hvide Sande Fjernvarme 2013).

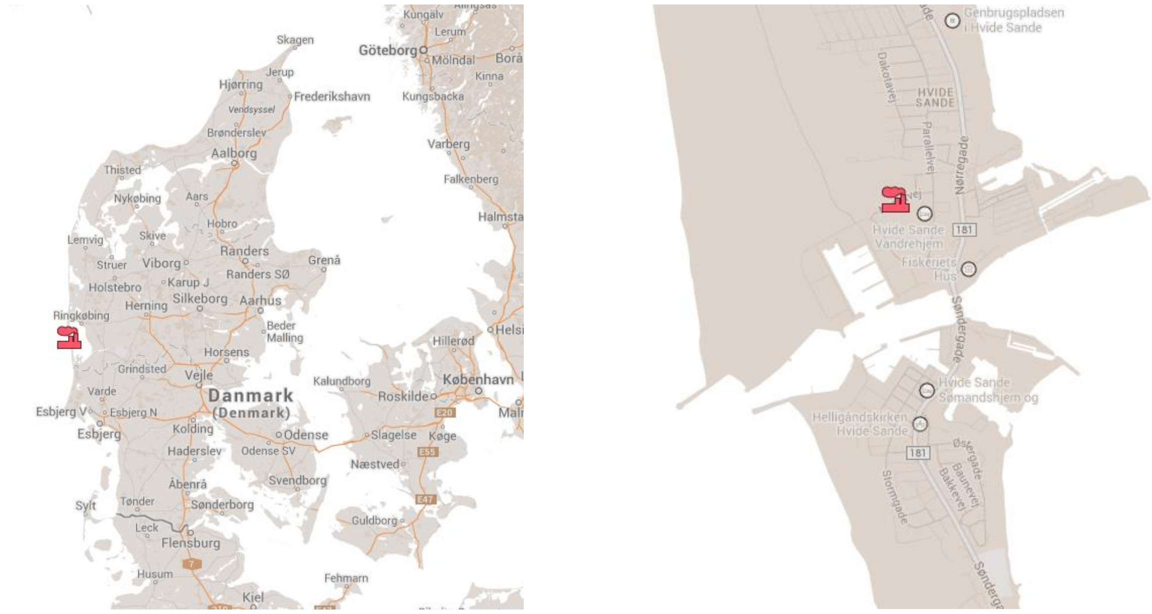


FIGURE 33 THE LOCATION OF HVIDE SANDE CHP (GOOGLE 2013)

The idea of DH in Hvide Sande was introduced in 1962, and until 1994, the DH supply was based on various forms of fuels, including waste oil, fish oil and wood. In 1994, the current plant was established with two gas boilers and two engines. Except for a 6 MW_e electric boiler, installed in 2011, all units on the plant run on natural gas, supplied via pipeline. The data sheet in Table 5 provides details on the single units.

TABLE 5 SPECIFIC DATA ON THE EQUIPPING OF HVIDE SANDE CHP

Name	Electricity input	Natural gas input	Electricity output	Heat output	Efficiency electricity	Efficiency heat
Unit	MW_e	MW	MW_e	MW_{th}	%	%
Engine 1	-	9.4	3.7	4.2	40	45
Engine 2	-	9.4	3.7	4.2	40	45
Small natural gas boiler	-	4	-	4	-	100
Large natural gas boiler	-	10	-	10,4	-	104
Electric boiler	6	-	-	6	-	100

HSCHP has a grid loss of 25 %, 7.1 percentage points higher than the Danish weighted average of 17.9 % (Danish District Heating Association 2013). This relatively higher loss can be attributed to the relatively long stretch of the town, where long distances increase the loss from the grid more than average (Bukholt 2013). The engines have a strike price around 67 EUR/MWh, and the electric boiler has a strike price of 2.7 EUR /MWh. The storage tank is 2 000 m^3, with 90° C in the top and 40° C in the bottom, equalling about 104 MWh of storage capacity, when the utilisation degree is 90 %.

The prospects of conducting a major overhaul on the electricity-producing units of DCHP have been investigated by the district heating think tank Green Energy. Figure 34 shows that among 160 DCHPs, 54 % do not know whether they will perform the overhaul when the amount of designated operating hours will have been spent. HSCHP falls in this category, and is thus representative in this regard. This hesitancy in the case of HSCHP is partly due to the time horizon of roughly 15 000 remaining engine hours and a current amount of approximately 500 operating hours per year. An according time horizon of 30 years makes it too early for HSCHP to decide (Bukholt 2013).

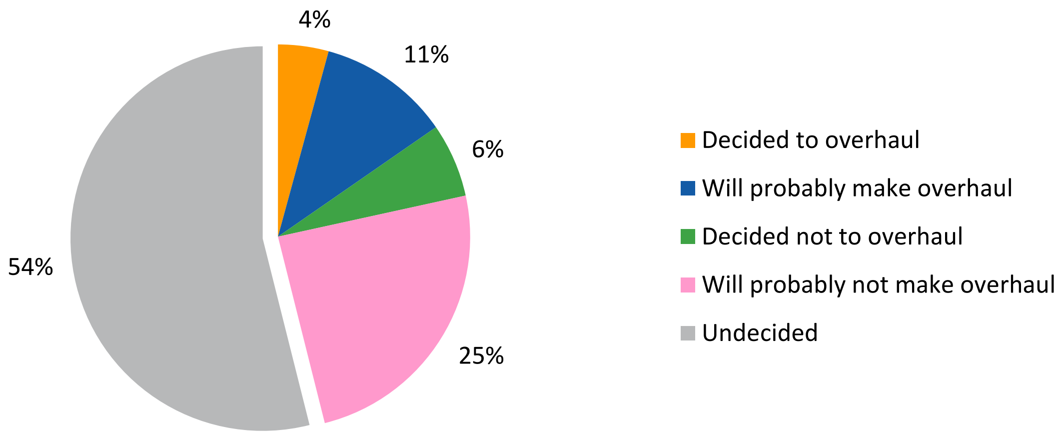


FIGURE 34 ATTITUDE TOWARDS OVERHAUL OF ELECTRICITY PRODUCING UNITS (GREEN ENERGY 2013C)

Regarding the plans for future investments, HSCHP again falls in the major category, since the plant is currently considering solar heating. As seen in Figure 35, 35 % of planned or considered decisions are solar heating.

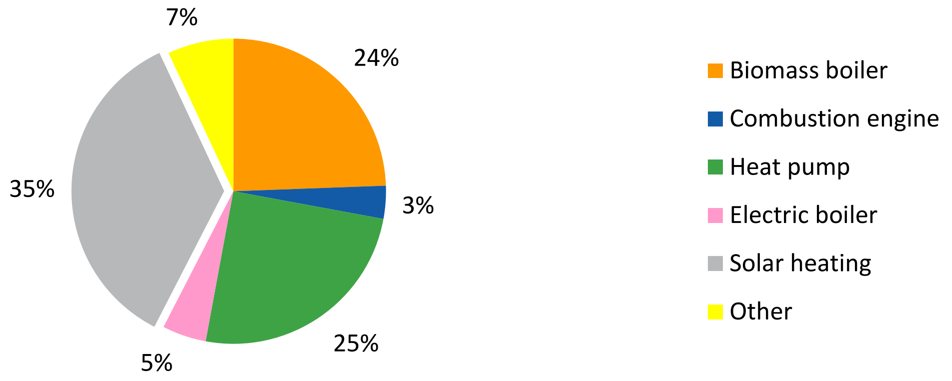


FIGURE 35 PLANS FOR FUTURE INVESTMENTS. SOME ARE ALREADY DECIDED, WHILE OTHERS ARE MERELY IDEAS (GREEN ENERGY 2013C)

The electricity production from HSCHP has seen a general decline during the last 15 years, as seen in Figure 36. This is a general tendency among DCHP in Denmark, as can be seen in Chapter 1.

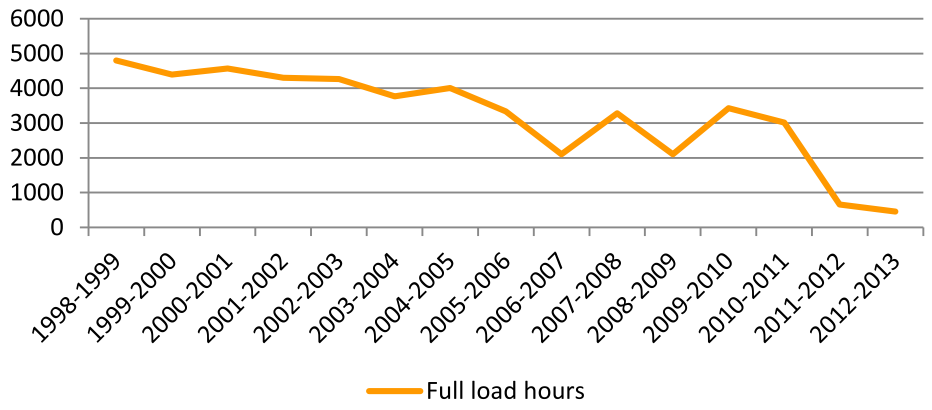


FIGURE 36 FULL LOAD HOURS ON HVIDE SANDE CHP (HVIDE SANDE FJERNVARME 2013)

HSCHP is a cooperative plant owned by local consumers, and is thus representative in this respect. Figure 37 illustrates the ownership structure of the Danish CHPs. It can be seen that CHPs are generally publicly owned, either by the municipality, the state or the consumers.

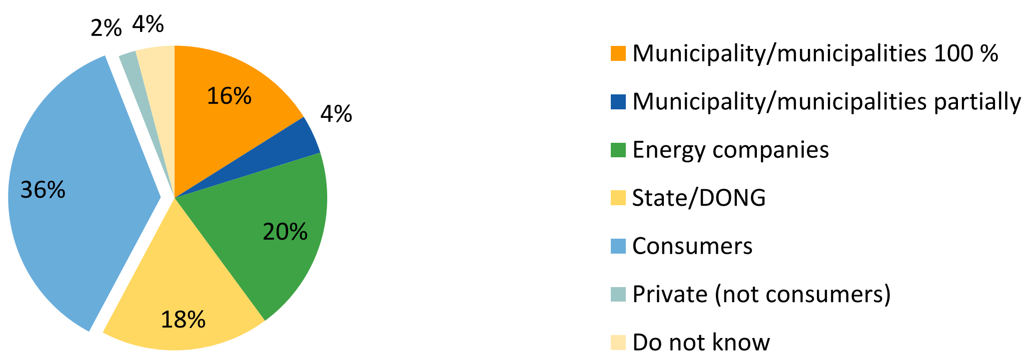


FIGURE 37 OWNERSHIP OF DCHP (GRAM MORTENSEN AND GOTTRUP 2007)

5.2.1. Participation in the Markets

During the 1980's and 1990's, DCHPs were operating according to heat demand, i.e. more or less constantly and with no incentive to adapt their production to the needs of the power system. With the introduction of the triple tariff[46] and the introduction of the DCHP on the power market, this has changed (H. Lund and Andersen 2005). The following sections present the various markets that are relevant to consider when studying and modelling DCHP.

Heat Market

The heat market is regulated through the Heat Supply Act (2011), which provides the foundation for Danish heat planning. Its purpose is to ensure the production of heating and hot water in the best socio-economic and most environmentally friendly manner and to reduce the consumption of fossil fuels. The act requires cost-based pricing[47], where it is defined that DH suppliers can factor in *energy, wages and other operational costs, administration and sales, expenses due to public obligations and energy savings activities* (Danish Ministry for Climate Energy and Building 2011). Heat markets are confined by the physical presence of the district heating (DH) systems' transmission of hot water, i.e. pipes in the ground. For DCHP this puts a natural limitation to any market expansion, since the plants are usually placed near the towns they supply. Due to losses in the DH-transmission grid, the supply to more thinly populated areas surrounding the cities will be uneconomic at a certain point. Although there is possibility for third party access to the DH-grid, the principle of cost-based pricing means that producers will have to return the profit to the consumers in the form of adjusted heat prices. Concerning the focus of this study, it can be argued that, since the Danish power sector is largely based on CHP, it means that plants will often have an additional income from heat production. The share of payment from district heating production can hence be considered as a kind of capacity payment. This definition should not be interpreted too rigidly, since there is a limit to the willingness to pay from DH consumers[48] and the co-production of electricity and heat might not necessarily be the cheapest option. Due to the latter, an interesting question comes to mind: if the opposite is the case for DCHP, i.e. that the electricity production is a heat-capacity payment for the DH. Elaborating on this subject, chairman of the Danish District Heating Association, Uffe Bro, has argued that the sole purpose of a cooperatively owned CHP is to supply heat at a low price (Skov and Petersen 2007). In the case of HSCHP and any other Danish DCHPs, the heat prices are determined by the difference between revenue and expenditure. Following the notion of Bro means that DCHPs are primarily defined as heat producers, while any other services which are provided, such as supplementing the heat production with revenue-generating electricity production, are secondary services. In this line of reasoning, the DCHP would always choose the type of equipping or economic structure that could reduce heat prices the most. This means that a DCHP would return to heat-only production, if there was an economic incentive to do so, while it seems unlikely that the plant would become a purely electricity-producing plant. It is thus important to be aware of the buffer-function of the heat/electricity-production for its counterpart.

5.2.2. Spot Market

While the prices in the heat market are required to be cost-based, this is not the case for the power markets. This section will cover the way in which HSCHP act on the spot market, since this is relevant in order to understand how the plant generates revenue. In the Nordic system, the spot market, called Elspot, is managed by the Nordic power exchange, Nord Pool Spot. In 2012, 77 % (334 TWh) of all power consumed in the Nordics was traded on the Nord Pool spot market(Nord Pool Spot 2013b). Every day, participants bid in their expected price and duration of power production or consumption for the following day, i.e. the day-ahead spot market. Gate closure[49] on the day-ahead spot market is 12-36 hours ahead of the hour of delivery, and is scheduled every day at noon. After this point, the system price and area

---

[46] Where tariff rates are split into three periods during the day: low, high and peak (Energinet.dk 2010)

[47] In energy economics also known as cost of service pricing (Energy Vortex 2013; Commission 2013)

[48] Chapter 10 in the Electricity Supply Act (2013d) describes settlements of electricity production, where it is specified that CHP are not allowed to price DH in a way that is unfair to the DH consumers. This is interpreted as a safeguard against having DH consumers pay a too large share of the production costs, enabling the generator to sell electricity cheaper.

[49] The time ahead of the production hour that producers can submit their bids

prices are calculated centrally. This relatively long lead-time can be explained by the need, particularly when the market was designed, to accommodate hydro, thermal and nuclear producers who benefit from ample time to plan production, partly due to ramping constraints. The DCHP were introduced to the day-ahead spot market in 2005 and by 2009 75 % of Danish CHP below 5 MW_e participated in this market (Bang, Fock, and Togeby 2012; Henrik Lund et al. 2012). In order to participate on the market, the generator is required to act through a balance responsible party (BRP) (Energinet.dk 2013b). Smaller generators such as HSCHP might not have the resources to participate in the spot market by themselves, so the contracting with a BRP can be helpful. The concrete procedure for the participation of HSCHP on the spot market is explained by Bukholt (2013) as follows:

1. The gas price for the preceding day is checked since this is the best available information on the level of gas prices
2. The bidding-price of the engines is calculated according to the gas price
3. Block-bids of four hours are submitted to the BRP. The bids are separated into time steps from 0:00-04:00, 04:00-08:00, 08:00-12:00 etc., and is reported to the BRP before 9 in the morning
4. If the plant wins no bids, it can still be activated for ancillary services

5.2.3. Taxes and Levies

This section provides an overview of the taxes that are levied on the DCHP. The purpose of this overview is to identify the inputs that will be part of the techno-economic modelling in Chapter 6. A general difference exists between the taxing of electricity and of heat. Taxes on heat are charged from the producers, while taxes on electricity are charged from the consumers. Regarding heat, this means that the amount lost in the distribution is levied, while the opposite is the case with electricity. Part of the reason for this is assumed to be competition: electricity is traded across borders in competition with other producers, while heat markets are local and not subject to competition in the same manner.

Energy Tax

The energy tax on natural gas, as is seen in Table 6, is part of the Danish excise duties.

TABLE 6 THE ENERGY TAX ON NATURAL GAS (SKAT 2013A)

Type of tax	Unit	Amount	Applies to engines	Applies to gas boilers
Energy tax on natural gas	EUR¢/Nm^3	37.47	X	X

CO_2 and Methane Tax

Also part of the excise duties, the CO_2 tax, the methane tax on piston engines and the electricity tax are seen in Table 7.

TABLE 7 CO2 AND METHANE TAX ON NATURAL GAS AND PISTON ENGINES (SKAT 2013B; SKAT 2013C)

Type of tax	Unit	Amount	Applies to engines	Applies to gas boilers	Applies to electric heating
CO_2 tax on natural gas	EUR¢/Nm3	4.96	X	X	
Methane tax on piston engines	EUR¢/Nm3	0.84	X		
Electricity (energy savings tax)	EUR¢/kWh	0.87			X

NO_x Tax

The NO_x tax covers nitrogen oxides emitted by the plant. The tax is differentiated, depending on the production unit, as is seen in Table 8.

TABLE 8 NOX TAX ON NATURAL GAS BOILERS AND ENGINES (SKAT 2013B)

Type of tax	Unit	Amount	Applies to engines	Applies to gas boilers
NO_x tax on natural gas for boilers	EUR¢/Nm3	0.54		X
NO_x tax on natural gas for engines	EUR¢/Nm3	1.89	X	

Electricity Tax

The tax on electricity for the production of heat is relevant for CHPs with electric boilers and electric heat pumps. The rate is provided in Table 9.

TABLE 9 TAX ON ELECTRICITY CONSUMPTION IN ELECTRIC BOILERS AND ELECTRIC HEAT PUMPS (SKAT 2013D; EMD INTERNATIONAL 2013A)

Type of tax	Unit	Amount
Electric heating tax	EUR¢/kWh	4.57

5.2.4. Subsidies and Reimbursements

Some of the taxes are reimbursed and, in addition, subsidies are provided for the DCHPs. Both elements are described in this section.

Production Independent Payment

The production independent payment (PIP) can be considered a kind of capacity payment for CHPs participating on the spot market. The PIP is provided to the plant according to a benchmark-income established in the years 2001-2003, prior to the entry on the market (EMD International 2013a). The amount is indexed according to the spot prices in the given month and therefore varies. Table 10 illustrates how the PIP is calculated. Until 2009, Ir was adjusted according to the index regulation, but since 2010 it is fixed at 1.223 (Energinet.dk 2013c; Danish Ministry for Climate Energy and Building 2013c).

TABLE 10 REGULATED INDEX FUNCTION WHICH DETERMINES THE LEVEL OF THE PRODUCTION INDEPENDENT PAYMENT

Regulated index function	
Spot price, EUR¢/kWh	Index factor
Spot price<11*Ir	1.4*Ir
11*Ir< Spot price< 34*Ir	1.4*Ir – 0.06087 * (Spot price-11*Ir)
34*Ir< Spot price	0

The expiration from 2019 is currently being discussed with concern in the Danish CHP sector (Tingkær 2013; Koch 2013). PIP for HSCHP is 838 718 EUR/year, and makes up a considerable share of the income, as is presented in Chapter 6.

New Production Independent Payment

In 2013, a production dependent payment was converted into a new production independent payment (NPIP). It is based on the highest amount of electricity production in kWh in any of the years 2005, 2006 or 2007, multiplied with 0.01 EUR. The amount is capped at 85810 EUR/year, which is also what most plants, including HSCHP will get. There is no scheduled expiry on the NPIP. (Danish Ministry for Climate Energy and Building 2013d)

E and V Formula

Since tax is not levied on electricity from plants that are allocated CO_2-quotas, the tax on fuels which are used for electricity production in CHPs is refunded. Specifically, the taxes on CO_2 and natural gas are remunerated (EMD

International 2013a). Since it can be difficult to allocate the exact distribution, two formal methodologies apply: the E formula and the V formula[50]. Based on monthly production of electricity and CHP-based heat, the distribution of taxes can be based in one of the two formulas. The preferred formula is chosen by the plant once every year. (SKAT 2013e)

V formula, applied by HSCHP:

$$Allocation\ of\ fuel\ for\ heat\ production = \frac{Heat\ produced}{1.2}$$

$$Allocation\ of\ fuel\ for\ electricity\ production = Total\ amount\ of\ natural\ gas\ consumed - \frac{Heat\ produced}{1.2}$$

The V-formula comes with a so-called caution rule, where the maximum allocation of fuel for electricity production is limited as described here:

$$Allocation\ of\ fuel\ for\ electricity\ production = \frac{Electricity\ produced}{0.35}$$

E formula:

$$Allocation\ of\ fuel\ for\ electricity\ production = \frac{Electricity\ produced}{0.67}$$

$$Allocation\ of\ fuel\ for\ heat\ production = Total\ gas\ consumption - Gas\ for\ electricity\ production$$

Reimbursement of CO_2- and Energy Tax on Boiler Operation

The use of both gas and electricity for DH production is partly reimbursed. The numbers are provided in Table 11. The caps set a minimum amount of tax which is not reimbursed to the producer.

TABLE 11 CAPS ON REIMBURSEMENT ON GAS AND ELECTRICITY CONSUMPTION FOR HEAT PRODUCTION (EMD INTERNATIONAL 2013A)

	Unit	Amount
Cap for reimbursement of CO_2 tax on heat produced from electric- or gas boiler	EUR¢/kWh of DH from plant	0.63
Cap for reimbursement of energy tax on heat produced from electric- or gas boiler	EUR¢/kWh of DH from plant	2.84

5.2.5. Fixed Costs

Downtime costs include various costs, such as costs for heating, insurance and mandatory inspections on the engines. The cost per engine has been estimated to be roughly 50 000 EUR/year/engine, a number confirmed by Bukholt (2013) to be likely. The number is relevant in case the plant wishes to decommission its engines entirely at some point. Operation and maintenance on the boiler is estimated to amount to 38 500 EUR/year, based on the size of the boiler and a point between the highest and lowest cost stated for gas boilers in the Danish Energy Agency' and Energinet.dk's (2013) Technology Data for Energy Plants.

5.2.6. Variable Costs

Variable costs are defined as costs that depend on the production of electricity and heat. This section describes the service agreement and natural gas contract. Service agreements are common in DCHPs, where they can have different designs, and are negotiated bilaterally. For the analysis in this study, they are relevant since operation and maintenance

[50] E for *elektricitet* – electricity and V for *varme* – heat

on the engines require expenses for regular services. In the case of HSCHP the current service agreement includes services until the major overhaul at 80 000 hours, which is not included in the agreement. At this point, the plant will have to decide if such an overhaul is preferred over the alternatives. The cost of the service agreement is based on the amount of electricity produced on the engines: 0.45 EUR¢/kWh. Contrary to other types of service agreements, there is no fixed cost in the service agreement of HSCHP.

Another variable cost is based in the use of natural gas and electricity. While HSCHP has an agreement on a fixed monthly cost for a certain amount of gas, this is not included here, nor in the modelling, due to the plant-specificity of that agreement. Concerning distribution tariffs, both electricity and natural gas tariffs are presented in Table 12.

TABLE 12 VARIABLE COSTS ORIGINATING FROM TARIFFS ON GAS AND ELECTRICITY (BUKHOLT 2013)

Name	Amount in DKK	Amount in EUR¢	Unit	Note	Applies to engines	Applies to gas boilers	Applies to electric boiler
GAS							
Transmission fee	0.0133	0.1783	Per m3	Collected by the gas trading company	X	X	
Distribution tariff	0.1636	2.1935	Per m3	Collected by the gas distribution company	X	X	
Emergency supply tariff	0.0288	0.3861	Per m3	Collected by the gas distribution company for Energinet.dk	X	X	
Additional charge for NCG	0.0551	0.7388	Per m3	Collected by the gas distribution company for gas exchange NCG	X	X	
ELECTRICITY							
Feed-in tariff to grid	0.0040	0.0536	Per kWh	Collected by BRP	X		
Volume fee	0.00026	0.0035	Per kWh	Collected by BRP	X		X
Production fee	0.00059	0.0079	Per kWh	Collected by BRP	X		
Consumption fee for Energinet.dk	0.00131	0.0176	Per kWh	Collected by BRP			X
Flexible basic charge	0.0045	0.0603	Per kWh	Collected by BRP			X
Balancing power charge	0.001	0.0134	Per kWh	Collected by BRP			X

CO_2-QUOTAS

According to the Danish Act on CO_2-quotas (2012), production units such as DCHP are allocated a certain amount of free quotas, based on benchmarking conducted by the European Commission. § 20 in the Heat Supply Act (2011) allows the generator to purchase or sell quotas. Any income or expense from this must be set off against the DH price, in accordance with the cost-based pricing of DH. Each allowance is the equivalent of one tonne of CO_2. In 2013, HSCHP has been allocated 8 273 free emission allowances, but in order to have the quota price reflected in the operation, these free allowances are not included in the modelling.

6. Techno-Economic Analysis

This chapter presents the techno-economic analysis in two aspects: preconditions and assumptions for the analysis and the concrete results of this analysis. In accordance with the research questions, the techno-economic analysis of the current and future equipping and economic performance of a DCHP will provide insight regarding the level of remuneration potentially needed from SR under different scenarios.

DCHPs need to know what market regulation can do and how to bend it in order to achieve their own strategic goals. DCHPs cannot wait until market regulation is fully implemented to think about how they will work for or against them. And sometimes DCHPs will need to disrupt their own business models before a rival or a new competitor does it for them. This slightly rephrased statement, originating from the consultancy McKinsey (2013)[51], deliberates the purpose of this study and this chapter in particular. In the following sections, the framework and the results of the techno-economic analysis will be presented.

6.1. Evaluation Parameters

The evaluation of the analysed scenarios will be carried out concerning three parameters: business economy, operation and the size of SR remuneration. These are detailed in Table 13.

TABLE 13 EVALUATION PARAMETERS APPLIED IN THE TECHNO-ECONOMIC ANALYSIS

Parameter	Unit	Purpose
Business economy	EUR/year	Comparison of the economic performance between scenarios. Additionally used for determining the remuneration from SR needed within the same scenario, when the DCHP is respectively on the spot market and under SR
	Heat price (EUR/MWh)	Indicator for the cost of heat
Operation	Balance price (EUR/MWh)	The balance price between units is investigated in order to determine the competitiveness of units that cause the given heat production
	Weekly production	The sample from a week of production, provides a concrete picture of operation under the given equipping
	Fuel consumption (Nm^3/MWh_{th})	An indicator for the fuel-intensity of the heat production
	Heat production (MWh)	Distribution of heat production on the different units of the DCHP
Size of SR remuneration	Size of remuneration (EUR/year)	Determined by the difference in operational income between two variants of the given scenario. The size of SR remuneration thus amounts to the difference between the revenue either with participation on the spot market or without participation on the spot market. See further details below this table
	Cost of capacity (EUR/MW_e)	Cost of capacity is derived from the size of SR remuneration and the amount of MW_e on the plant, i.e. cost per MW_e.

The terminology used in the description of business-economic parameters is defined as follows:

- Total revenue: The sum of revenue generated in the scenario. Given as an absolute number

[51] Original quote: *Top leaders need to know what technologies can do and how to bend it to their strategic goals. Leaders cannot wait until technologies are fully baked to think about how they will work for-or against them. And sometimes companies will need to disrupt their own business models before a rival or a new competitor does it for them.*

- Total expenditure: The sum of expenditure in the scenario. Given as an absolute number
- Operation income: The real number, resulting from subtracting the expenditure from the revenue. Since none of the scenarios provide a positive result, the negative value is divided on the heat consumption. Operation income thereby defines the heat price

It is important to be aware that the *Size of SR Remuneration* indicates a breaking point[52] as it marks either a greater incentive to operate on the spot market or to operate as an SR. Size of SR remuneration indicates the point where the plant is equally well off with remuneration as on the spot market. In other words, the amount represents the gap in revenue of being on and off the spot market respectively. Furthermore, it is important to note that the remuneration cannot be related to the cost of new entry (CONE) since the techno-economic analysis solely considers operation during a single year, assuming that all investments are sunk costs. Instead, the remuneration can be interpreted as the opportunity cost the plant has to consider when it operates either on the spot market or under SR for one year. Finally, the level of remuneration within each scenario solely describes the cost of being off the spot market in the given scenario. Remuneration levels are hence not comparable between scenarios since they are based on plants with different types of equipping. The scenario *4hp* is elaborated with an investment analysis in order to determine if the business economically positive result of having a heat pump in 2020 carries through in an investment in 2013, compared to business as usual.

6.2. Assumptions on the Analysed Scenarios

The modelling is based on HSCHP[53] and the Danish energy regulation, as presented in Chapter 5. Only if differences from the data presented in these chapters are apparent, it will be noted in the specific scenario description or in the following sections.

6.2.1. General Assumptions

2020 is a leap year, but to obtain comparable results, the 29th of February 2020 has been removed from the projections of prices. All monetary amounts in the analysis are in 2013-EUR and taxes and subsidies are assumed to be the same as in 2013, unless otherwise noted. For simplicity reasons in the modelling, the expenditure for the service agreement has been defined as a variable cost per produced MWh. Expenditure for operation and maintenance is implicit in the service agreement. NPIP is maintained in all scenarios where the existing engines are present, since CHP capacity is required in order to receive the subsidy (Danish Ministry for Climate Energy and Building 2013d). Regarding the economic aspects, Table 14 summarises the changes performed in the modelling between 2013 and 2020. These elements are specified in the following sections and in the specific scenario descriptions.

TABLE 14 CHANGES IN THE MODELLING PARAMETERS FROM 2013 TO 2020

Name	2013	2020
Spot market	Based on 2012 and 2013 market data from TSO Energinet.dk	Spot-variation: Ea Energy Analyses. Average price: Danish Energy Agency (2013b)
Natural gas bought, molecule price	Average price in 2013 from gas exchange Gaspoint Nordic	Based on projection of average annual price from Danish Energy Agency
PIP	Presently paid to HSCHP	Expires 1st January 2019
CO_2-quotas	Average price in 2013 is 4.38 EUR/tonne, according to EEX	Price for CO_2-quotas increased to 21.72 EUR/tonne according to Danish Energy Agency

[52] Similar to, but not the same as, the marginal bidding price on the spot-market

[53] The electric boiler and second boiler of HSCHP have not been included in the modelling, since a more generic type of plant is desired, solely with one boiler and two engines for the modelling

6.2.2. Operation

At HSCHP, there are two boilers, and production from the larger and more efficient boiler is often directed to the heat storage. In the modelling, this is not allowed, since the purpose with the modelling is not an optimization of boiler operation, but an investigation of the consequences of different types of equipping. Boiler 2 is entirely excluded, since the larger and more efficient Boiler 1, which in the modelling is allowed to produce in partial load, can cover heat demand at all times during the year. No expenditure for starting either the engine or the boiler has been assumed. Furthermore, the boiler has no minimum operating time, while the engines are modelled with a minimum operating time of three hours. Week 9[54] has been chosen for the illustration of weekly operation, since there is a combination of ample heat demand[55], periods with spot prices sufficient for engine-operation, and adequate solar radiation for solar heating[56].

6.2.3. Numerical Inputs to the Model

Summarisations of the input data of the model are seen in the following tables. All data derives from Bukholt (2013) is presented in Chapter 5.

TABLE 15 TECHNICAL FOUNDATION OF THE SCENARIOS

Technical input parameter	Amount or size	Unit
Heat consumption	30 731	MWh_{th}/year
Per engine input	9.4	MW natural gas
Per engine electric output	3.7	MW_e
Per engine heat output	4.2	MW_{th}
Natural gas boiler input	10	MW natural gas
Natural gas boiler output	10.4	MW_{th}
Heat storage	104	MWh_{th}

TABLE 16 GAS-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS

Input parameter	Amount	Unit	Applies to engines	Applies to gas boiler
Transmission fee	0.18	EUR¢/Nm^3	X	X
Distribution tariff	2.19	EUR¢/Nm^3	X	X
Emergency supply tariff	0.39	EUR¢/Nm^3	X	X
Additional charge for NCG	0.74	EUR¢/Nm^3	X	X
Energy tax on natural gas	37.47	EUR¢/Nm^3	X	X
CO_2 tax on natural gas	4.96	EUR¢/Nm^3	X	X
Methane tax on piston engines	0.84	EUR¢/Nm^3	X	
NO_x tax on natural gas for boilers	0.54	EUR¢/Nm^3		X
NO_x tax on natural gas for engines	1.89	EUR¢/Nm^3	X	

[54] 5th to 12th of March
[55] Average outside temperature of -4.1 °C during the week
[56] Hourly average solar radiation of 113 W/m^2

TABLE 17 ELECTRICITY-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS

Input parameter	Amount	Unit	Applies to engines	Applies to gas boiler	Applies to electric heating
Feed-in tariff to grid	0.54	EUR/MWh	X		
Volume fee	0.03	EUR/MWh	X		X
Production fee	0.08	EUR/MWh	X		
Consumption fee for Energinet.dk	0.18	EUR/MWh			X
Flexible basic charge	0.60	EUR/MWh			X
Balancing power charge	0.13	EUR/MWh			X
Electricity (energy savings tax)	8.72	EUR/MWh			X
Electric heating tax	45.72	EUR/MWh			X
Electricity market	Spot	-	X		X

TABLE 18 CO2-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS

Input parameter	Amount	Unit	Applies to engines	Applies to gas boiler
CO_2-price 2013	4.38	EUR/allowance	X	X
CO_2-price 2020	21.72	EUR/allowance	X	X

TABLE 19 REIMBURSEMENT-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS. * FOR SIMPLICITY REASONS IN THE MODELLING, THE CAUTION RULE HAS NOT BEEN INCLUDED IN THE V-FORMULA

Input parameter	Amount	Unit	Applies to engines	Applies to gas boiler	Applies to electric heating
E- or V-formula	V-formula*	-	X		
Cap for reimbursement of CO_2 tax on heat produced from electric- or gas boiler	6.30	EUR¢/kWh of DH from plant		X	X
Cap for reimbursement of energy tax on heat produced from electric- or gas boiler	28.42	EUR¢/kWh of DH from plant		X	X

TABLE 20 SUBSIDY-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS. *PAID AMOUNT DEPENDS ON SPOT MARKET PRICES

Economic input parameter	Amount	Unit	Applies to engines
Production independent payment*	838 718	EUR/year	X
New production independent payment	85 810	EUR/year	X

TABLE 21 MAINTENANCE-RELATED ASSUMPTIONS AND INPUTS FOR THE SCENARIOS. DATA BASED ON DANISH ENERGY AGENCY AND ENERGINET.DK (2013)

Economic input parameter	Amount	Unit	Applies to engines	Applies to gas boiler
Gas boiler O&M	3 700	$EUR/MW_{th}/year$		X
Per engine service agreement	4.542	EUR/MWh	X	
Fixed costs per engine	50 000	$EUR/MW_e/year$	X	

6.2.4. Gas Prices

The average gas price for 2013 has been derived from the gas exchange, Gaspoint Nordic (2013), by averaging daily prices per 12 November 2013: 0.341 EUR/Nm^3. For 2020, a price projection by Danish Energy Agency (2013b) has been applied: 0.340 EUR/Nm^3. Current gas prices are higher than the prices seen in the projection by Danish Energy Agency. It is assumed in the analyses that this tendency will not continue, but that prices will converge towards the projection in 2020.

6.2.5. Spot Market Prices

Spot market prices for 2013 have been derived by converting hourly 2012-prices from Energinet.dk to an index, and multiplying this with the average hourly price of Western Denmark (DK1) per 12 November 2013. 2020-prices are based on the Danish Energy Agency's (2013b) projection of the average system price in Nord Pool Spot. A specific projection for DK1 is not available. Since the numbers provided in this projection are provided on a 2011-level, it has been necessary to index these to a 2013-level, according to the net price index, given by the Ministry of Economic Affairs and the Interior (2013). The projected price from the Danish Energy Agency has been indexed according to a projection of hourly prices for DK1 made by the consultancy Ea Energy Analyses[57]. This procedure has been chosen in order to provide the variations supplied by the hourly data, while maintaining the Danish Energy Agency publication as the reference for the annual price-level. As seen in Figure 38, 2020-prices are never negative. The reason is found in the modelling assumptions for the data, where the Balmorel-model optimises the system to avoid negative prices. The lack of negative prices is thus an inherent assumption in the modelling. There are some discrepancies in the assumptions made for the 2020-spot price calculation and the present study. These include CO_2-prices which are EUR 10/tonne; approx. the double amount is applied in this present study (see section on CO_2-quotas, Section 6.2.6). For natural gas, an average price around EUR 7/GJ is applied by Ea Energy Analyses, while this present study applies an average price of EUR 9.7/GJ. The assumption in this present study is that the importance lies in determining orders of magnitude in the projections rather than specific numbers. Hence, the differences are not considered any further in the study.

[57] The study and dataset is at the time of conducting this study unpublished, and therefore not publically available

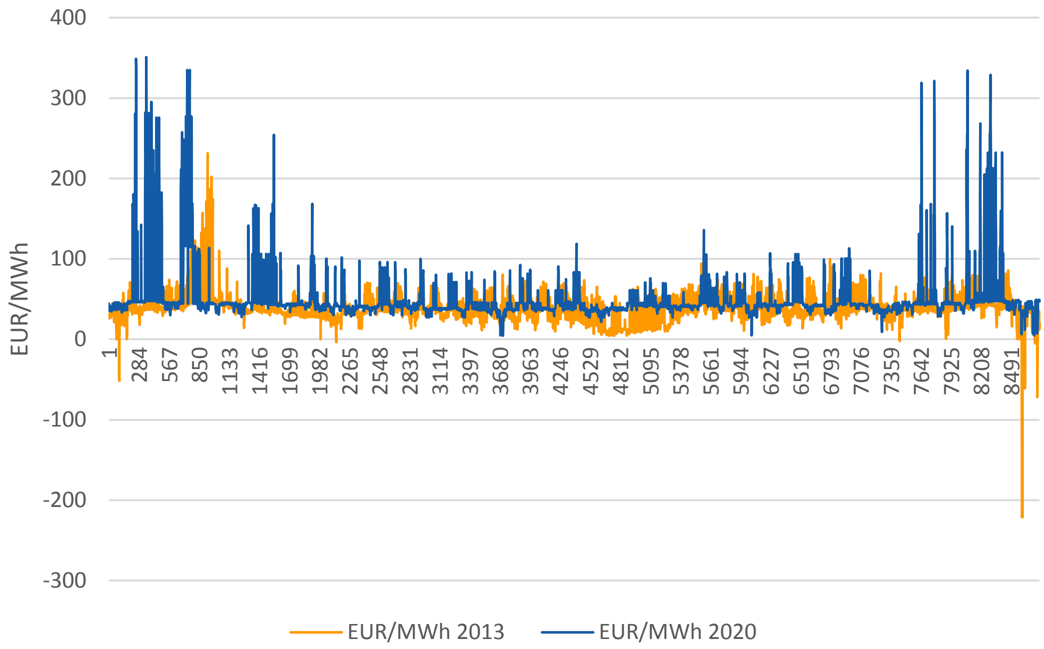


FIGURE 38 PROJECTED SPOT MARKET PRICES FOR 2013 AND 2020

Spot prices are generally higher in 2020, indicated by the average price of 50.76 EUR/MWh, compared to 40.06 EUR/MWh in 2013. On the spot market, the average prices vary from hour to hour, day to day and year to year. This is illustrated by the price duration curves on Figure 39 to Figure 41, depicting the average DK1 spot prices 2006-2012 and the prices applied in this study: 2013 and 2020. It is worth noticing that the price cap of EUR 2 000/MWh is not reached in any of these years.

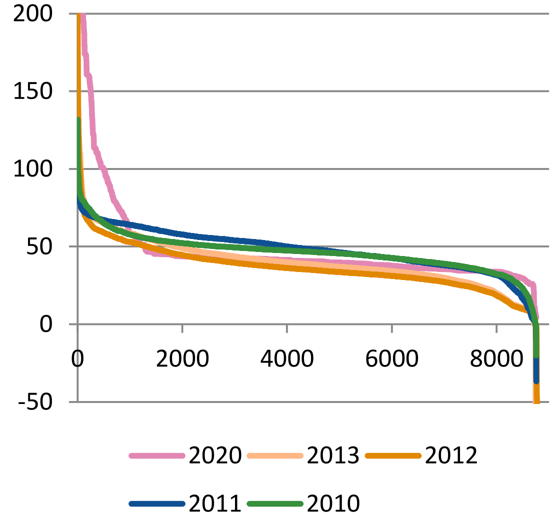


FIGURE 39 PRICE DURATION CURVE. CUT OFF AT 200 EUR/MWH AND -50 EUR/MWH. VERTICAL AXIS: EUR/MWH

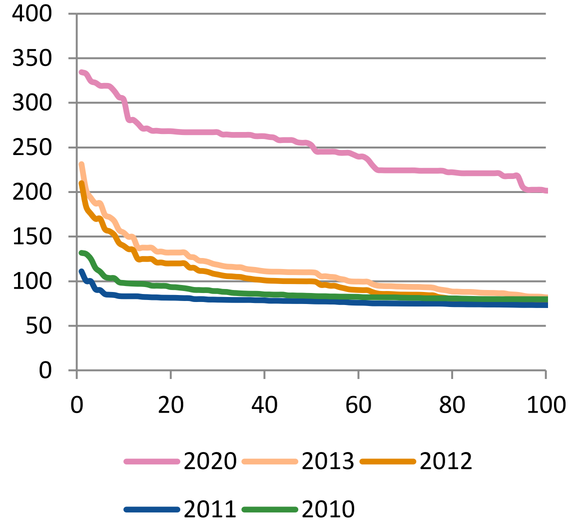


FIGURE 40 DURATION CURVE OF 100 HIGHEST HOURS. VERTICAL AXIS: EUR/MWH

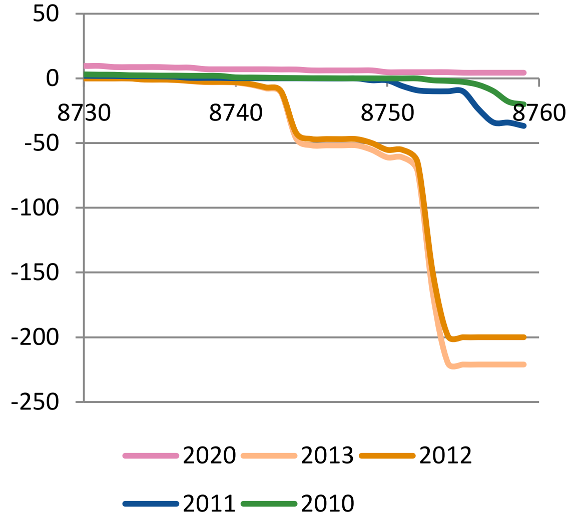


FIGURE 41 DURATION CURVE OF THE 30 HOURS WITH LOWEST PRICES. VERTICAL AXIS: EUR/MWH

The price variance has a multitude of explanations, including precipitation for Nordic hydro power, demand for electric-heating during cold periods and availability of large producers such as nuclear power plants (Houmøller 2013b). As 2012 lays the pattern for the time series of 2013 in the model, the two curves follow the same trajectory while they are slightly different in distribution due to the larger average spot price in 2013.

6.2.6. CO_2-Quota Prices

The price for 2013 has been derived from auction data of European Emission Allowances (EUA) from the European Energy Exchange (2013). The price of 4.38 EUR/EUA is an annual average of 2013-prices per 12 November 2013. The increased quota-price of 22.48 EUR/EUA for 2020 is derived from projections conducted by the Danish Energy Agency (2013b). Although HSCHP are allocated a certain amount of free quotas, it has been chosen to exclude these from the modelling, in order to allow quota-prices to be reflected in operation costs directly.

6.2.7. Meteorological Data

In *3sol*, solar heating is included in the modelling. The data utilised here fore is the total solar radiation derived from the DRY-dataset (design reference year) for the areas of eastern, western and southern Jutland and western Funen. DRY-data is embedded in energyPRO. The hourly average radiation applied in the model is 116 W/m^2/year. Temperature data is utilised in all scenarios in order to determine the heat-demand. This data is also derived from DRY-data specifically for western Jutland. The same temperature-dataset is used for the 2013 and 2020 scenarios.

6.3. Scenario Analysis

This section presents each scenario in detail. Each scenario is analysed in three variants: one where the plant is participating in the spot market, one where it is operating under SR-regulation and one where the engines are removed entirely from the plant. They are named and described in the following way, with the business as usual scenario, *2bau*, as example:

- Name: *2bau*
    - Framework condition: Engines are participating on the spot market
    - Purpose: This base variant of the scenario simulates a reference situation without payment from SR
- Name: *2bau-SR*
    - Framework condition: Engines are still present, but not participating on the spot market
    - Purpose: This simulates the operation income without revenue from the spot market, and serves to determine the level of payment from SR which would incentivise the plant to shift away from the spot market
- Name: *2bau-no eng*
    - Framework condition: Engines and their associated costs are entirely removed from the plant
    - Purpose: This simulates a situation where the plant has entirely decommissioned its engines, either because it cannot or will not continue operation with these. Fuel consumption will be similar to the SR-variant, but the economy will be different due to the absence of fixed costs from engines. This scenario will have a constant difference in expenditure from the SR-scenario of 100 022 EUR/year, since this is the assumed sum of fixed costs of the engines. The no eng-variant will not vary from the SR-variant in any other way, and is thus solely included for comparison

In the analysis of SR-variants, the variable costs of operating the engines are not included since it is not analysed how often the engine would be needed as SR. The real amount is expected to be insignificant as the engines are assumed to be running only relatively few hours per year. Fixed costs for engines are still included in SR-variants, while these costs are not included in the no eng-variants. Table 22 provides an overview of the scenarios, their purposes and for which year the analysis is carried out.

TABLE 22 OVERVIEW OF THE ANALYSED SCENARIOS

Number	Scenario	Abbreviation	Equipping	Purpose	2013	2020
1	Reference scenario	*1ref*	Current equipping	Establishing the current status for comparison with alternatives	X	
2	Business as usual scenario	*2bau*	Current equipping	Investigation of the consequences of doing nothing until 2020. Contemporary scenario for comparison with other scenarios		X
3	Current equipping + Solar	*3sol*	Current equipping and 10 000 m2 solar heating	Analysed since solar heating is a popular alternative among DCHPs, including HSCHP		X
4	Current equipping + Heat pump	*4hp*	Current equipping and 2 MW_e heat pump	Analysed since HP might be an economically attractive solution, and since HP might become an important contributor to integration of variable renewable energy		X
5	New engine	*5eng*	Current equipping and new gas engine with high efficiency	Analysed in order to see if there are benefits of allocating the old engines to SR, while letting a new participate on spot market		X

6.3.1. Scenario 1: Reference Scenario

The *1ref* shows the 2013-status of the plant. Spot- and gas market prices from 2013 are used, as well as the subsidies PIP and NPIP. As illustrated in Figure 42, the equipping is a boiler and two engines.

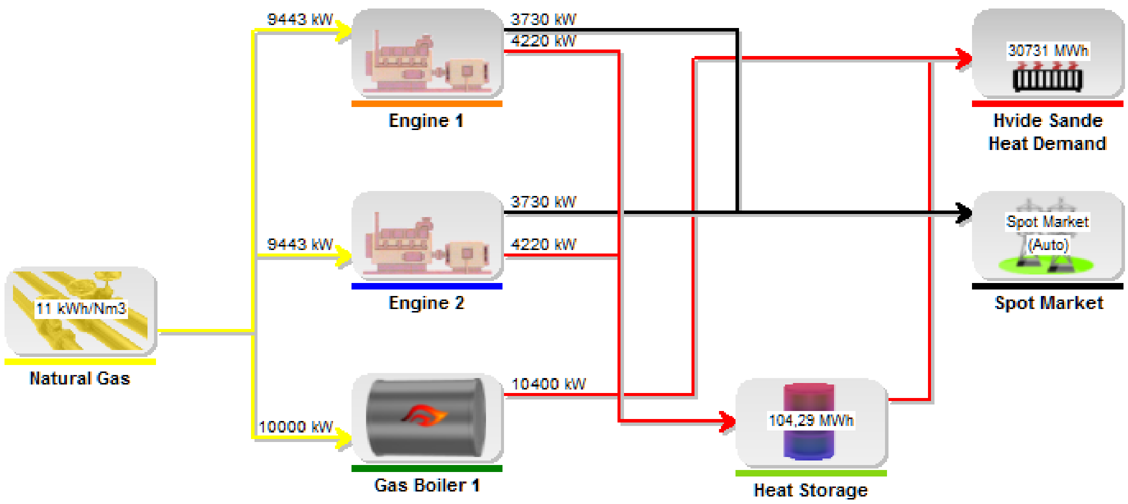


FIGURE 42 EQUIPPING IN *1REF*

Business Economy

As seen in Figure 43 and in Table 23, the revenue in *1ref* is generated mainly from subsidies, and to a lesser extent from electricity production. Heat price in *1ref* is 49 EUR/MWh. See Figure 43 and Table 23 for details.

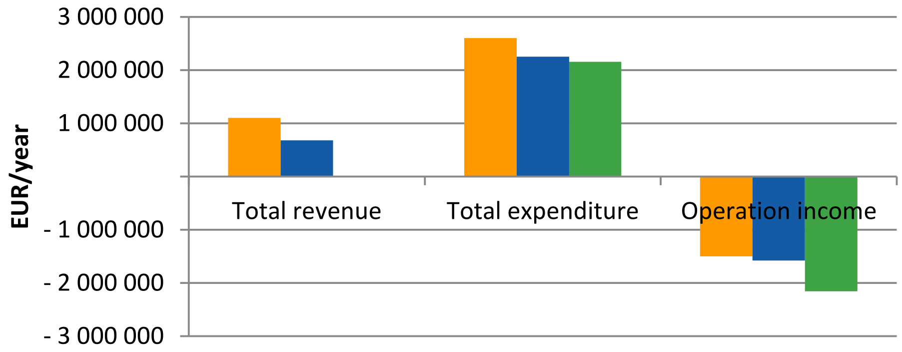


FIGURE 43 BALANCE FOR *1REF*-VARIATIONS

TABLE 23 SPECIFIED BALANCE SHEET FOR *1REF*-VARIATIONS

	1ref		*1ref-SR*		*1ref-no eng*	
	EUR/year	Share	EUR/year	Share	EUR/year	Share
REVENUE	1 104 237	100%	679 638	100%		
Electricity sales on spot market	424 599	38%		0%		
Subsidy	679 638	62%	679 638	100%		
EXPENDITURE	2 601 258	100%	2 255 667	100%	2 155 646	100%
Natural gas bought	1 178 797	45%	915 247	41%	915 247	42%
Electricity tariffs and fees	3 832	0%		0%		0%
Natural gas transport	120 980	5%	93 932	4%	93 932	4%
Taxes and levies, engines	251 450	10%		0%		0%
Taxes and levies, boiler	846 908	33%	1 081 573	48%	1 081 573	50%
Service agreement and fixed costs, engines	126 792	5%	100 022	4%		0%
O&M boiler	38 480	1%	38 480	2%	38 480	2%
CO_2-quotas bought/sold	34 019	1%	26 414	1%	26 414	1%
OPERATION INCOME	- 1 497 021		- 1 576 029		- 2 155 646	

Operation

The balance price of the engines and the Gas Boiler 1, illustrated in Figure 44, is equivalent to 59 EUR/MWh$_e$. At 40 EUR/MWh$_e$, the average spot price in 2013 is significantly lower than the balance price, which indicates why the engines produce relatively little. Figure 45 exemplifies the weekly production, where the significant share of boiler production is seen.

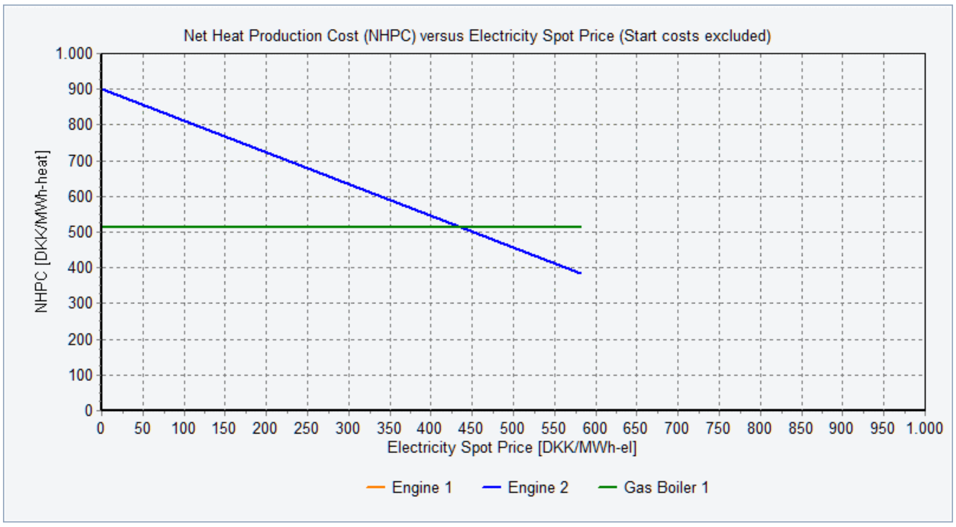


FIGURE 44 BALANCE PRICE (DKK) BETWEEN BOILER AND ENGINES. UNINTENTIONAL CUTOFF OF LINES IS CAUSED BY SOFTWARE

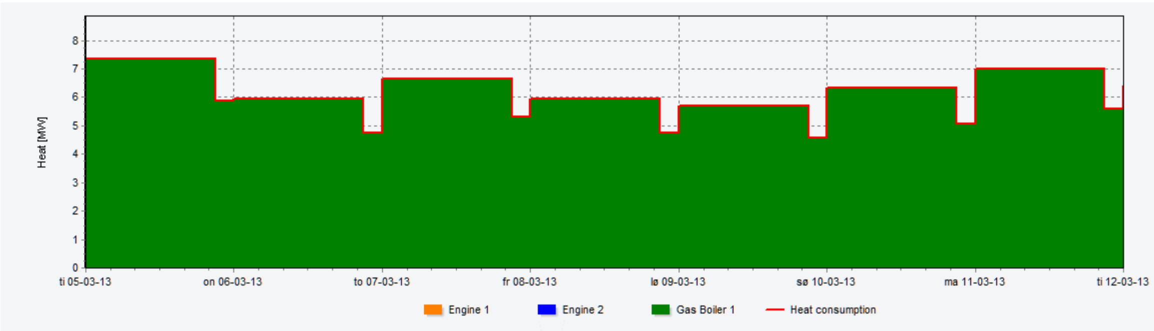
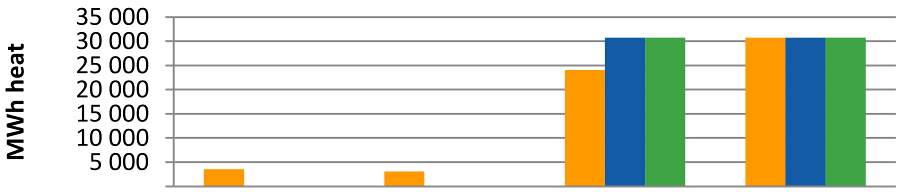


FIGURE 45 OPERATION IN *1REF* FROM 5 TO 12 OF MARCH 2013

As seen in Figure 46, the majority of the heat production in *1ref* takes place in Gas Boiler 1 (78 %), while the engines (22 %) contribute less in comparison. This leads back to the high balance price of the engines and their relatively low production. The fuel to heat ratio in *1ref* is 112.6 Nm^3/MWh_{th}.



	Engine 1	Engine 2	Gas Boiler 1	Total
1ref	3 574	3 093	24 063	30 731
1ref-SR			30 731	30 731
1ref-no eng			30 731	30 731

FIGURE 46 ALLOCATION OF HEAT PRODUCTION

Size of Strategic Reserve Remuneration

Especially for this scenario, it is important to note that the setting of *1ref* and *1ref-SR* both have revenue from PIP and NPIP. Neither types of subsidy are in *1ref-no eng*. As seen in Figure 47, the gap in revenue is significantly larger in *1ref-no eng*, which is explained by the complete reliance on the boiler and the absence of NPIP and PIP. The size of SR remuneration, 79 008 EUR/year, should be attributed to the missing revenue from spot market operation in *1ref-SR*. The cost of capacity in *1ref* is calculated to be 10 591 EUR/MW_e/year.

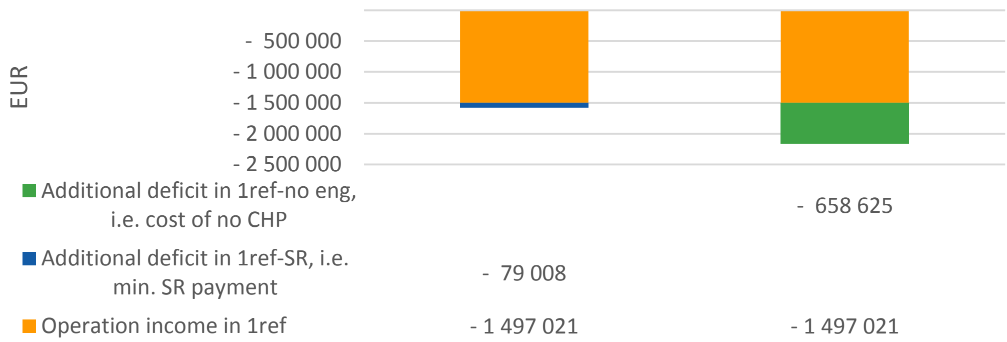


FIGURE 47 AMOUNT OF REMUNERATION NEEDED FROM SR

6.3.2. Scenario 2: Business as Usual Scenario

The *2bau* scenario is similar to the reference scenario, *1ref*, except for the CO_2-quota-, gas- and spot market prices, which are updated to 2020-projections. See Table 24 for details on economic differences and Figure 48 for equipping.

TABLE 24 ECONOMIC DIFFERENCES IN *2BAU*, COMPARED TO *1REF*

Scenario 1: Reference Scenario	Scenario 2: Business as Usual
2013 spot market prices	2020 spot market prices
2013 gas prices	2020 gas prices
Price of CO_2-quotas: 4.38 EUR/EUA	Price of CO_2-quotas: 21.72 EUR/EUA
PIP and NPIP	NPIP

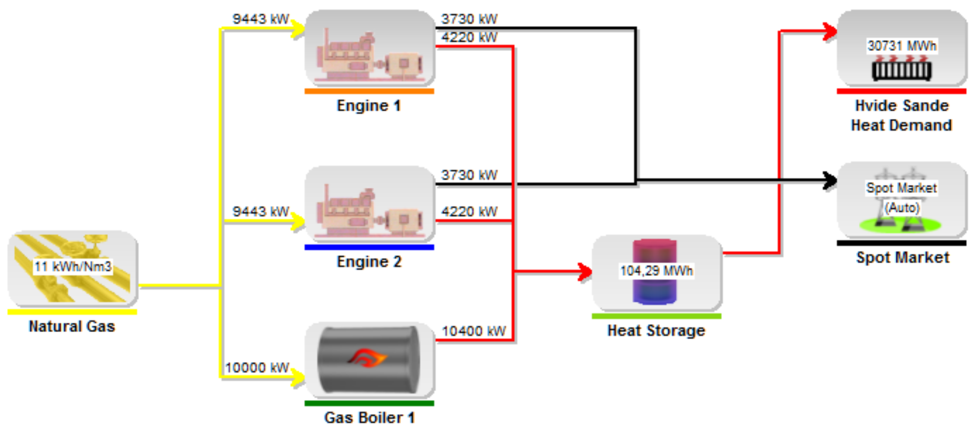


FIGURE 48 EQUIPPING IN *2BAU*

Business Economy

At 90 %, the revenue in *2bau* is largely generated from electricity production for the spot market, while the NPIP just contributes 10 %. This change from *1ref* can be accredited to the higher spot prices and a slightly lower gas price. The total operational income is 405 995 EUR/year less than in *1ref*, which can be accredited to the absence of the PIP. The heat price in *2bau* is 62 EUR/MWh. See Figure 49 and Table 25 for details.

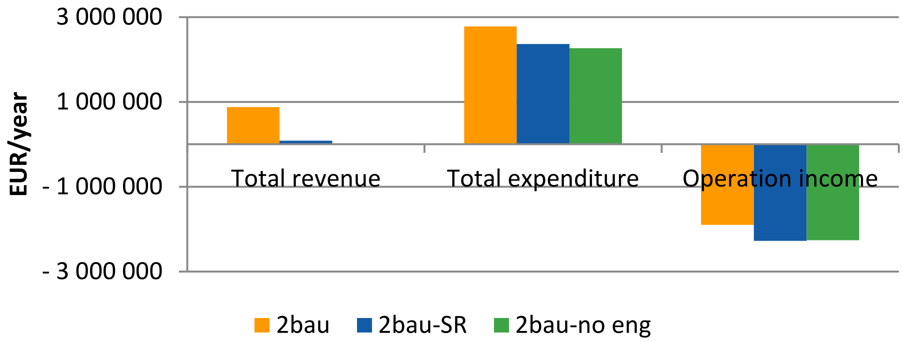


FIGURE 49 BALANCE FOR *2BAU*-VARIATIONS

TABLE 25 SPECIFIED BALANCE SHEET FOR *2BAU*-VARIATIONS

	Scenario 2		Scenario 2-*SR*		Scenario 2-*no eng*	
	EUR/year	Share of total	EUR/year	Share of total	EUR/year	Share of total
REVENUE	875 015	100%	85 810	100%	-	-
Electricity sales on spot market	789 206	90%	-	0%	-	-
Subsidy	85 810	10%	85 810	100%	-	-
EXPENDITURE	2 778 031	100%	2 364 573	100%	2 264 551	100%
Natural gas bought	1 200 076	43,2%	913 377	38,6%	913 377	40%
Electricity tariffs and fees	4 140	0%	-	0%	-	0%
Natural gas transport	123 571	4%	94 050	4%	94 050	4%
Taxes and levies, engines	973 887	35%	-	0%	-	0%
Taxes and levies, boiler	832 839	30%	1 082 926	45,8%	1 082 926	48%
Service agreement and fixed costs, engines	128 944	5%	100 022	4,2%	-	0%
O&M boiler	38 480	1%	38 480	1,6%	38 480	2%
CO_2-quotas bought/sold	178 321	6%	135 720	5,7%	135 720	6%
OPERATION INCOME	- 1 903 015		- 2 264 551		- 2 264 551	

OPERATION

Operation in *2bau* is characterised by a slightly larger production on the engines (1 707 h), compared to *1ref* (1 580 h). This can be explained by the increase in spot prices in 2020, where a larger amount of hours is above the strike-price of the engines. The balance price between boilers and engines is changed, as seen in Figure 50where the balance price in *2bau*, 64 EUR/MWh, is 5 EUR higher than in *1ref*. As illustrated by the amount of operating hours on the engines, this rise is mitigated by the comparatively larger rise in spot prices, which allows the engines to operate more. The weekly operation is exemplified in Figure 51.

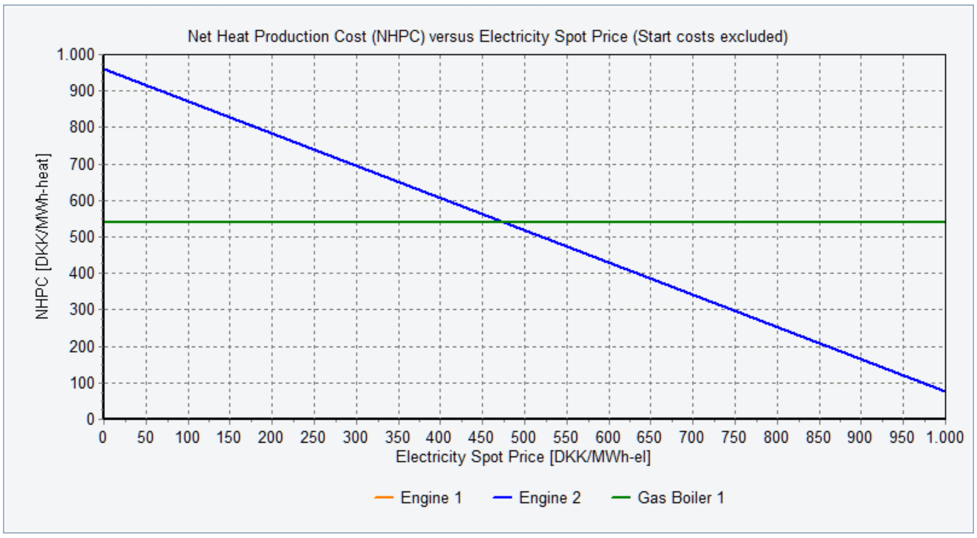


FIGURE 50 BALANCE PRICE (DKK) BETWEEN BOILER AND ENGINES

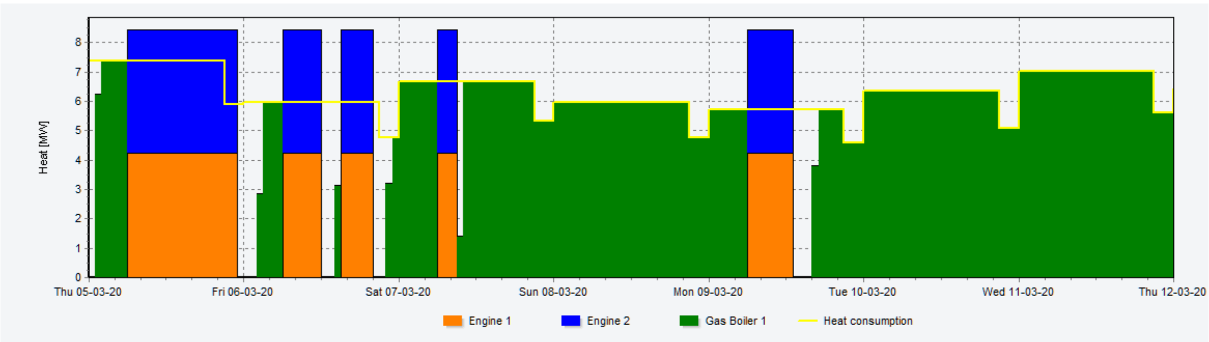
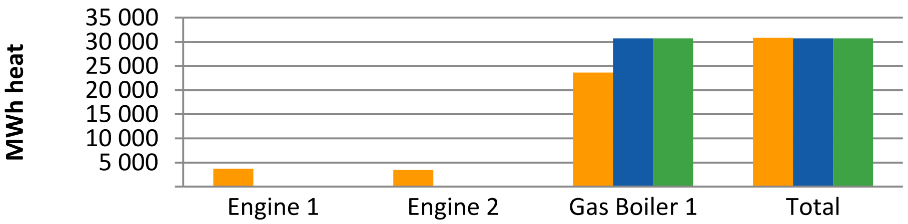


FIGURE 51 OPERATION IN *2BAU* FROM 5 TO 12 OF MARCH 2020

As seen in Figure 52, the absolute majority of the heat production in *2bau* takes place in Gas Boiler 1 (77 %), while the engines, at 23%, increased their share slightly compared to *1ref*. Again, this leads back to the high balance price of the engines and their relatively low production. The explanation for the increase in the engines' share can be found in the higher spot market prices. The fuel to heat index is 112.6 Nm^3/MWh_{th}.



	Engine 1	Engine 2	Gas Boiler 1	Total
2bau	3 726	3 477	23 664	30 867
2bau-SR			30 731	30 731
2bau-no eng			30 731	30 731

FIGURE 52 ALLOCATION OF HEAT PRODUCTION

Size of Strategic Reserve Remuneration

The amount of remuneration needed from SR in *2bau* is 296 659 EUR more than the amount seen in the more subsidised *1ref*, where being on or off the spot market does not make a significant difference since the electricity production is relatively limited. Figure 53 illustrates the size of the SR remuneration.

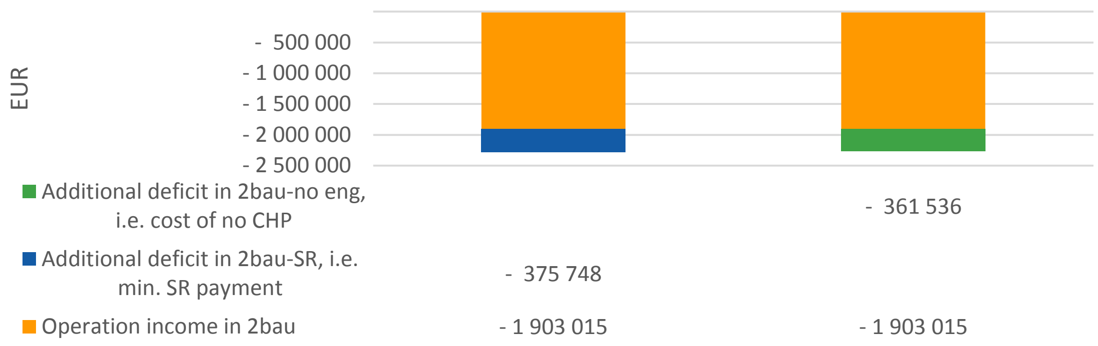


FIGURE 53 AMOUNT OF REMUNERATION NEEDED FROM SR

The capacity cost in the *2bau-SR* amounts to 50 368 EUR/MW$_e$/year, 39 778 EUR more than the amount seen in *1ref*.

6.3.3. Scenario 3: Current equipping + solar

HSCHP is regulated by the declaration on the approval of public heat supply (2013b). This means that HSCHP, along with many other DCHPs, is obliged to use natural gas for its heat production. The plant is currently investigating the prospects of 10 000 m2 solar heating, since this could legally displace some of the natural gas-based production. The size of the solar heating array is determined by the amount of ground physically available for deployment nearby. In *3sol*, it is assumed that the solar heating has been deployed in the period between 2013 and 2020. Data on the concrete HSCHP solar heating array is limited, so certain assumptions have to be made on the technical specifications. The input for the solar heating collector is thus based on data from ARCON Solar's (2013) type HT-SA 28/10. The collector panels are assumed to be placed in a 45° angle facing to the south. Changes between *2bau* and *3sol* are seen in Table 26 and Table 27.

TABLE 26 TECHNICAL DIFFERENCES IN *3SOL*, COMPARED TO *2BAU*

Scenario 2: Business as Usual	Scenario 3: Current Equipping + Solar
Gas boiler and two engines	As in BAU, but with 10 000 m2 solar heating

TABLE 27 ECONOMIC DIFFERENCES IN *3SOL*, COMPARED TO *2BAU*. PRICE BASED ON DANISH ENERGY AGENCY AND ENERGINET.DK (2013)

Scenario 2: Business as Usual	Scenario 3: Current Equipping + Solar
No solar O&M included	Solar O&M included: 0.57 EUR/MWh

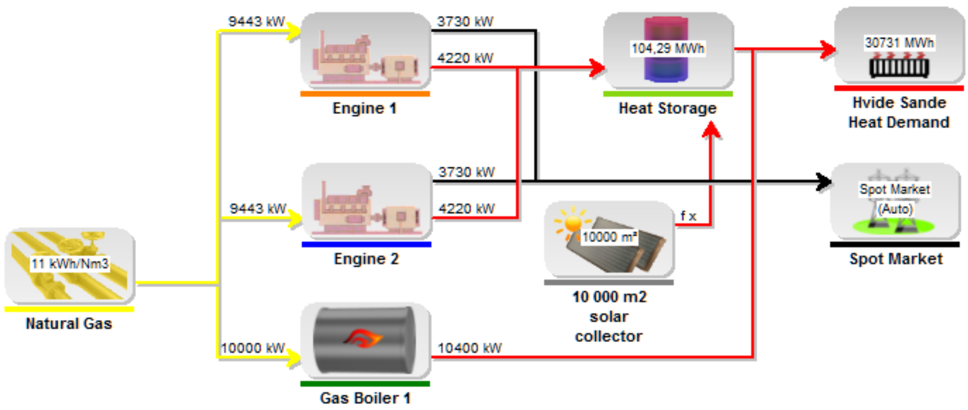


FIGURE 54 EQUIPPING IN *3SOL*

BUSINESS ECONOMY

As in *2bau*, revenue in *3sol* is, to a large degree, generated from electricity production for the spot market, while the NPIP just contributes 10 %. The revenue is 35 405 EUR less than in *2bau*, which can be attributed to both the engines and the solar collector feeding in to the heat storage. Storage capacity will, in some occasions, not allow for production from the engines since it is already filled by the solar heating collector. Despite the lower revenue, the operation income is 394 680 EUR larger, i.e. 'closer to zero', than *2bau*. This is attributed to the displacement of natural gas by solar heating, which weighs more in the balance than the lost revenue. The heat price in *3sol* is 49 EUR/MWh, 13 EUR/MWh less than in *2bau*. See Figure 55 and Table 28 for details.

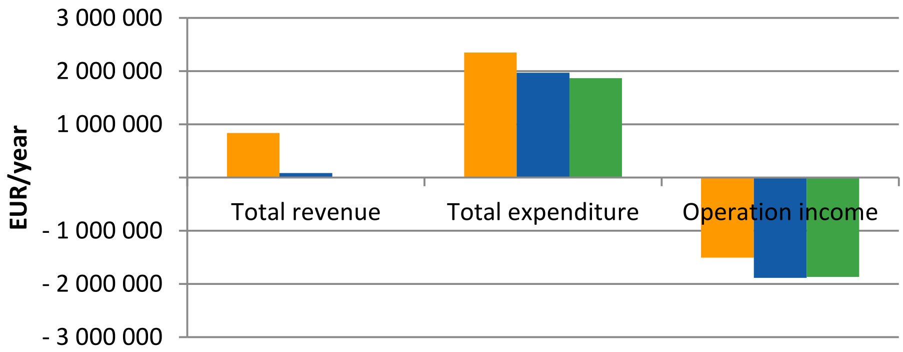


FIGURE 55 BALANCE FOR *3SOL*-VARIATIONS

TABLE 28 SPECIFIED BALANCE SHEET FOR *3SOL*-VARIATIONS

	3sol		*3sol-SR*		*3sol-no eng*	
	EUR/year	Share of total	EUR/year	Share of total	EUR/year	Share of total
REVENUE	839 610	100%	85 810	100%	-	-
Electricity sales on spot market	753 800	90%	-	0%	-	-
Subsidy	85 810	10%	85 810	100%	-	-
EXPENDITURE	2 347 945	100%	1 969 891	100,0%	1 869 869	100%
Natural gas bought	1 014 139	43%	750 126	38%	750 126	40%
Electricity tariffs and fees	3 852	0%	-	-	-	0%
Natural gas transport	104 425	4%	77 240	4%	77 240	4%
Taxes and levies, engines	252 723	11%		0%		0%
Taxes and levies, boiler	653 517	28%	889 371	45%	889 371	48%
Service agreement and fixed costs, engines	126 927	5%	100 022	5%	-	0%
O&M boiler	38 480	2%	38 480	2%	38 480	2%
CO_2-quotas bought/sold	150 692	6%	111 462	6%	111 462	6%
OPERATION INCOME	- 1 508 335		- 1 869 869		- 1 869 869	

OPERATION

The balance price is similar to *2bau*, since there are no changes in the parameters of the gas boiler or the engines. The balance price is illustrated in Figure 56 and an example of weekly operation is seen in Figure 57. Note that the operating costs of the solar collector are so small (0.57 EUR/MWh in O&M) that they are not visible in the figure.

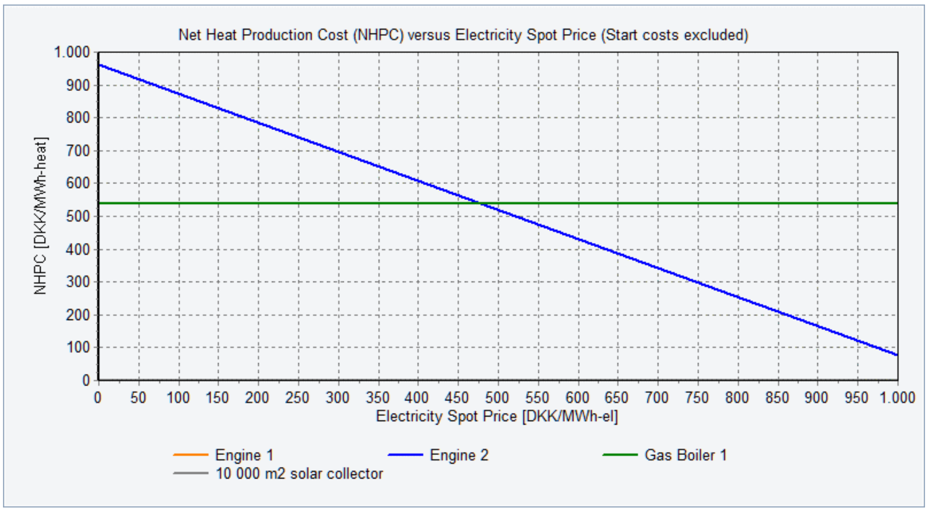


FIGURE 56 BALANCE PRICE (DKK) BETWEEN SOLAR HEATING, BOILER AND ENGINES

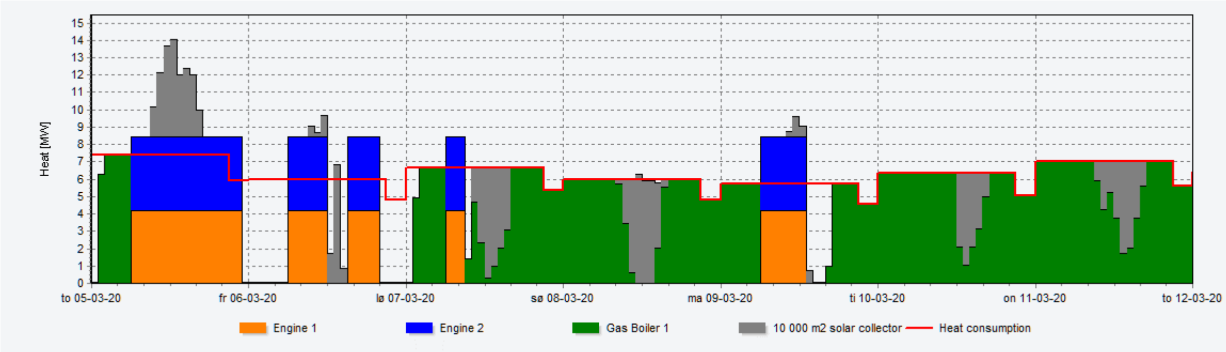
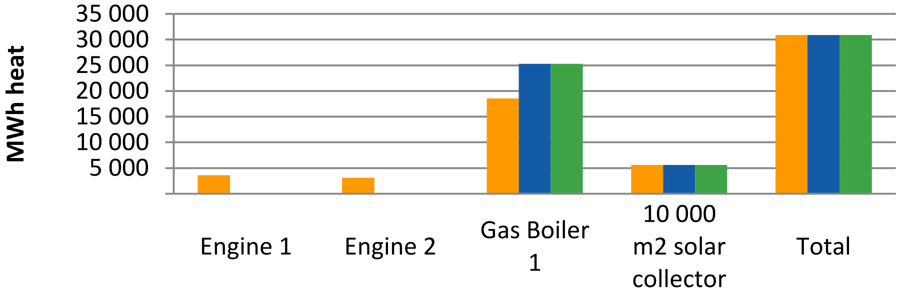


FIGURE 57 OPERATION IN *3SOL* FROM 5 TO 12 OF MARCH 2020

Like in *2bau*, the majority of the heat production in *3sol* takes place in Gas Boiler 1 (60 %), as is seen in Figure 58. This is lower than in *2bau*, and is due to the 18 % coverage of heat production from the solar collector. The engines have slightly reduced their share to 22 %, and thus *3sol* shows that the solar heating primarily displaces production on the boiler. This can be explained by the relatively few operating hours of the engines, meaning that heat storage capacity will only rarely become a limiting factor. Since the boiler poses the majority of the heat production, it is the production from this unit which is most affected by the solar heating. The fuel to heat index in *3sol* is 96.7 Nm^3/MWh_{th}, 18.3 Nm^3/MWh_{th} lower than in *2bau*.



	Engine 1	Engine 2	Gas Boiler 1	10 000 m2 solar collector	Total
3sol	3 595	3 106	18 569	5 597	30 867
3sol-SR			25 270	5 597	30 867
3sol-no eng			25 270	5 597	30 867

FIGURE 58 ALLOCATION OF HEAT PRODUCTION

SIZE OF STRATEGIC RESERVE REMUNERATION

The amount of remuneration from SR in *3sol* is just 2 EUR less than in *2bau*. While the operational income has been reduced significantly between *2bau* and *3sol*, the very small difference in SR indicates that the introduction of solar heating does not affect the size of SR remuneration. SR remuneration levels are seen in Figure 59.

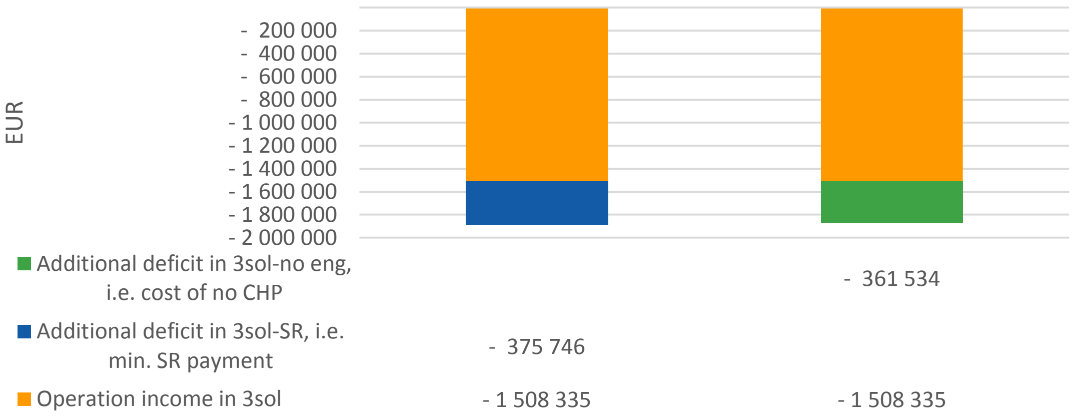


FIGURE 59 AMOUNT OF REMUNERATION NEEDED FROM SR

The cost of capacity in *3sol-SR* is calculated to be 50 368 EUR/MW_e/year, the same as *2bau-SR*. The explanation is the same as is found in the section Size of Strategic Reserve.

6.3.4. Scenario 4: Current Equipping + Heat Pump

In *4hp*, it is analysed how an electric heat pump will influence operation and economy on the plant. The heat pump is assumed to utilise ambient air temperature at a constant COP[58] of 2.9. This means an input of 1 MW_e provides an output of 2.9 MW_{th}. Technological data is sourced from Danish Energy Agency and Energinet.dk (2013), while start-stop costs are not included and the heat pump is allowed to start and stop without limitations during the intervals. Furthermore, the heat pump is assumed to be able to run on partial load, as suggested by Danish Energy Agency and Energinet.dk (2013). As seen in Figure 60, an initial analysis has been carried out for determining the optimal size of the heat pump. This type of analysis is solely carried out for the heat pump, due to limitations in time for the study. The chosen selection is based on the operational income, and on the assumption that the plant will choose the heat pump with the best value, i.e. a relatively small investment[59] and relatively large savings.

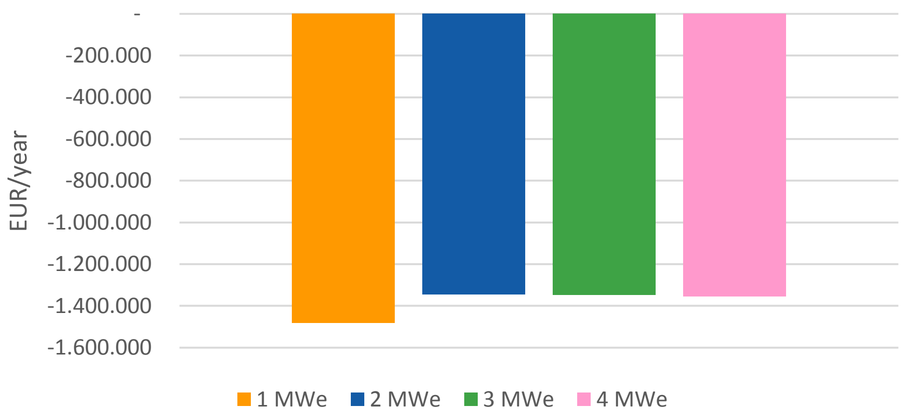


FIGURE 60 OPERATION INCOME WITH VARIOUS SIZES OF HEAT PUMPS

[58] Coefficient of performance: the relation between input energy and output energy. In this case electricity in and heat out

[59] Size of heat pump is considered a proxy for size investment in this case

Referring to Figure 60, it is seen that the operation income is level from 2 MW_e onwards; hence, 2 MW_e is chosen for further analysis. Changes from *2bau* are seen in Table 29 and Table 30, and the equipping is illustrated in Figure 61.

TABLE 29 TECHNICAL DIFFERENCES IN *4HP* COMPARED TO *2BAU*

Scenario 2: Business as Usual	Scenario 4: Current Equipping + Heat Pump
No heat pump	As in BAU, supplemented with a 2 MW_e heat pump with COP 2.9

TABLE 30 ECONOMIC DIFFERENCES IN *3SOL*, COMPARED TO *2BAU*. COST DATA BASED ON DANISH ENERGY AGENCY AND ENERGINET.DK (2013)

Scenario 2: Business as Usual	Scenario 4: Current Equipping + Heat Pump
No heat pump	Heat pump O&M included: 3 650 EUR/MW_{th}/year
	Consumption fee for Energinet.dk 0.1756 EUR/MWh
	Flexible basic charge 0.6033 EUR/MWh
	Electricity (energy savings tax) 8.715 EUR/MWh
	Electric heating tax 45.72 EUR/MWh
	Volume fee: 0.0349 EUR/MWh
	Cap for reimbursement of CO_2 tax on heat produced from electric- or gas boiler: 6.302 EUR¢/kWh of DH from plant
	Cap for reimbursement of energy tax on heat produced from electric- or gas boiler: 28.42 EUR¢/kWh of DH from plant

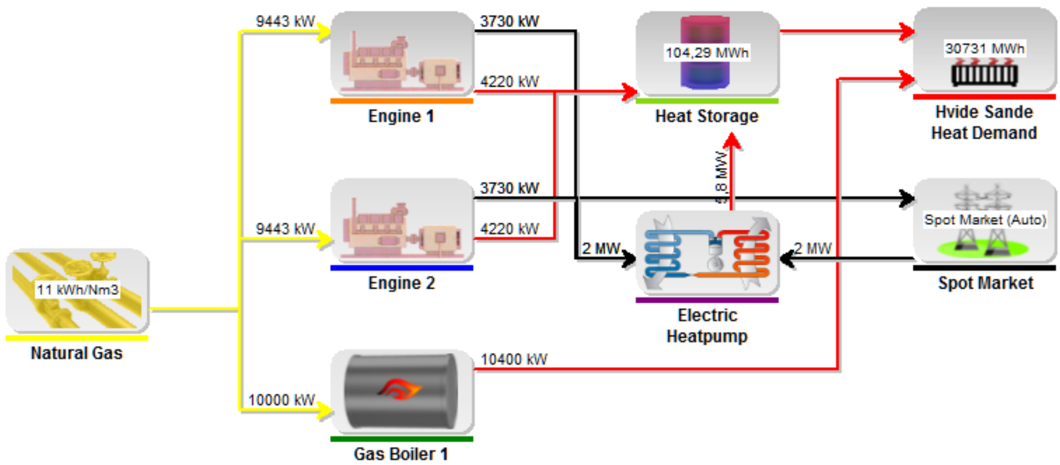


FIGURE 61 EQUIPPING IN *4HP*

BUSINESS ECONOMY

As in *2bau* and *3sol*, to a large degree the revenue in *4hp* is generated from electricity production for the spot market (87 %), whereas NPIP contributes 13%. The revenue is 211 105 EUR less than in *2bau*. As in *3sol*, the difference is attributed to the storage capacity, which, in some occasions, does not allow for production from the engines since it is already filled by the heat pump. The operation income is 557 187 EUR better, i.e. less expensive, than in *2bau*. This is attributed to the displacement of boiler production by the heat pump, whereby expenditure for fuel is reduced. See Figure 62 and Table 31 for details. Heat price in *4hp* is 44 EUR/MWh.

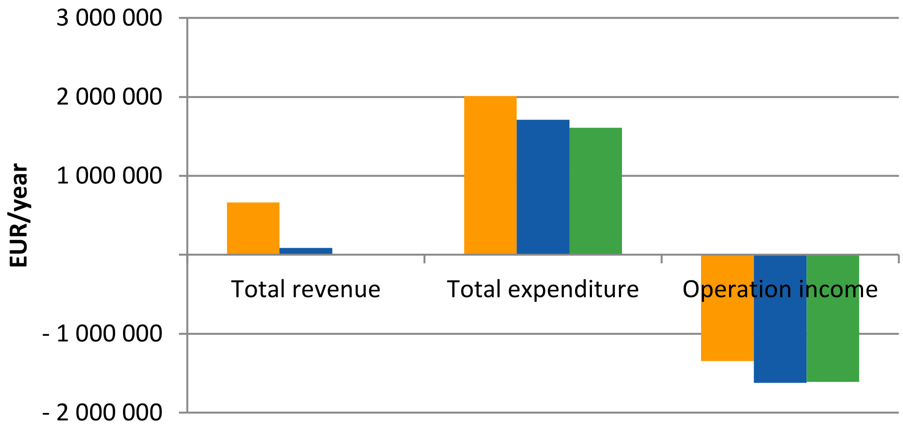


FIGURE 62 BALANCE FOR *4HP*-VARIATIONS

TABLE 31 SPECIFIED BALANCE SHEET FOR *4HP*-VARIATIONS

	4hp		*4hp-SR*		*4hp-no eng*	
	EUR/year	Share of total	EUR/year	Share of total	EUR/year	Share of total
REVENUE	663 911	100%	85 810	100%	-	-
Electricity sales on spot market	578 101	87%	-	0%	-	-
Subsidy	85 810	13%	85 810	100%	-	-
EXPENDITURE	2 009 740	100%	1 708 634	100%	1 608 412	100%
Natural gas bought	306 244	15%	43 471	3%	43 471	3%
Electricity tariffs and fees	2 538	0%	-	-	-	0%
Natural gas transport	31 534	2%	4 476	0%	4 476	0%
Taxes and levies, engines	166 625	8%	-	0%	-	0%
Taxes and levies, boiler	1 208	0%	51 540	3%	51 540	3%
Service agreement and fixed costs, engines	117 761	6%	100 022	6%	-	0%
O&M boiler	38 480	2%	38 480	2%	38 480	2%
O&M heat pump	21 170	1%	21 170	1%	21 170	1%
Electricity consumption heat pump	350 812	17%	410 545	24%	410 545	26%
Taxes and distribution fees heat pump	927 862	46%	1 032 471	60%	1 032 471	64%
CO_2-quotas bought/sold	45 505	2%	6 459	0%	6 459	0%
OPERATION INCOME	- 1 345 829		- 1 608 412		- 1 608 412	

OPERATION

Apart from the addition of the heat pump, operation is similar to *2bau*, since there are no changes in the parameters of the gas boilers or engines. The balance price of the heat pump and the engines is on average 76 EUR/MWh, 12 EUR higher than the balance price of the engines and the boiler. As seen on Figure 63, the heat pump is competitive in a very large spectrum of spot prices.

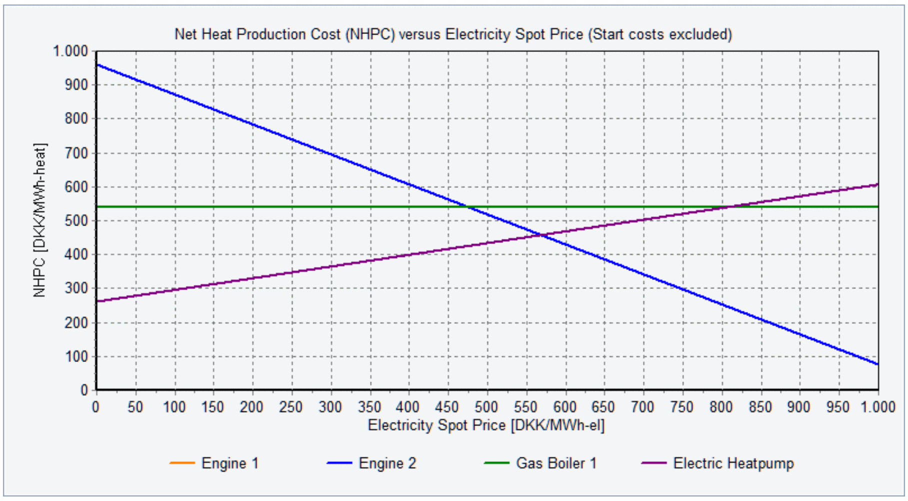


FIGURE 63 BALANCE PRICE (DKK) BETWEEN HEAT PUMP, BOILER AND ENGINES

Figure 64 shows the contribution from the different units in the period 5-12 March 2020 to the heat production. The introduction of the heat pump makes a significant difference, and the competitive price makes it operate much like a mid- to baseload unit (5 582 operating hours). With 54 operating hours, production from the boiler has been almost entirely displaced by the heat pump throughout the year.

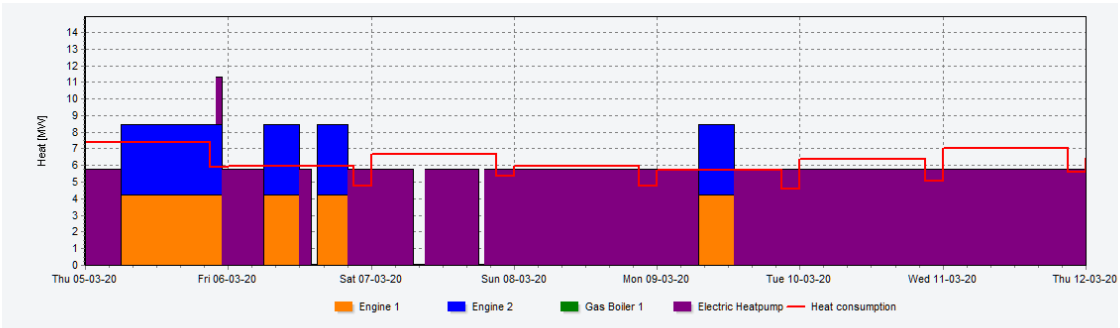


FIGURE 64 OPERATION IN *4HP* FROM 5 TO 12 OF MARCH 2020

As is seen in Figure 65, production from the gas boiler is almost entirely displaced by the heat pump (86 %). The reason is the low balance price of the heat pump which enables it to fill the storage, thereby mostly eliminating the need for the boiler. The share of the engines has been reduced to 14 %. The fuel to heat ratio in *4hp* is 29.2 Nm^3/MWh_{th}, a quarter of *2bau*.

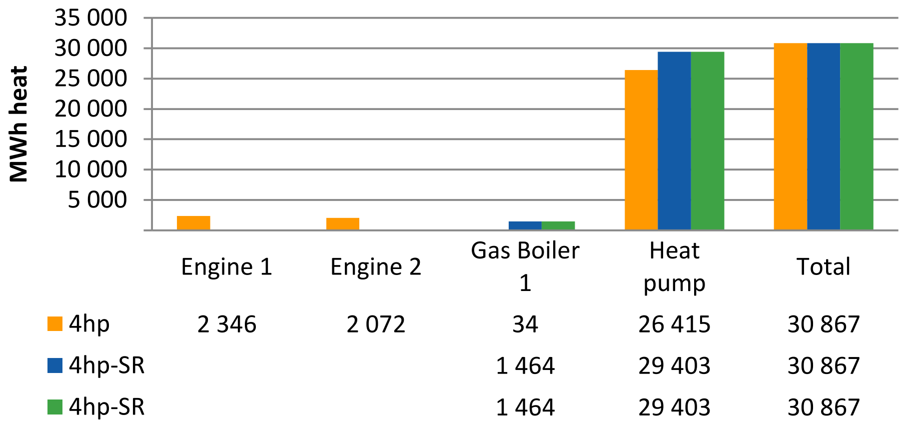


FIGURE 65 ALLOCATION OF HEAT PRODUCTION

Size of Strategic Reserve Remuneration

The amount of remuneration from the SR in *4hp* is 26 % less (98 753 EUR) than in *2bau*. This can be explained by the significant amount of heat production from the heat pump which not only covers the heat demand but also sends excess production to the heat storage. This results in a relatively large reduction in the operation of the engines, whereby the revenue is reduced. Meanwhile, the expenditure does not see a similar reduction since the relation between expenses in *4hp* and *4hp-SR* is unchanged in relation. This reduces the difference in operational income between *4hp* and *4hp-SR*, compared to *2bau* and *2bau-SR*, and therefore reduces the size of SR remuneration. The size of SR remuneration is illustrated on Figure 66.

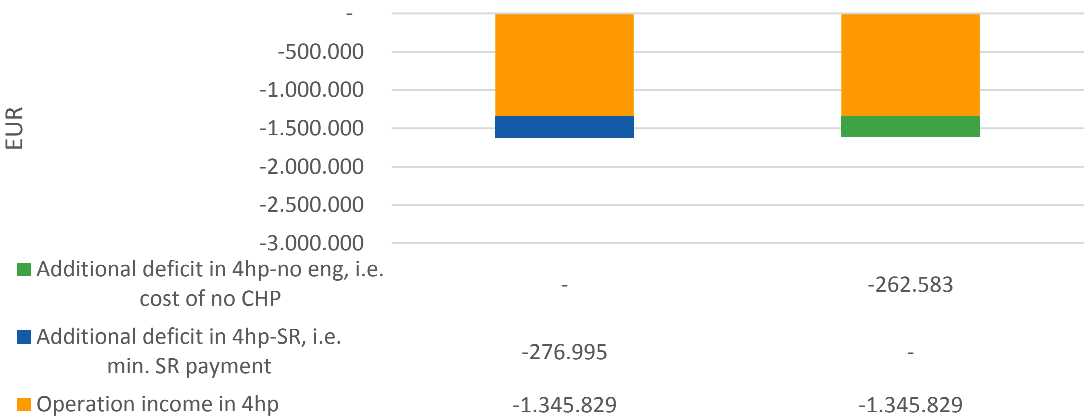


FIGURE 66 AMOUNT OF REMUNERATION NEEDED FROM SR

The cost of capacity in *4hp-SR* is calculated to be 37 131 EUR/MW_e/year, which is 13 238 EUR less than in *2bau*.

6.3.5. Scenario 5: New Engine

In *5eng*, the consequences of adding a new, more efficient engine are analysed. Furthermore, this new engine will stay on the spot market in the *5eng-SR* and *5eng-no eng* variants. Regarding the existing, less efficient engines, they are treated as in the previous scenarios. *5eng* is included in the analysis in order to determine whether plants would benefit from adding a new engine, while keeping their old engines, thus maintaining capacity in the power system by acting on the spot market and under SR at the same time. It is assumed that the presence of the new engine in the no-eng-scenario will make the plant qualify for NPIP. This assumption is based on an interpretation of the Electricity Supply Act, where a plant qualifies according to its production in 2005-2007. The size and data for the engine is based on Skagen CHP, which has installed three engines with absorption heat pumps, resulting in 104 % efficiency (EMD International 2013b). Changes between *2bau* and *5eng* are seen in Table 32 and Table 33, and the equipping is illustrated in Figure 67.

TABLE 32 TECHNICAL DIFFERENCES IN *5ENG* COMPARED TO *2BAU*

Scenario 2: Business as Usual	Scenario 5: New Engine
One gas boiler and two engines	As in BAU, but with a new engine with 104 % efficiency: 41 % electric efficiency, 63 % heat efficiency, assuming an absorption heat pump utilising the flue gas from the engine

TABLE 33 ECONOMIC DIFFERENCES IN *5ENG* COMPARED TO *2BAU*

Scenario 2: Business as Usual	Scenario 5: New Engine
No new engine	In the SR- and no eng-variants of *5eng*, the new engine stays on the spot market. It is assumed that the plant will qualify for the NPIP
	It is assumed that the new engine has similar characteristics to the existing engines regarding tax and O&M

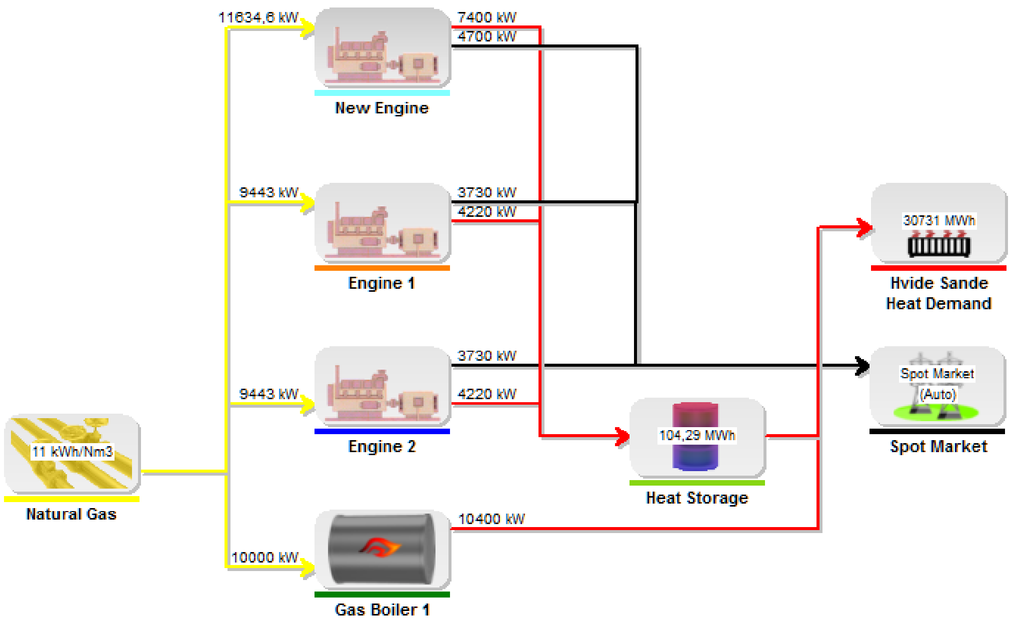


FIGURE 67 EQUIPPING IN *5ENG*

BUSINESS ECONOMY

Revenue in *5eng* is largely generated from electricity production for the spot market (92 %), while the NPIP contributes 6 %. This is due to the significant share of revenue generated by the more efficient new engine that has raised the revenue by 260 456 EUR compared to *2bau*. The operation income is 97 158 EUR larger, i.e. 'closer to zero', than *2bau*. See Figure 68 and Table 34 for details. The heat price in *5eng* is 59 EUR/MWh. A noteworthy difference from the other scenarios is the revenue generated by the new engine. This adds a spot market revenue to the NPIP in the *5eng-SR* and *5eng-no eng* scenarios, and explains why there is larger revenue in the two alternatives if compared to earlier scenarios.

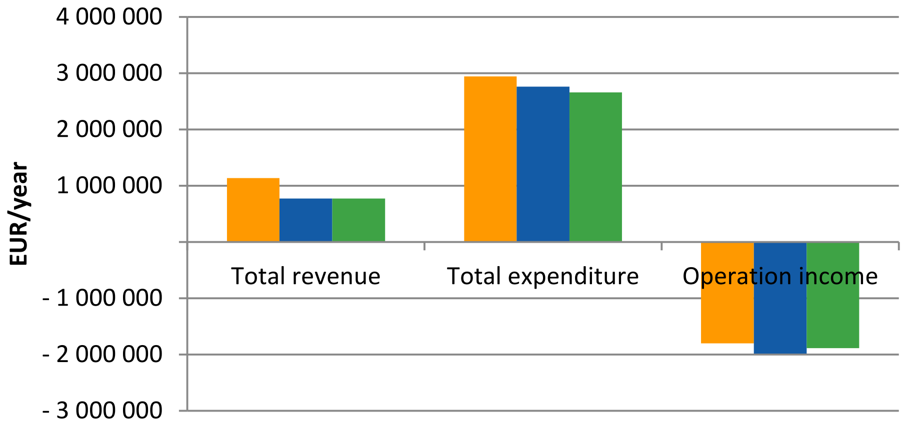


FIGURE 68 BALANCE FOR *5ENG*-VARIATIONS

TABLE 34 SPECIFIED BALANCE SHEET FOR *5ENG*-VARIATIONS

	5eng		*5eng-SR*		*5eng-no eng*	
	EUR/year	Share of total	EUR/year	Share of total	EUR/year	Share of total
REVENUE	1 135 472	100%	768 894	100%	768 894	100%
Electricity sales on spot market	1 049 662	92%	683 085	89%	683 085	89%
Subsidy	85 810	8%	85 810	11%	85 810	11%
EXPENDITURE	2 941 329	100%	2 756 053	100%	2 656 031	100%
Natural gas bought	1 274 121	43%	1 143 412	41%	1 143 412	43%
Electricity tariffs and fees	6 539	0%	4 976	0%	4 976	0%
Natural gas transport	131 195	4%	117 736	4%	117 736	4%
Taxes and levies, engines	514 598	17%	434 392	16%	434 392	16%
Taxes and levies, boiler	591 365	20%	662 367	24%	662 367	25%
Service agreement and fixed costs, engines	195 707	7%	184 789	7%	84 768	3%
O&M boiler	38 480	1%	38 480	1%	38 480	1%
CO_2-quotas bought/sold	189 323	6%	169 901	6%	169 901	6%
OPERATION INCOME	- 1 805 857		- 1 987 159		- 1 887 137	

OPERATION

The operation of the existing engines and gas boilers is similar to *2bau*, since there are no changes in their parameters. For the new engine, Figure 69 illustrates the significantly smaller balance price of 44 EUR/MWh_e, which is 20 EUR less than the existing engines.

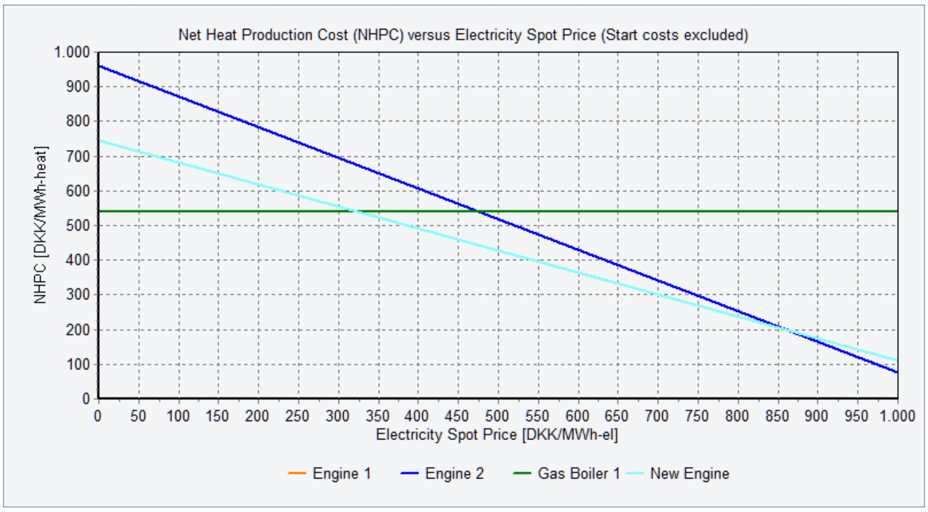


FIGURE 69 BALANCE PRICE (DKK) BETWEEN NEW ENGINE, BOILER AND EXISTING ENGINES

Figure 70 shows the contribution of the different units to the heat production. The new engine operates for a longer time and more frequently than the existing engines due to the relatively low balance price.

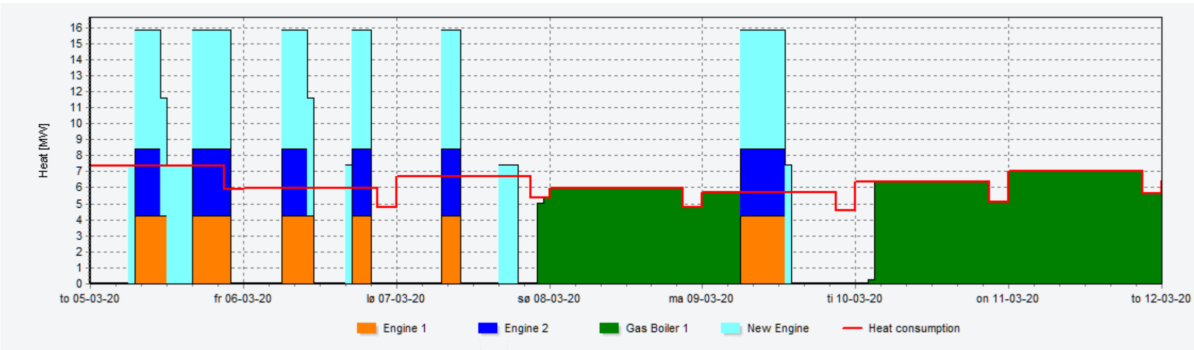
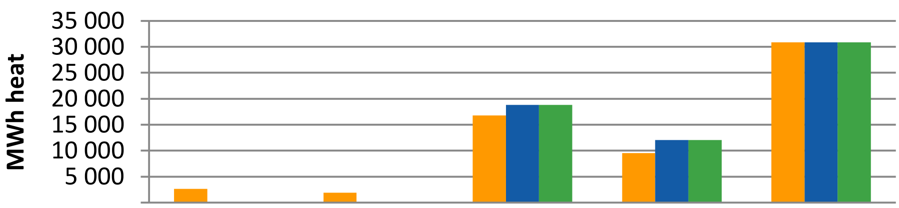


FIGURE 70 OPERATION IN *5ENG* FROM 5 TO 12 OF MARCH 2020

As is seen in Figure 71, the gas boiler contributes the majority (54 %) of the heat production. Production from the new engine is 31 %. The share of the old engines has been reduced to 15 %, caused by the limitation in storage capacity and the priority for production on the new engine. The fuel to heat ratio in *4hp* is 121.6 Nm^3/MWh_{th}, which is 6.6 Nm^3/MWh_{th} more than *2bau*.



	Engine 1	Engine 2	Gas Boiler 1	New Engine	Total
5eng	2 604	1 907	16 803	9 553	30 867
5eng-SR			18 820	12 047	30 867
5eng-SR			18 820	12 047	30 867

FIGURE 71 ALLOCATION OF HEAT PRODUCTION

Size of Strategic Reserve Remuneration

The amount of remuneration from SR in *5eng* is 52 % (194 447 EUR) less than in *2bau*. The explanation is that, contrary to all other scenarios in this study, *5eng-SR* makes revenue from the new engine in all scenario variants. This results in revenues which are rather similar in size and, since the expenditure does not increase equivalently to the revenue, the size of the SR remuneration is decreased compared to *2bau*. Furthermore, *5eng-no eng* stands out as the variant with the lowest SR remuneration due to the reduction in expenditure that arises from the decommissioning of the two existing engines. This impact is not seen in any other scenario.

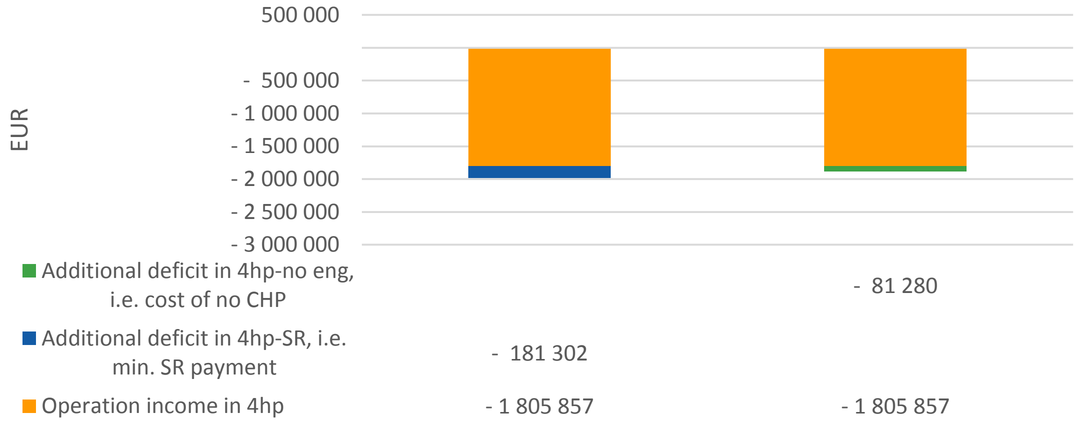


FIGURE 72 AMOUNT OF REMUNERATION NEEDED FROM SR. NOTE THAT THE NEW ENGINE IS OPERATING ON THE SPOT MARKET IN ALL VARIANTS OF *5ENG*

Cost of capacity in *5eng-SR* is calculated to be 24 303 EUR/MW$_e$/year, 26 065 EUR less than *2bau*.

6.4. Investment Analysis of the Heat Pump-Scenario

Based on the result for *4hp*, where a heat pump increased the operation income considerably, it is relevant to consider whether an investment already made in 2013 would pay off. Table 35 shows the investment costs assumed for the investment in a new heat pump. All other conditions are as those which are described for the model of 2013, *1ref*, and for the heat pump specifications, *4hp*, except that the heat pump has 0.2 less in COP. The reduced COP is due to the assumption that COP will be slightly increased through technological development by 2020. All data on the heat pump is based on Danish Energy Agency (2013).

TABLE 35 PARAMETERS USED IN THE INVESTMENT ANALYSIS

Heat pump	Amount	Unit
Electricity input	2	MW$_e$
Heat output	5.6	MW$_{th}$
Investment cost per MW$_{th}$	680 000	EUR/MW$_{th}$
Specific investment in 2013	3.808.000	EUR
Assumed interest rate	5	%

The modelling shows that adding a heat pump in 2013 provides a significant increase in operational income. This is seen in Table 36, which summarises the results that are seen in the more detailed Table 37.

TABLE 36 OPERATING INCOMES OF OPERATION WITH AND WITHOUT HEAT PUMP

Operating income in 2013 with current equipping [EUR]	Operating income in 2013 with current equipping and a heat pump [EUR]	Difference, i.e. savings [EUR]
-1 497 021	-918 434	578 587

TABLE 37 BALANCE SHEET FOR INVESTMENT IN HEAT PUMP AND *1REF*

	2013 with heat pump		*1ref*	
	EUR/year	Share of total	EUR/year	Share of total
REVENUE	787 460	100%	1 104 237	100%
Electricity sales on spot market	107 821	14%	424 599	38%
Subsidy	679 638	86%	679 638	62%
EXPENDITURE	1 705 894	100%	2 601 258	100%
Natural gas bought	91 471	5%	1 178 797	45%
Electricity tariffs and fees	699	0%	3 832	0%
Natural gas transport	9 388	1%	120 980	5%
Taxes and levies, engines	46 152	3%	251 450	10%
Taxes and levies, boiler	7 858	0%	846 908	33%
Service agreement and fixed costs, engines	104 935	6%	126 792	5%
O&M boiler	38 480	2%	38 480	1%
O&M heat pump	20 440	1%		
Electricity consumption heat pump	355 227	21%		
Taxes and distribution fees heat pump	1 028 604	60%		
CO_2-quotas bought/sold	2 640	0%	34 019	1%
OPERATION INCOME	- 918 434	100%	- 1 497 021	

The simple payback period for this investment is

$$\frac{3808000\ EUR}{578587\ EUR/year} = 6.6\ years$$

According to Bukholt (2013), the preferred payback time for investments in HSCHP is 10 years, so the simple payback period indicates that the investment might be relevant, which justifies the following more elaborate investment-analysis. Table 38 shows the annual change in the net price index (NPI), the nominal amortisation[60] and the account balance with a 5 % interest until 2020.

[60] Nominal amortisation is here defined as the annual savings made, adjusted for the annual change in NPI

TABLE 38 NOMINAL AMORTISATION, ANNUAL CHANGE IN NPI AND ACCOUNT BALANCE. REFERENCE FOR NPI IS THE MINISTRY FOR ECONOMIC AFFAIRS AND THE INTERIOR (2013) **AND DTU** (2013)

Year	Unit	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Change in NPI	%	0	1.6	1.9	1.9	1.9	2.0	2.1	2.1	1.9	1.9	1.9
Amortisation	EUR	578 587	587 844	599 013	610 394	621 992	634 431	647 755	661 357	673 923	686 728	699 776
Balance	EUR	-3 229 413	-2 803 040	-2 344 179	-1 850 994	-1 321 552	- 753 198	- 143 104	511 098	1 210 577	1 957 833	2 755 500

The investment-analysis assumes that the investment is made in the very beginning of the year, that the savings are earned in the end of the year and that the interest rate is accounted in the very beginning of the following year. As Table 38 shows, the investment in the heat pump provides a positive account balance already in year 2019, i.e. a payback period of less than seven years, three years less than required at HSCHP. Concluding on this analysis, the rather short payback period means that the investment in a heat pump under the given conditions would be beneficial for the plant. The results of the analysis should be approached with certain caveats: the assumption of a constant COP of 2.8, and not correcting price variations for fuel, EUAs or electricity.

6.5. Partial Conclusion

The techno-economic analysis of the five scenarios reveals quite different results, depending on the equipping of the plant. In this partial conclusion, the results are compared and discussed in the following order: business economy, heat production and size of SR remuneration.

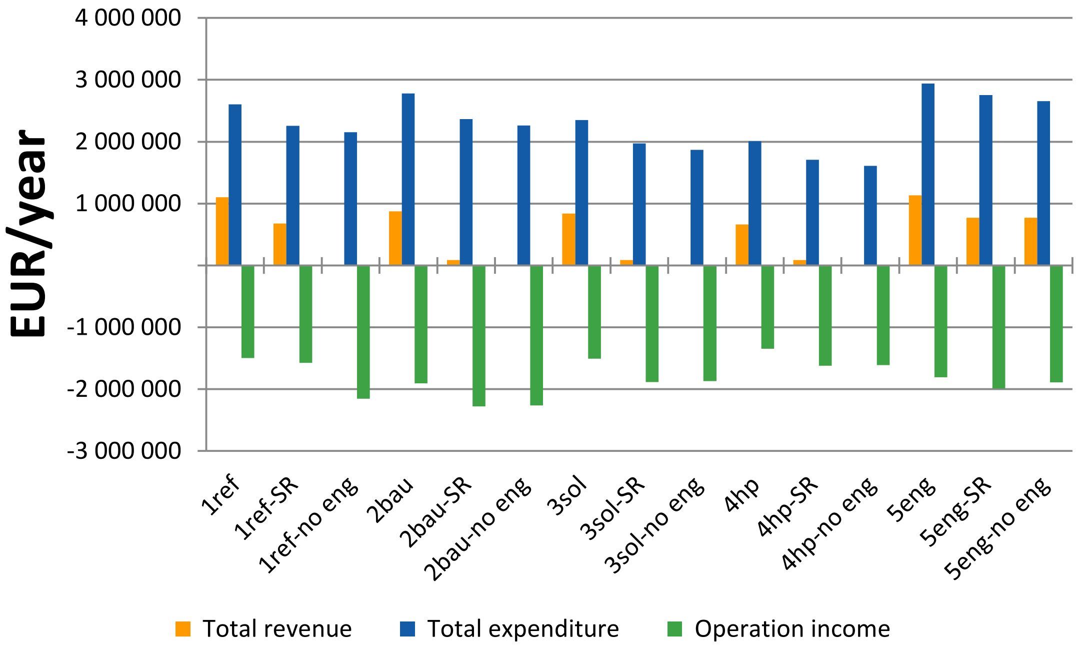


FIGURE 73 BUSINESS ECONOMIC RESULTS OF OPERATION WITH DIFFERENT TYPES OF EQUIPPING, AND IN DIFFERENT VARIATIONS WITHIN EACH SCENARIO

Figure 73 displays the revenue, the expenditure, the sum of these two and the operational income for all scenarios. The results seen in Figure 73 indicate that economically rational plants would search for alternatives to their business as usual (scenario *2bau*), since this is the most expensive, i.e. poorest operation income, of all scenarios. The explanation for the low operation income in *2bau* is that, although the gas price is roughly the same, and the annual average electricity price increases from 40 EUR/MWh to 51 EUR/MWh, the absence of the PIP is so significant that maintaining business as usual in 2020 will worsen the business economy on an overall scale. The 2020-scenario-variants in 2020 with the best operation income are listed below:

1. *4hp*: Current equipping and a heat pump – 29 % below *2bau*
2. *3sol*: Current equipping and solar heating – 21 % below *2bau*
3. *4hp-no eng*: Decommissioning the engines and adding a heat pump – 15 % *2bau*

It is clear that the heat pump makes a significant contribution to the operation income. The explanation can be found in its ability to displace large amounts of natural gas and the related costs of this fuel. It is worth noticing that the third-most attractive solution is *4hp-no eng*, i.e. an equipping entirely without capacity for electricity production. The difference between the least (*4hp*) - and most (*2 bau-no eng*) expensive scenario-variation is about 920 000 EUR/year, a significant amount for a DCHP. Furthermore, it is worth noticing that *1ref* comes in as the second-best variant of all, indicating that, in any case, the DCHP will generate a lower operational income in 2020 if not investing in a heat pump. Finally, the main conclusion to draw from the list is that SR does not contribute to maintaining capacity from DCHP in the Danish energy system. While option 3 is important to consider, it is unlikely that any plant would prefer this to option 1, since both have the same equipping from the outset. If anything, option 3 could arise in a situation where the lifetime of the engines runs out and no overhaul or reinvestment is chosen. In that case, SR in the current design would not make any difference, since it merely provides incentive for plants to participate in SR, and to maintain electric capacity in situations where the plant would see better business economy in abandoning electric generation capacity. None of the analysed scenarios show that the *no eng*-option has better business-economy than participation on the spot market.

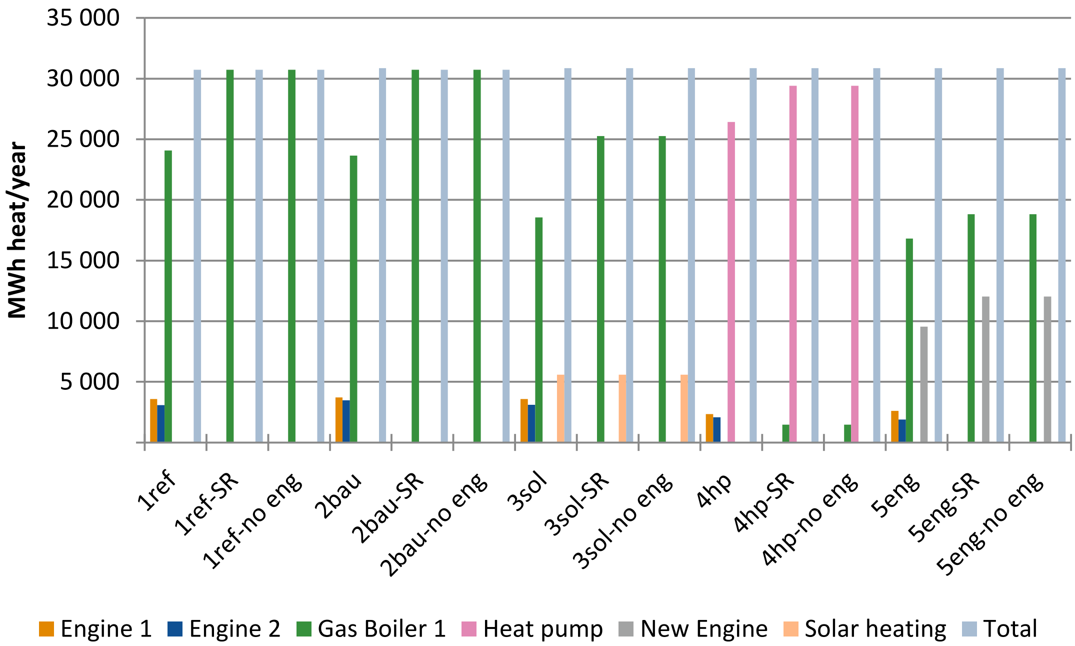


FIGURE 74 HEAT PRODUCTION IN SCENARIOS WITH DIFFERENT TYPES OF EQUIPPING, AND IN DIFFERENT VARIATIONS WITHIN EACH SCENARIO

Figure 74 compares the results regarding fuel consumption, where the pattern of expenditure from Figure 73 is reflected in the natural gas-based heat-production, not counting the impact from PIP. In short, the lower reliance on heat production in natural gas-based units leads to a lower expenditure and vice versa. *4hp* sees a significant amount of heat produced by the heat pump. The displacement effect is seen on both, the engines and on the boiler, and, moreover, to a larger degree than in *3sol*. This is caused by the low heat production cost of the heat pump and its ability to generate the heat for storage. *5eng* also displays a large displacement of heat production from the boiler, but, in comparison, more production is displaced from the existing engines. The latter can be explained by the limited storage capacity, where the more efficient new engine generates more revenue per unit of storage capacity than the existing engines.

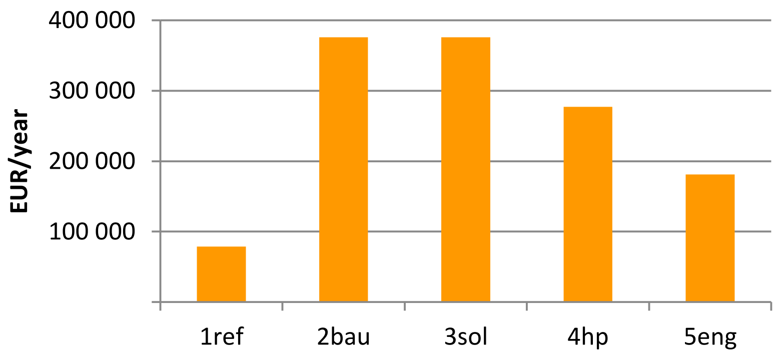


FIGURE 75 SIZE OF STRATEGIC RESERVE REMUNERATION FOR ALL SCENARIOS

The size of the strategic reserve remuneration is analysed for each scenario, by comparing the operational income of participating and not participating on the spot market respectively. The results are listed in Figure 75, and it is important to understand that the amounts are not directly comparable, i.e. one cannot simply choose the lowest remuneration as the optimal solution. This is due to the difference in equipping which is seen in each scenario. In other words, the stated amount tells what the minimum SR remuneration should be under the particular equipping of the given scenario, i.e. the marginal balance price of participating in an SR.

1ref has by far the smallest size of SR, due to the low electricity production. Since the revenue from the engines is relatively small in 2013, it only makes a small difference whether the plant is on or off the spot market. Hence, the equivalent SR remuneration is small.

For *2bau*, the impact of the higher electricity prices is clear, since the production, and hence the revenue, from the engines is increased. The difference in operational income between being on and off the spot market is thereby increased leading to a higher SR remuneration.

3sol displays a level of SR remuneration very close to the one in *2bau*. This can be explained by the relatively small impact made by the solar heating on the ability of engines to produce heat for the storage. This means that the relative difference between *3sol* and *3sol-SR* is similar to the difference seen between *2bau* and *2bau-SR*.

4hp has the highest operational income of all scenarios, while its SR remuneration is medium-sized, compared to the other scenarios. The dominance of the heat production from the heat pump and the displacement of engine-production in *4hp*, means that the difference between the operation income in *4hp* and *4hp-SR* becomes smaller in relation to the difference seen in *2bau*.

5eng displays the smallest SR remuneration of all 2020-scenarios. This is due to the dominance of the new engine in all variations of the scenario, including the base-scenario, where not only the boiler but also the revenue-generating old engines are significantly reduced. This evens out the revenue and expenditure among the scenario-variations, leading to small differences between them and, therefore, a relatively small SR remuneration.

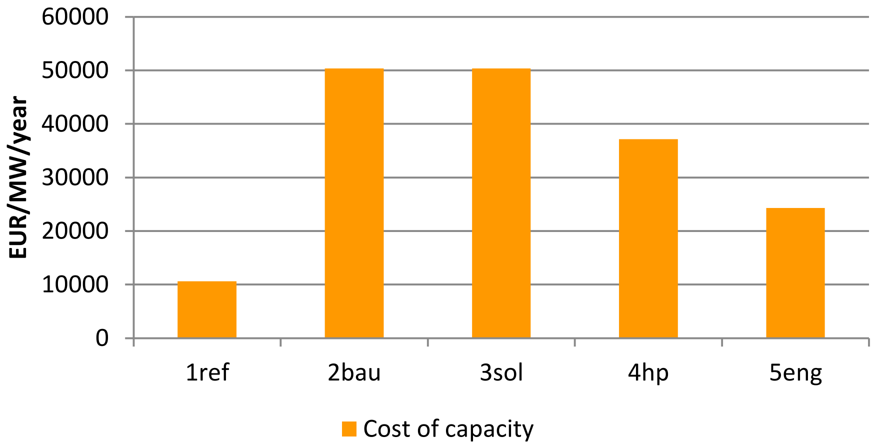


FIGURE 76 COST OF CAPACITY FOR ALL SCENARIOS

As seen in Figure 76, the cost of capacity follows the same pattern as the SR remuneration, and the causes are the same as the ones explained for the size of SR remuneration. It is to be noticed that the costs of capacity can be used as a direct measure against other types of capacity remuneration. Moreover, it can be used as an input in determining the costs and benefits of SR as a CRM.

Finally, the investment analysis shows that, under the assumptions made in the modelling, investing in a 2 MW_e heat pump with COP 2.8 already in 2013, will be business-economically feasible for a plant like HSCHP. In this case, the payback period on the investment is seven years, which is three years less than required by HSCHP.

7. Sensitivity Analyses

Several elements in the analyses are dependent on certain assumptions, which might prove to have importance for the conclusions. This chapter will provide a brief overview of selected parameters, to clarify if changes in these parameters will significantly affect the results of the analyses. The focus will be on the techno-economic analysis.

7.1. Interest Rate for Investment

In this section, it is investigated how resilient the investment analysis is to changes in the interest rate. A 5 % interest rate is assumed in the original investment analysis, and Figure 77 displays alternative interest rates of 10, 15 and 20 %. The sensitivity analysis shows that the internal rate of return is 14.4 %, which leads to the conclusion that the investment is resilient to rather high interest rates, in case the ten-year return on investment is preferred.

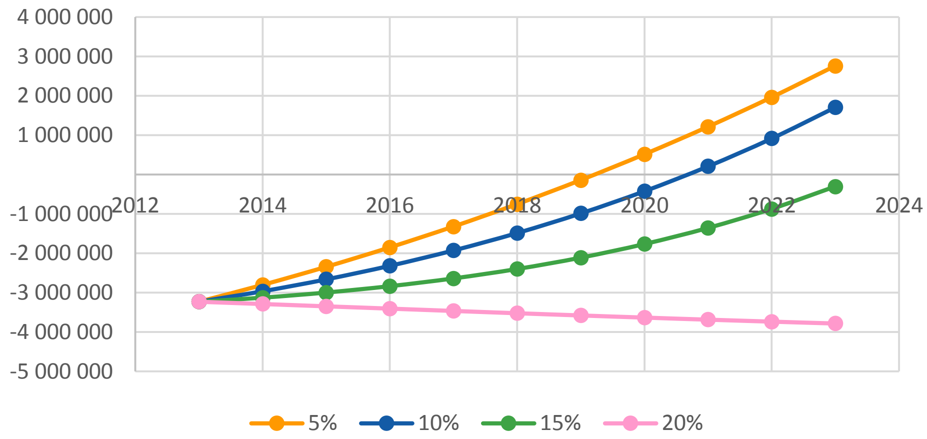


FIGURE 77 IMPACT OF VARIOUS INTEREST RATES ON THE BALANCE OF THE INVESTMENT

7.2. Storage Capacity

The techno-economic analysis has shown that storage capacity has been a limiting factor of different degrees in the analyses. This section explores the operation income in all scenarios, with increasing levels of storage capacity. All other conditions are assumed constant. Figure 78 shows variation from original base scenario, where even under the largest change seen in 5eng, the change in operating income is less than 2 % of the base scenario. This leads to the conclusion that while storage capacity might be a limiting factor, it is so only to a smaller extent under the conditions analysed.

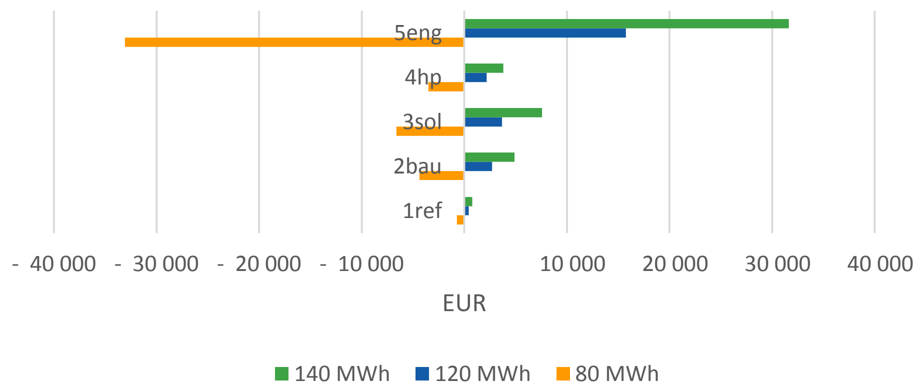


FIGURE 78 DEVIATION IN OPERATING INCOME FROM ORIGINAL SCENARIOS CAUSED BY CHANGES IN STORAGE CAPACITY

7.3. Gas Prices

The projection of electricity price for 2020 is based on data from Ea Energy Analyses. This dataset has been created with certain assumptions on CO_2- and gas prices, which are different from the prices applied in the techno-economic analysis. This section investigates the impact of modelling with prices closer to the ones assumed by Ea Energy Analyses. Instead of the gas price of 0.340 EUR/Nm^3 applied in the techno-economic analyses, Ea Energy Analyses assumes a significantly lower price of 0.268 EUR/Nm^3. For CO_2, instead of 22.48 EUR/EUA as applied in the techno-economic analyses, the study by Ea Energy Analyses assumes 10 EUR/EUA. As seen on Figure 79, the deviation from the original base scenarios is significant in all scenarios, but more in scenarios with a high consumption of natural gas, such as 5eng. This is not surprising, since lowering both CO_2- and gas prices makes it less costly to operate gas-consuming units.

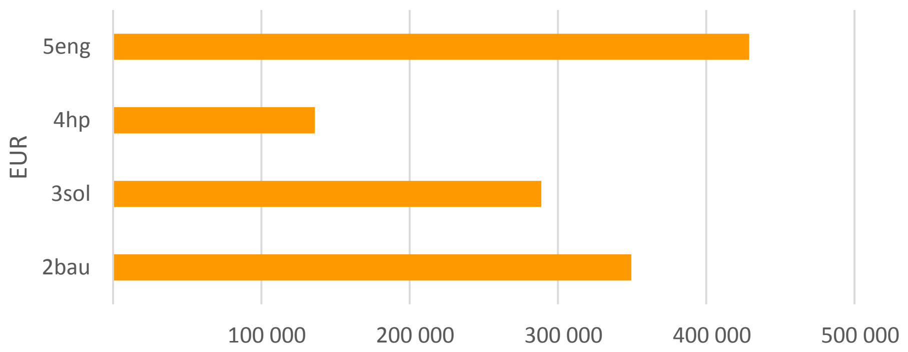


FIGURE 79 DEVIATION IN OPERATING INCOME FROM ORIGINAL SCENARIOS CAUSED BY CHANGES IN GAS- AND CO2-PRICES

Assumptions on future gas prices differ, which is exemplified by IEA (2013) [61], with a projection for a 2020 average price of natural gas to 0.385 EUR/Nm^3. This rise is explained with the expiry of long-term gas contracts that are to be re-negotiated in the period. It can be concluded that the assumptions on the prices is very significant, and it is anticipated that especially the fuel-price is relevant in this regard.

7.4. Heat Pump Operation

It has been assumed that the heat pump analysed in the techno-economic analysis is able to run in partial load and with no minimum operating time. Since priority has not been on the technical specifications of the equippings analysed in the scenarios, it is considered relevant to analyse the degree of impact that these parameters make on the results of the heat pump scenario. In the first sensitivity analysis, the heat pump operates with a minimum operating-time of two hours. Secondly, it is analysed how the absence of partial load affects the operation economy. Results are seen in Table 39.

TABLE 39 ECONOMIC IMPACTS OF CHANGING OPERATION OF HEAT PUMP

4hp original	4hp min. 2 hours	Difference from 4hp	4hp no partial load	Difference from 4hp
-1 345 829	-1 345 963	134	-1 347 319	1 490

The results show impacts below 1 % of the operational income of 4hp. Such small impacts indicates that the operation of the heat pump under these limitations in flexibility and duration of operation is not a significant factor.

[61] Since IEA applies higher heating value, the number has been adjusted according to lower heating value which is customary in Denmark

8. DISCUSSION

Several elements have emerged which are considered important to the outcomes of the study. These elements range from the delimitation, over the methodology and data applied, to the future development in the Danish energy system. This chapter will touch upon those elements and provide brief considerations on their potential impact on the study. The perspectives are considerations by the author, and are generally not subject to references to other sources, unless noted.

8.1. SUSTAINABILITY IN THE STUDY

The study programme under which this thesis is conducted is called Sustainable Energy Planning and Management, making considerations on key aspects of sustainability in the study, relevant. Sustainability is here considered in the three aspects: social, economic and environmental.

8.1.1. SOCIAL SUSTAINABILITY

DCHPs are largely publically or cooperatively owned, and acts as a direct link between heat- and electricity consumers, and the larger power system. If applying CRM causes moving away from this structure, it is assumed that local engagement in energy production might be reduced, in favour of a potentially more centralised and professionalised power system. A second aspect is the transfer of wealth from consumers to producers. CRM can be defined to be a monetisation of security of supply, potentially leading to imbalances in the distribution of security of supply among consumers. Care should be given to the design of tariff-structure, to avoid a socially imbalanced CRM.

8.1.2. ECONOMIC SUSTAINABILITY

The whole exercise of CRMs is to create a business economically viable environment for producers, which provide incentive for the societally desired level and type of supply. Economic sustainability is here defined as the balance where both societal and business interests are met. In the case of DCHP, these actors will only stay on the power market as long as this contributes to lower costs of heat generation. A larger socio-economic study is needed to determine whether society's interests are served best by DCHPs or alternative solutions. While it is difficult to draw conclusions for DCHPs on the foundation of this study, it appears that the market principles in the EOM is indeed functioning on the larger scale, while this might not be sufficient to allow CHPs to renew their electricity generating capacity in 2020.

8.1.3. ENVIRONMENTAL SUSTAINABILITY

In the case studied, the electricity generation on the plant is natural gas-based, and as such not a renewable energy source. Environmental impact depends on the kind of pollutant in focus, and in this study, gas-based electricity is considered to have a generally smaller environmental impact than coal-based electricity. Considerations on environmental sustainability are hence dependent on the marginal producer in the power system, where a coal-fired plant displaced by DCHP is environmentally preferential. In the transition period that the Danish power system is currently undergoing, the DCHPs appear to be a relevant contributor, since these are able to provide fast backup for wind power. In the longer term, fossil fuels are not considered sustainable, and the DCHPs are thus expected to change fuels or cease natural gas-based energy production.

8.2. FUTURE DEVELOPMENT OF SPOT MARKET

Interaction between variable renewable electricity sources and thermal power generation is already now of considerable importance, and is expected to increase as more VRE is introduced. Increased amounts of subsidised renewable energy might further decrease the electricity prices and reduce operation on the thermal plants. Displacement of marginal thermal plants can cause electricity prices to drop, which is beneficial for consumers, but can potentially reduce revenue for renewable energy as well as thermal plants. Such a development might on the short term mean that SR is a feasible temporary solution, but on the longer term require a substantial restructuring of the power market[62]. Another aspect of more renewable energy is that increased amounts of VRE might increase the demand for ancillary services, such as intraday balancing. This demand is caused by the difficulty in precise predictions of VRE, and might be a potential business opportunity for fast DCHPs, depending on the level of competition with surrounding markets. One such potential competitor is hydropower, which with about half of total installed capacity in the Nordics is potentially the largest supplier of fast and flexible capacity (International Energy Agency and Nordic Energy Research 2013). Yet another factor is carbon pricing. If the price on EUAs increase, this can benefit DCHPs due to their generally lower emissions compared to coal-based plants.

8.2.1. Smart Energy Systems

Smart energy systems is here considered as a collective name for multiple aspects of a more dynamic energy system. The involvement of the consumer-side is considered important in smart energy systems, since this will make the system more flexible (Botterud and Doorman 2008). However, it might have implications for DCHPs under SR, since increased shares of DR can increase competition within the scheme. The Swedish case is an example of this, where relatively large shares of DR are contracted. The same has been the case in PJM, as illustrated by Figure 80, where DR takes a considerable share of the capacity supplied in the capacity market. Although initially intended to attract new capacity, the experience from PJM shows that the amount of resources attracted from sources other than new generation capacity, was surprisingly large. If the same will be the case for SR in Denmark, DCHPs might face considerable competition, in case the scheme is designed with competitive bids. An indicator of potentially larger DR is a political decision, where all Danish consumers must be supplied by smart meters by 2020 (Danish Ministry for Climate Energy and Building 2013e).

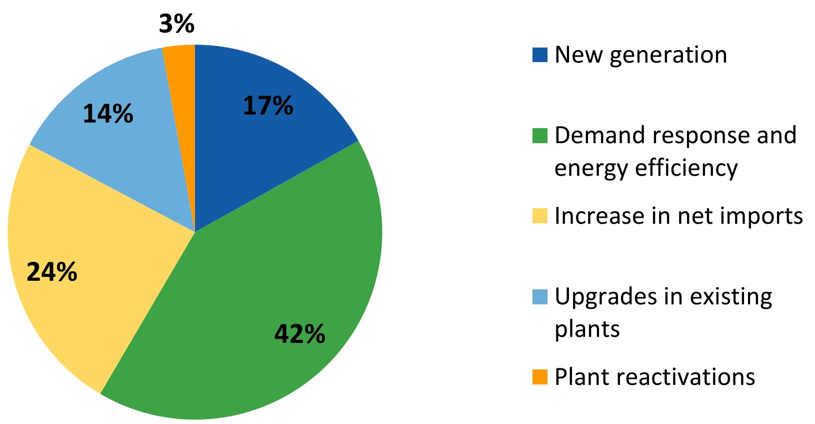


FIGURE 80 AMOUNT OF CAPACITY SUPPLIED IN THE PJM MARKET THROUGH 2014/2015. BASED ON SPEES, NEWELL AND PFEIFENBERGER (2013)

8.3. Methodology

The methodology applied in the study, is in this section discussed with a focus on the consequences for the results.

8.3.1. Focus of the Study

The focus on CRM might leave out important elements of flexibility in the power system. This means that capacity might not be sufficient in an energy system which is also dependent on flexibility expressed as the ability to ramp and cycle electricity generation sufficiently fast. Hence, the study could be expanded to include flexible CRM. This matter has been pointed out by actors such as Stuart Bradford of Shell Energy Europe (Montel Online 2013f) and the GIVAR Project

[62] This matter of a well-functioning market, that allows for business-economic as well as socio-economic benefits in the transition to a renewable energy system, could be defined as *market adequacy*

conducted by IEA[63]. In practice, this can turn out to be difficult, since the requirement for flexibility in the system is even less clear than the demand for capacity. Another aspect to consider is the general approach to security of supply, where it can be questioned whether it is preferable to depend on fuel imports such as coal, gas, oil and biomass from foreign countries, or if it is preferred to be dependent on electricity from the neighbours. These questions relate very much to the discussion of maintenance of national generation capacity versus reliance on import of electricity. While several types of analysis can be made on the subject, it is to a large degree a political question. The answer to this question will have significant impact on whether supply is maintained through mechanisms such as SR, or through increased interconnection to surrounding countries.

8.3.2. Modelling in energyPRO

> *Making assumptions is the first step when building models and this represents the true weak point of a model. Assumptions are made during the description of the system to be modeled and of the relationships between variables* (Boisseleau 2004, 109)

The quote by Boisseleau sums up the general concern regarding models. On a more concrete level, four matters regarding modelling is dealt with in this section. Firstly, since the new engine in the *5eng*-scenario is larger than normal DCHP engines, it might have been relevant to apply a smaller engine that would correspond better to the heat demand and heat storage in the scenario. Secondly, plants participating under SR are assumed to suffer losses or fines if they cannot deliver generation when called in. This means that they must be able to cool production away, in case they have to operate in periods longer than the capacity of the heat storage, where the heat demand in insufficient to absorb supply. Such a cooling unit could have been included in the modelling in order to reflect its fixed costs under SR-regulation. Thirdly, the *4hp*-scenario could have been expanded with an analysis of the heat pump as a unit operating under SR. This would be relevant, due to the large amount of operating hours of the heat pump, which opens up for the opportunity of offered the heat pump as DR-capacity. Finally, the absence of ancillary services in the modelling means that revenue earned through this market is not included in the base-variants of each scenario. The consequence is that SR remuneration is assumed to be smaller than it would be with ancillary services, assuming that the plant was not allowed to participate on these markets if under SR regulation.

8.3.3. Delimitations

The delimitations presented in Chapter 1 mean that certain elements have not been addressed in the study. This section summarises what these delimitations mean for the analysis. One of the most important delimitations is the absence of a socio-economic analysis. Such an analysis would provide a larger perspective of the performance of SR and DCHP under SR, compared to the alternatives. Additionally, it could entail more detailed analysis of the periods which precede and exceed 2020, where investments and market conditions might vary. The system-perspective where interactions with the power system as a whole is also left out. The absence of the above-mentioned analyses makes the comparison of the results to alternative types of CRM difficult. However, this has been the condition from the outset, due to the sheer magnitude of such a study, which would require a different scope and significantly more time than which has been available for this study. Finally, the techno-economic modelling would benefit from more detailed specifications on the technologies applied. Especially the assumption on a constant COP and heat source for the heat pump gives subject to concerns on the results. Since the heat source and the corresponding COP might vary over the year, the techno-economic analysis in *4hp* and the investment analysis can prove to be too optimistic.

8.3.4. The Design of Strategic Reserves as CRM

Regarding strike price, two options have been discussed: at 0.1 EUR/MWh above spot price and at the price cap of the market. The first option takes away scarcity rent from the generators, and to avoid that impact it has been suggested to relocate the strike price to the price cap. In the real world, this might result in complications, due to high political

[63] See for instance http://www.iea.org/topics/renewables/givar/

sensitivity towards very high electricity prices. This is expected to be especially pertinent in countries with a large share of electric heating. Since electric heating is very limited in Denmark, such political sensitivity is expected to be less of an issue. Still, having a strike price at the price cap, i.e. average VOLL, might not be optimal. This is due to the fact that at prices of average VOLL, *consumers, on the average, are indifferent whether they receive power, so the social benefit of the reserve is minimal (zero in theory) and the effect is limited to 'keeping the lights on'* (Brunekreeft et al. 2011, 29). Thus, the benefit in such a design lies with the generator. Under this logic, the strike price should be low enough to provide benefits for the consumer, and high enough to provide sufficient scarcity rent for the generator, essentially lowering the strike price from VOLL. Another aspect of the design of SR, is the fundamental assumption of either spot market participation or as SR. As seen in Sweden where DR can participate on the spot market, intermediate designs could be considered. In that case, the calculation of SR remuneration would become more complex, and perhaps resemble what is now seen in the PIP, and the capacity payments seen in Spain. It could be imagined that such an approach would be taken, if policy makers decided to take the same, and more regulatory, approach to thermal plants as has been seen towards renewable energy. Finally, Chapter 4 presented an array of criticisms against the concept of CRM and SR. It should be noted that the majority of the criticism included in this section is postulates, which would benefit from being elaborated with actual power system modelling and socio-economic analysis. This study has been a contribution to such analyses, but much analysis remain to clarify real impacts.

8.4. Data

To obtain hourly values for spot prices in 2020, a 2020-dataset from Ea Energy Analyses was indexed according to an average electricity price provided by Danish Energy Agency. This dataset contained no negative values, due to the assumptions in the model which generated this dataset. While it would be preferred to make a sensitivity analysis of the impact of these spot prices in 2020, this has not been possible within the duration of the study. The most pertinent issue to investigate would be whether more extreme fluctuations in the prices would result in different results of the techno-economic analysis. Especially the fact that the dataset contains no negative prices would be relevant to address, since negative prices could turn expenditure for electricity consumed by the heat pump into revenue earned by the heat pump.

8.5. Partial Conclusion

The aspects related to sustainability in this study shows that DCHP as SR appears to be beneficial in the transition to a renewable energy system, but that the plants will need to change from fossil fuels to renewable energy. It can be concluded that neither SR nor DCHP are intrinsically sustainable solutions, but that they together or separately can make a relevant contribution in the transition to a sustainable energy system. Regarding the development of the market, it appears that SR can be a relevant temporary option to apply, since the future development of the energy system is uncertain, and since market-interaction between the Danish energy system and surrounding energy system is expected to be significant. On the other hand, political priorities might pull in a direction where national priorities are preferred, and in this case, SR can be a means to maintain thermal generators in an increasingly regulated energy system. Competition from DR in a smarter energy system can occur both with and without SR. Increased amounts of DR on the spot market can reduce price spikes and hence revenue for generators. Regarding SR, participation of DR can cause competition with DCHPs, causing reduction in SR remuneration for DCHP or a full displacement of the DCHP, similar to the merit order effect currently seen in the spot market. Regarding the methodology, further studies might benefit from including flexibility as an addition to capacity, since this might be in larger demand in the future. The modelling applied in the techno-economic analysis could similarly benefit from a larger degree of detail, especially regarding inclusion of ancillary services and of more detail in the assumptions and technical specifications of the equipping. Among the most important delimitations made in the study, is the matter of a local business-economic perspective versus a broader socio-economic and power system-perspective. These perspectives are necessary to apply, if comparison between different types of CRM is to be made on the societal and power system-level. Finally, further analysis should be carried out towards the sensitivity of the results to variations of the spot market prices, since this can affect operation income.

9. CONCLUSION

This final chapter concludes the study. The results from the analyses are addressed according to the research questions. This allows for recommendations in relation to the application of strategic reserves and the participation of decentralised combined heat and power plants in such a capacity remuneration mechanism. The research questions will provide the framework for this chapter, and since question 2, 3 and 4 are closely related, they will be treated under the same section.

9.1. QUESTION 1

What are the general energy-economic implications of strategic reserves as a capacity remuneration mechanism?

The analysis has been carried out in two steps, where general energy economic parameters were identified, followed by an analysis of how SR would perform within each parameter. The results are seen in Table 40.

TABLE 40 EVALUATION OF THE ENERGY ECONOMIC IMPACTS OF SR

Parameter	Evaluation
Technology neutrality, hereunder participation of demand-side	Limited amount of selected plants and demand response
Relation to market power	Robust, but generators can threaten to decommission plants. Can to some degree mitigate market power through DR
Sensitivity to state of the market	Low. The amount of contracted reserves can be adjusted from year to year
Impact on EOM	If the strike price is lower than the price cap, then high. Additionally, there might be situations where capacity is withheld despite spot prices over marginal cost of plants
Sensitivity to reduction in demand	Low. Assuming that the demand is reduced, SR can be adjusted downwards accordingly the next year
Sensitivity to increase in low-cost generation	Low. Assuming that SR capacity is contracted through bids among selected plants and assuming that the low-cost generation causes spot market prices to fall, bids for the SR are assumed to decrease as a result
Sensitivity to CO_2-prices	Low-medium. Assuming a Danish context where participating plants would be relatively efficient, relative profitability towards German capacity might increase if CO_2-prices increase. This would lead to increased costs of remuneration in SR
Incentive to preserve capacity in power system	High. This is the purpose of remunerating generators in SR
Investment incentive	None, still up to EOM
Revocability	Straightforward
Complexity	Low
Compatibility with surrounding markets	Can be implemented directly
Controllability of costs	Yes, since they are largely determined by the size of SR
Stabilisation of electricity prices	If dispatch at 0.1 EUR/MWh above spot price, then yes

Moreover, an important aspect of the design of energy markets is that solutions should be comprehensive. With few exceptions, the treatment of a comprehensive regulation of the energy market has not been encountered in the literature on CRM and SR reviewed for this study. Instead, most perspectives on CRM appears to have a somewhat narrow focus on securing sufficient capacity, but not as a part of a wide-ranging analysis of the needs and opportunities of the energy system. This underlines the importance of such a focus in further studies of CRM, which could be substantiated by analyses on business-economy, socio-economy and concrete power systems. Another important finding within a more policy-related domain is how optimisation needs to happen on the energy market, when the production portfolio and policy goals are dynamic and influenced by the surrounding markets and power systems. Incremental changes, such as a temporary SR mechanism, might not suffice in the longer term, but could be the preferred solution if adopting a *wait and see*-stance towards regulation of the market. The analysis has shown that SR is a feasible option on the short term, when addressing the majority of elements presented in Table 40. However, further analysis is needed to determine whether SR will be sufficient, if wanting to maintain policy goals in the long term of 10-30 years. Of special importance would be to determine the incentive for investment in new capacity and if this capacity should carry characteristics that would enable it to operate in a power system with significant variability and uncertainty in generation, low electricity prices caused by low-cost VRE and constraints based on location of generation and demand. With the current design of SR, none of these elements are addressed.

9.2. Question 2, 3 and 4

Question 2: What is the economic and operational performance of a Danish decentralised combined heat and power plant with various types of equipping under current- and 2020-conditions on the spot market?

Question 3: What should be the concrete remuneration from a strategic reserve to decentralised combined heat and power plants in current and future conditions, in order to provide a business-economic incentive for participating in a strategic reserve?

Question 4: Will such remuneration from SR contribute to maintaining electrical generation capacity among decentralised combined heat and power plants?

The analysis takes point of departure in a case study on the Hvide Sande CHP. This plant is considered a critical case, whereby the conclusions made for Hvide Sande CHP are assumed valid for other natural gas-based Danish DCHPs, since the equipping and operating conditions of the plant are similar to many other Danish plants. DCHPs such as HSCHP are considered to have relatively high variable costs, but at the same time, they are relatively flexible plants. These characteristics resembles peak-load plants, which are considered to be well suited for a power system, where demand for operating hours is reduced, while the demand for flexibility is increased.

The techno-economic analysis has revealed important information on the operational and economic performance of the case, where the latter is displayed in Figure 81. It can be concluded that economically rational plants in 2020 would search for alternatives to business as usual (*2bau*), since this is the poorest performing scenario regarding economy. The economic performance of 2013 is only surpassed by a single scenario (*4hp*), which leads to a general conclusion on the future of DCHPs: under the conditions analysed in this study, DCHPs will be economically worse off in 2020, unless a heat pump is part of their equipping. All things being equal, this means that heat prices will increase as well. Apart from the 2013-scenario (*1ref*), the three best-performing scenario-variations are as follows:

1. *4hp*: Current equipping and a heat pump – 29 % below *2bau*
2. *3sol*: Current equipping and solar heating – 21 % below *2bau*
3. *4hp-no eng*: Decommissioning the engines and adding a heat pump – 15 % *2bau*

None of the analysed scenarios show that the *no eng*-option has better business-economy than participation on the spot market. The main conclusion to draw from this is that SR is not necessary, in order to maintain capacity from DCHP in the Danish energy system. While option 3 is important to consider, it is unlikely that any plant would prefer this to option 1, since both have the same equipping from the outset. If anything, option 3 could arise in a situation where the lifetime of the engines runs out and no overhaul or reinvestment is chosen. In that case, SR in the current design would not make any difference, since it merely provides incentive for plants to participate in SR, and to maintain electric capacity in situations where the plant would see better business economy in abandoning electric generation capacity. Additionally, the analyses show a general tendency, where lower reliance on heat production from natural gas-based units means lower expenditure and vice versa. While this might not be any different from today, it provides a general incentive for DCHPs to move away from natural gas. To avoid arbitrary and sub-optimal solutions conducted by the individual plants, such a move should be actively managed by authorities and directed according to national priorities.

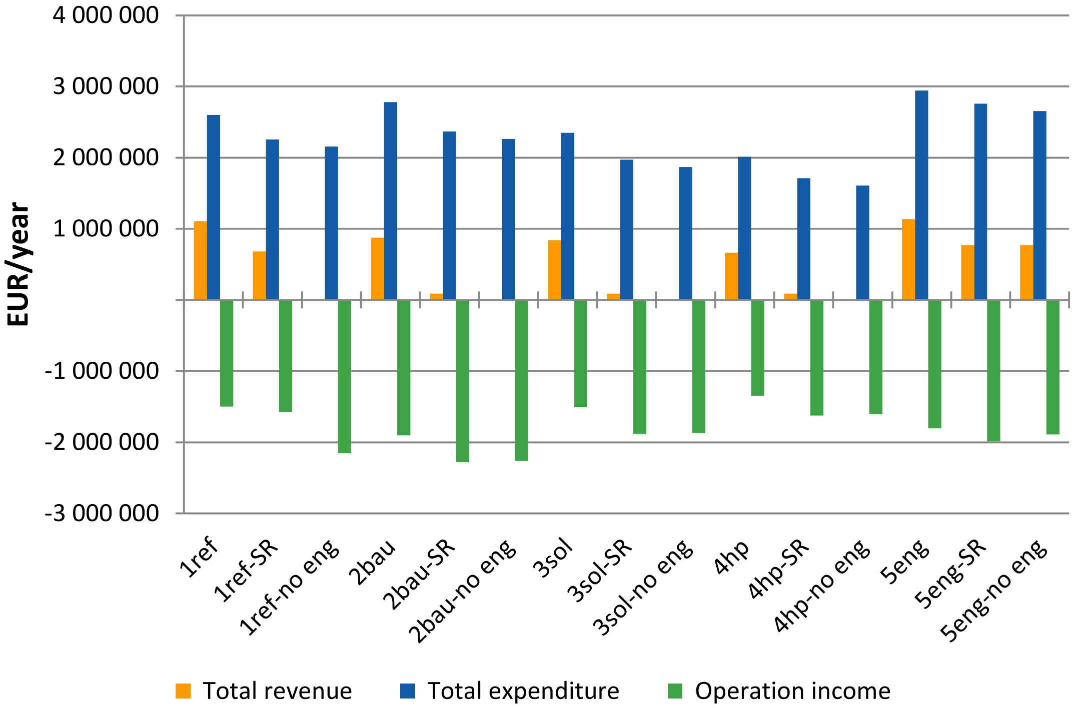


FIGURE 81 BUSINESS ECONOMIC RESULTS OF OPERATION WITH DIFFERENT TYPES OF EQUIPPING, AND IN DIFFERENT VARIATIONS

The level of remuneration found for the scenarios is seen in Figure 82. Since 2009, the Swedish SR remuneration has seen a span in remuneration from 3 948 EUR/MW$_e$ to 9 934 EUR/MW$_e$. Apart from the *1ref*, cost of capacity in all scenarios is considerably higher than the Swedish case, indicating that Danish DCHPs cannot supply capacity at a similar price. This conclusion is based on the assumption that Swedish SR remuneration between 2009 and 2014 is comparable to Danish SR remuneration in 2020, and should hence not be considered anything more than an approximation.

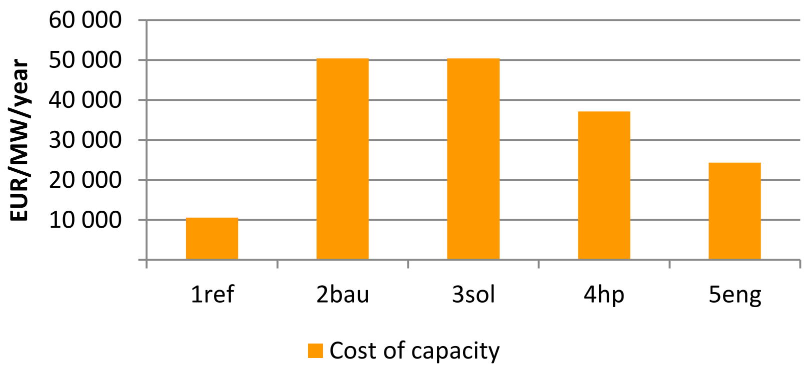


FIGURE 82 COST OF CAPACITY FOR ALL SCENARIOS

HSCHP currently receives a PIP of 838 718 EUR/year. Assuming that the plant would maintain its current equipping until 2020, where it would enter as a SR, the size of SR remuneration would be 375 748 EUR/year, which is less than half of current PIP. From this can be concluded that public expenditure for the plants will be reduced in 2020, and that there will be room for economic manoeuvre, before reaching subsidy levels seen in 2013.

The operational impact of different equippings on the spot market, as SR and with no engines, is seen in Figure 83. It is seen that the heat source with the lowest cost is first priority, which often leaves the existing engines out. In all scenarios but *4hp* and its variations, the gas boiler is dominant. This is relevant, since such large boiler-share puts a chip in the Danish pride of a highly efficient and largely CHP-based energy system, and it can be questioned whether this utilisation of high-value fuel, natural gas, is reasonable. Furthermore, the continued large dependence on natural gas-based production reveals that the current awkward situation, where policy-makers are balancing between the benefits of the tax revenue generated by natural gas and the political priority to reduce fossil fuels-consumption, remains unresolved in 2020.

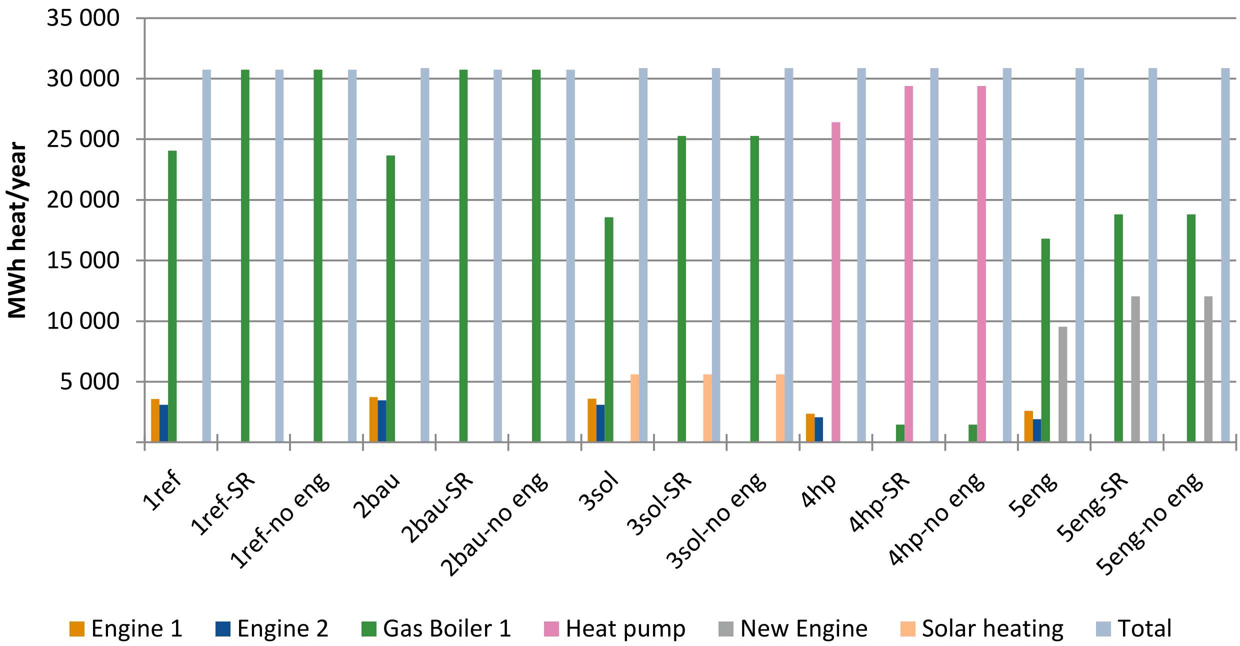


FIGURE 83 HEAT PRODUCTION IN SCENARIOS WITH DIFFERENT TYPES OF EQUIPPING, AND IN DIFFERENT VARIATIONS WITHIN EACH SCENARIO

Certain assumptions apply to the techno-economic analyses, which have justified a sensitivity analysis. The analyses of selected topics show low sensitivity to interest rates in the investment scenario, and to heat storage capacity. Results are on the other hand highly sensitive to gas prices, where increases or reductions affect the operation and the operational income.

9.3. Recommendations

Depending on the perspective and political aims, the recommendations can take different directions. In order to cover a broad spectrum with the recommendations, two *stances*, i.e. approaches to regulation of the power system, have been identified: the *wait and see*-stance and the *holistic planning*-stance.

1. *What are the general energy-economic implications of strategic reserves as a capacity remuneration mechanism?*
    - ❖ The assumption in the Swedish SR is that participating plants would be decommissioned, if not remunerated under the SR regime. The energy economic analysis shows that SR in theory is a relevant

and efficient tool to achieve maintenance of capacity on the power market. It is easily revocable, and can be beneficial as a measure to ensure regulation of capacity in the Danish context, where a complete restructuring of the power market would be legally challenging, and require close coordination with an increasingly larger power system and power market. This approach can be expressed as the *wait and see*-stance

- ❖ Alternatively, policymakers might prefer a more guided and fundamental re-structuring of the Danish power system, where increased amounts of planning and regulation will ensure the development of an energy system, which corresponds to national targets. It could be imagined that such an approach would be relevant, in case socio-economic analyses would show benefits of such an approach. This approach can be expressed as the *holistic planning*-stance

2. *What is the economic and operational performance of a Danish decentralised combined heat and power plant with various types of equipping under current- and 2020-conditions on the spot market?*
    - ❖ Wait and see-stance: Since the techno-economic analyses show that the business-economy of the plant will deteriorate by 2020 in all scenarios but the heat pump scenario, DCHPs should not hesitate to search for alternative equippings, or even alternative business models. This relates to a general perspective, where the transition of the power system is expected to generate an increase demand for energy services, while traditional fixed-flow energy production is assumed to become less important. In the identification of new business-models, the following points provides a guideline that regulators as well as DCHPs need to consider:
        - ♦ On what should the company base its income?
        - ♦ How should the company organise its activities?
        - ♦ Which markets should the company focus on?

      Furthermore, the surplus of generating capacity that results from adding RE capacity to already capacity-saturated markets is expected to provide opportunity – perhaps even a need – for providing flexibility services from the existing assets. This market might be the direction to look for DCHPs that see their electricity production decrease
    - ❖ Holistic planning-stance: If DCHPs are a preferred part of the energy system in 2020, the decreased income should be addressed in a long-term perspective, where reinvestments in and overhaul of electricity generation capacity would be incentivised. Otherwise, plants are expected to find alternative equippings and business models, which might not be in line with national priorities

3. *What should be the concrete remuneration from a strategic reserve to decentralised combined heat and power plants in current and future conditions, in order to provide a business-economic incentive for participating in a strategic reserve?*
    - ❖ Wait and see-stance and holistic planning-stance: The techno-economic analyses have identified the levels of SR remuneration for DCHPs to be larger than the levels currently seen for the larger plants participating in the Swedish SR. While this comparison should be taken with some caution due to the differences in space and time, it indicates that DCHPs could be poorly ranked in the competition against larger Danish plants. This relates to both stances, but the solutions differ. In the wait and see-stance, the competition issues would presumably not be addressed, since this stance is expected to intervene only on the larger aspects of planning. Contrary to this point, the holistic planning-stance would need to differentiate remuneration among different types of contributors, i.e. DCHPs and larger plants, if it is preferred to maintain DCHPs in the system. A similar approach is seen in Sweden where SR is split between generation and DR

4. *Will such remuneration from SR contribute to maintaining electrical generation capacity among decentralised combined heat and power plants?*
    - ❖ Wait and see-stance: The techno-economic analyses shows that none of the scenarios would benefit from SR remuneration, since the best business-economic results are among the variations where the plant participates on the spot market. In other words, there is no need for SR to maintain capacity among DCHPs
    - ❖ Holistic planning-stance: While the same conclusion can be drawn here as in the wait and see-stance, it could be imagined that there would be a preference for life-extension of electric capacity beyond the operating hours of the equipping. Such incentive is not provided by SR, but could be added according to the need, for instance by increasing the level of SR remuneration. In designing SR and its remuneration, it is important to be aware that DCHPs would always choose the solution that provides the lowest heat price for the consumers. This means that electricity generation capacity is a secondary service on the plant, which is solely supposed to generate revenue that can lower heat prices. This insight is pertinent, if maintaining national generation capacity is a priority

BIBLIOGRAPHY

Andersen, Ib. 2008. *Den Skinbarlige Virkelighed : Om Vidensproduktion Inden for Samfundsvidenskaberne*. Frederiksberg : Samfundslitteratur.

Andreasen, Peder Ø. 2013. “Forsyningssikkerhed i En Fremtid Med ” Ustyrlig ” Energiproduktion Elforsyningssikkerhed”. Copenhagen, Denmark: Energinet.dk.

Arcon Solar. 2013. “ARCON Solfanger - Type HT-SA 28/10.”

Bang, C, F Fock, and M Togeby. 2012. “The Existing Nordic Regulating Power Market.” *Ea Energy Analysis*. Copenhagen. http://ea-energianalyse.dk/reports/1027_the_existing_nordic_regulating_power_market.pdf.

Baritaud, Manuel. 2012. “Securing Power During the Transition.”

Blinder, Alan S. 2004. *Microeconomics : Principles and Policy*. Edited by William J Baumol. Mason, Ohio : Thomson / South Western.

Boisseleau, F. 2004. *The Role of Power Exchanges for the Creation of a Single European Electricity Market: Market Design and Market Regulation*. Delft: Delft University Press. http://www.cgemp.dauphine.fr/fileadmin/mediatheque/centres/cgemp/Theses_soutenues/BoisseleauTheseNl.pdf.

Botterud, a, and G Doorman. 2008. “Generation Investment and Capacity Adequacy in Electricity Markets.” *International Association for Energy Economics. …*: 877–884. http://doi.acm.org/10.1145/1982185.1982376.

Brunekreeft, Gert, Niclas Damsgaard, Laurens de Vries, Peter Fritz, and Roland Meyer. 2011. “A Raw Model for a North European Capacity Market”. Stockholm.

Bukholt, Jørgen. 2013. “Interview with Jørgen Bukholt”. Hvide Sande.

Bundesministerium der Justiz. 2013. *Verordnung Zur Regelung Des Verfahrens Der Beschaffung Einer Netzreserve Sowie Zur Regelung Des Umgangs Mit Geplanten Stilllegungen von Energieerzeugungsanlagen Zur Gewährleistung Der Sicherheit Und Zuverlässigkeit Des Elektrizitätsversorgungssystems*.

Bundesnetzagentur. 2013. “Feststellung Des Reservekraftwerksbedarfs Für Den Winter 2013 / 14 Und Zugleich Bericht Über Die Ergebnisse Der Prüfung Der Systemanalyse”. Bundesnetzagentur.

CEER. 2010. “Guidelines of Good Practice on Estimation of Costs Due to Electricity Interruptions and Voltage Disturbances”. Brussels.

Chandler, Hugo. 2011. “Harnessing Variable Renewables : A Guide to the Balancing Challenge.”

Cochran, Jaquelin, Lori Bird, Jenny Heeter, and Douglas J Arent. 2012. “Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience.”

Commission, California Public Utilities. 2013. “Cost of Service.” Accessed December 20. http://www.cpuc.ca.gov/cfaqs/costofservice.htm.

Cramton, Peter, and Axel Ockenfels. 2011. “Economics and Design of Capacity Markets for the Power Sector” (May): 1–36.

Cramton, Peter, Axel Ockenfels, and Steven Stoft. 2013. “Capacity Market Fundamentals.” *Economics of Energy & Environmental Policy* 2 (2) (April 1): 27–46. doi:10.5547/2160-5890.2.2.2. http://www.iaee.org/en/publications/eeeparticle.aspx?id=46.

CREG. 2012. “Study on Capacity Remuneration Mechanims”. Vol. 09. Brussels.

———. 2013. “Capacity Remuneration Mechanisms.”

Danish District Heating Association. 2013. “Benchmarking Statistik 2012/2013”. Kolding.

Danish Energy Agency. 2013. “Download Premade Maps.” Accessed December 20. http://www.ens.dk/en/info/facts-figures/energy-info-maps/download-premade-maps.

———. 2005. “Heat Supply in Denmark, Who, What, Where, and Why.” *January, Copenhagen*. Copenhagen. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Heat+Supply+in+Denmark+Who+What+Where+and+-+Why#0.

———. 2012a. “Annual Energy Statistics.” http://www.ens.dk/en/info/facts-figures/energy-statistics-indicators-energy-efficiency/annual-energy-statistics.

———. 2012b. “Energiproducenttællingen”. Copenhagen, Denmark: Danish Energy Agency.

———. 2013a. “Danish Reply to the Commission’s Public Consultation on Generation Adequacy, Capacity Mechanisms and the Internal Market in Electricity”. Copenhagen.

———. 2013b. “Samfundsøkonomiske Beregningsforudsætninger.” http://www.ens.dk/info/tal-kort/fremskrivninger-analyser-modeller/samfundsokonomiske-beregnings-forudsaetninger.

———. 2013c. “Alle Elmålere Vil Være Fjernaflæste i 2020.” http://www.ens.dk/info/nyheder/nyhedsarkiv/elmaalere-vaere-fjernaflaeste-2020.

Danish Energy Agency, and Energinet.dk. 2013. “Technology Data for Energy Plants.” http://www.risoe.dk/rispubl/NEI/NEI-DK-5719.pdf.

Danish Ministry for Climate Energy and Building. 2011. *Varmeforsyningsloven - Bekendtgørelse Af Lov Om Varmeforsyning*. https://www.retsinformation.dk/Forms/r0710.aspx?id=139597#Kap4.

———. 2012. “Lov Om CO2-Kvoter.” https://www.retsinformation.dk/Forms/r0710.aspx?id=144102#Kap4.

———. 2013a. “Energipolitisk Redegørelse 2013”. Copenhagen.

———. 2013b. *Projektbekendtgørelsen - Bekendtgørelse Om Godkendelse Af Projekter for Kollektive Varmeforsyningsanlæg*. Ministry of Climate, Energy and Building. https://www.retsinformation.dk/Forms/R0710.aspx?id=145836#Kap6.

———. 2013c. “Bekendtgørelse Om Pristillæg Til Elektricitet Produceret Ved Decentral Kraftvarme M.v.” https://www.retsinformation.dk/Forms/R0710.aspx?id=152628.

———. 2013d. *Bekendtgørelse Af Lov Om Elforsyning*. https://www.retsinformation.dk/Forms/R0710.aspx?id=159158.

———. 2013e. “Smart Grid-Strategi”. Copenhagen: Ministry of Climate, Energy and Building.

Danmarks Statistik. 2013. "Statistikbanken." http://www.dst.dk/da/.

DECC. 2011. *Planning Our Electric Future: A White Paper for Secure, Affordable and Low-Carbon Electricity*. *Vaccine*. Vol. 30 Suppl 4. http://books.google.com/books?hl=en&lr=&id=pG6ZCiAg9UEC&oi=fnd&pg=PA3&dq=Planning+our+electric+future:+a+White+Paper+for+secure,+affordable+and+low-carbon+electricity&ots=rXrAmNuS4m&sig=itfRPRYcunOHSnsUEFdp5VoBdgY.

Den Store Danske. 2013. "Hvide Sande | Gyldendal - Den Store Danske." *Den Store Danske*. http://www.denstoredanske.dk/Danmarks_geografi_og_historie/Danmarks_geografi/Jylland/Hvide_Sande.

Dong Energy. 2012. "Årsrapport 2012". Fredericia.

DTU. 2013. "Transportøkonomiske Enhedspriser". Lyngby: Danish Technical University. http://www.modelcenter.transport.dtu.dk/Publikationer/Transportoekonomiske-Enhedspriser.

Elgaard, Thomas. 2013. "Eftersyn Af Det Nordiske Regulerkraftmarked". Energinet.dk.

EMD International. 2013a. "Oversigt over Fjernvarmeværkers Væsentligste Tilskud Og Afgifter". Aalborg.

———. 2013b. "Skagen Varmeværk." http://www2.emd.dk/plants/skagen/.

Energinet.dk. 2010. "Hvad Er En Treledstarif for Værker?" http://energinet.dk/DA/El/Vaerker/Afregning/Spoergsmaal-og-svar/Sider/Hvad-er-en-treledstarif-for-vaerker.aspx.

———. 2012. "Internationale Erfaringer Med at Sikre Kapacitet Til Elmarkedet". Fredericia.

———. 2013a. "Det Nordiske Elsystem." http://energinet.dk/DA/OM-OS/Sider/Det-nordiske-elsystem.aspx.

———. 2013b. "Roles." http://energinet.dk/EN/El/Engrosmarked/Viden-om-engrosmarkedet/Sider/Roller.aspx.

———. 2013c. "Værker På Markedsvilkår." http://energinet.dk/DA/El/Vaerker/Vaerker-paa-markedsvilkaar/Sider/Vaerker-paa-markedsvilkaar.aspx.

Energy Vortex. 2013. "Cost of Service, Cost-of-Service (COS), Cost-of-Service Pricing." Accessed December 20. http://www.energyvortex.com/energydictionary/cost_of_service__cost_of_service_%28cos%29__cost_of_service_pricing.html.

ENTSO-E. 2013. "Regional Groups." https://www.entsoe.eu/about-entso-e/system-operations/regional-groups/.

European Energy Exchange. 2013. "EU Emission Allowances." https://www.eex.com/en/Download/Market-Data/EU Emission Allowances - EEX.

European Energy Exchange AG. 2013. "The Need for and Design of Capacity Mechanisms in Germany". Leipzig.

European Union. 2006. *Electricity Supply Directive*. Vol. 2004. Brussels: European Union.

———. 2009. *Electricity Market Directive 2009/72/EC*. Vol. 2008. Brussels.

EY. 2013. "Benchmarking European Power and Utility Asset Impairments."

Finon, D, and F Roques. 2012. “European Electricity Market Reforms: The ‘Visible Hand’ of Public Coordination.” *Economics of Energy & Environmental Policy* 2 (2) (April 1): 16–18. doi:10.5547/2160-5890.2.2.6. http://www.iaee.org/en/publications/eeeparticle.aspx?id=50.

Flyvbjerg, B. 1991. *Rationalitet Og Magt. - Bind I : Det Konkretes Videnskab*. Kbh. : Akademisk Forlag.

Gaspoint Nordic. 2013. “Market Data.” http://www.gaspointnordic.com/market-data.

Google. 2013. “Google Maps.” https://maps.google.dk/.

Gram Mortensen, Bent Ole, and Rikke Gottrup. 2007. *Kommunal Varmeplanlægning i Retlig Belysning*. Edited by Bent Ole Gram Mortensen. Kbh. : Jurist- og Økonomforbundet.

Green Energy. 2013a. “Driftstimer Hos de Decentrale Kraftvarmeværker (161213)”. Kolding: Green Energy.

———. 2013b. “20131013_Spørgeskema 2”. Kolding: Green Energy.

———. 2013c. “Green Energy Survey”. Kolding: Green Energy.

Green, Richard. 2006. “Electricity Liberalisation in Europe—how Competitive Will It Be?” *Energy Policy* 34 (16) (November): 2532–2541. doi:10.1016/j.enpol.2004.08.016. http://linkinghub.elsevier.com/retrieve/pii/S0301421504002599.

Heijden, Kees Van der. 1996. *Scenarios: The Art of Strategic Conversation*. http://books.google.dk/books/about/Scenarios.html?id=oZYoAQAAMAAJ&pgis=1.

Hogan, William W. 2013. “Electricity Scarcity Pricing Through Operating Reserves.” *Economics of Energy & Environmental Policy* 2 (2) (April 1). doi:10.5547/2160-5890.2.2.4. http://www.iaee.org/en/publications/eeeparticle.aspx?id=48.

Houmoller, Anders. 2013. “The Liberalized Electricity Market.”

Houmøller, Anders Plejdrup. 2013a. “Interview with Anders Houmøller”. Copenhagen.

———. 2013b. “System Price 1992-2013”. Houmøller Consulting.

Hvelplund, Frede. 2013. “Presentation by Frede Hvelplund”. Copenhagen: 4th Generation District Heating - Second Annual Conference.

Hvelplund, Frede, and Henrik Lund. 1998. *Feasibility Studies and Public Regulation in a Market Economy*. Edited by Frede Hvelplund and H. Lund. *Aalborg University, Denmark*. Aalborg: Aalborg University. http://www.plan.aau.dk/digitalAssets/5/5508_218.pdf.

Hvide Sande Fjernvarme. 2013. “Annual Reports - Hvide Sande Fjernvarme A.M.B.A.” *Årsrapport*. Hvide Sande: Hvide Sande Fjernvarme. http://hvidesandefjernvarme.dk/default.asp?kategori1=2b&id1=26.

IEA. 2012. “Energy Technology Perspectives 2012 Pathways to a Clean Energy System.” *Energy Technology Perspectives 2012 Pathways to a Clean Energy System*: 1–12.

———. 2013. *World Energy Outlook 2013*. Paris: IEA. doi:10.1787/weo-2013-en. http://www.oecd-ilibrary.org/energy/world-energy-outlook-2013_weo-2013-en.

IHS CERA. 2013. “Keeping Europe’s Lights On.”

International Energy Agency and Nordic Energy Research. 2013. “Nordic Energy Technology Perspectives”. Paris.

ISO New England. 2013. “ISO New England - Glossary & Acronyms.” Accessed December 16. http://www.iso-ne.com/support/training/glossary/index-p6.html.

Jensen, Henrik R, and Jesper Jespersen. 2007. *Introduktion Til Mikroøkonomi / Erik Gaden, Henrik R. Jensen Og Jesper Jespersen*. Edited by Erik Gaden. Kbh. : Jurist- og Økonomforbundets Forlag.

Joskow, Paul L. 2013. “Symposium on ‘Capacity Markets’.” *Economics of Energy & Environmental Policy* 2 (2). http://faee.liane.net/files/file/aee/IAEE TOC/EEEP2013_2_editorial.pdf.

Koch, Jesper. 2013. “SURVIVAL OF LOCAL CHP PLANTS”. Copenhagen: Green Energy.

Lauge Pedersen, Sigurd. 2013. “Elforsyningssikkerhed – Hvad Er Det for Noget?” Copenhagen: Danish Energy Agency.

Lévêque, François. 2007. *Competitive Electricity Markets and Sustainability*. Edward Elgar Publishing. http://books.google.com/books?id=eQ2BRLrYW7wC&pgis=1.

Lidegaard, Martin. 2013. “Energiaftalens Analyser - En Midtvejsstatus”. Copenhagen.

Lund, H., and a.N. Andersen. 2005. “Optimal Designs of Small CHP Plants in a Market with Fluctuating Electricity Prices.” *Energy Conversion and Management* 46 (6) (April): 893–904. doi:10.1016/j.enconman.2004.06.007. http://linkinghub.elsevier.com/retrieve/pii/S0196890404001463.

Lund, Henrik, Anders N. Andersen, Poul Alberg Østergaard, Brian Vad Mathiesen, and David Connolly. 2012. “From Electricity Smart Grids to Smart Energy Systems – A Market Operation Based Approach and Understanding.” *Energy* 42 (1) (June): 96–102. doi:10.1016/j.energy.2012.04.003. http://linkinghub.elsevier.com/retrieve/pii/S0360544212002836.

Manyika, James, Michael Chui, and Jacques Bughin. 2013. “Disruptive Technologies: Advances That Will Transform Life, Business, and the Global Economy.” *McKinsey Global* …. http://www.mckinsey.com/insights/business_technology/disruptive_technologies.

Ministry of Economic Affairs and the Interior. 2013. “Konvergensprogram Danmark 2013”. Copenhagen.

Montel Online. 2013a. “Nordic States Say Capacity Mechanisms Will Distort Markets.”

———. 2013b. “The Energy-Only Market’s Days Are Numbered.” *Montel Power News*.

———. 2013c. “Dansk Energibransje Savner Informasjon Om Kapasitetsmangel.”

———. 2013d. “National Capacity Market No Solution to Intermittency – Acer.”

———. 2013e. “German Capacity Market Splits Nordic Majors.”

———. 2013f. “Capacity Markets Likely to Continue in Medium Term – Shell.” *Montel Power News*.

———. 2013g. “‘ UK Capacity Market Only a Medium-Term Insurance Policy ’.” *Montel Power News*, September 5.

———. 2013h. “Capacity Mechanisms May Distort Energy Market – Acer.” *Montel Power News*, September 10.

———. 2013i. “EC Gears up for Capacity Payments Battle with Member States.” *Montel Power News*, November 15.

NEPP. 2011. “Results: Capacity Mechanisms.”

Nord Pool Spot. 2013. “Curtailment.” Accessed December 17. http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/Curtailment/.

———. 2013a. “No. 52/2013 - Nord Pool Spot to Introduce New Minimum and Maximum Price Caps.” http://www.nordpoolspot.com/Message-center-container/Exchange-list/2013/09/No-522013---Nord-Pool-Spot-to-introduce-new-minimum-and-maximum-price-caps/.

———. 2013b. “Trading and Services.” http://nordpoolspot.com/TAS/.

Näringsdepartementet. 2010a. *Förordning Om Effektreserv*. Näringsdepartementet. https://lagen.nu/2010:2004.

———. 2010b. *Lag Om Dels Fortsatt Giltighet Av Lagen (2003:436) Om Effektreserv, Dels Ändring i Samma Lag*.

O’Briain, Tadhg. 2013. “Generation Adequacy in the Internal Market : Guidance to Optimise Public Interventions”. Paris: DG ENER.

Rautkivi, Matti. 2013. “Flexibility Is Needed - but the Current Electricity Market Structures Don’t Reward It.” Accessed December 16. http://www.smartpowergeneration.com/spg/discussion/flexibility_is_needed_-_but_th.

Rautkivi, Matti, and Melle Kruisdijk. 2013. “Future Market Design for Reliable Electricity Systems in Europe.” In *POWERGEN Europe 2013*. Vienna.

SKAT. 2013a. “SKAT: E.A.4.4.7.1 Afgiftssatser.” http://www.skat.dk/SKAT.aspx?oID=2061637&chk=208670.

———. 2013b. “SKAT: E.A.4.5.6 Afgiftens Størrelse Og Beregning.” http://skat.dk/SKAT.aspx?oID=2060519&chk=208670.

———. 2013c. “SKAT: E.A.4.3.9.2 Satser for Afgiftslempelse.” http://skat.dk/SKAT.aspx?oID=2061613&chk=208670.

———. 2013d. “SKAT: E.A.4.3.6.1 Afgiftssatser Og Beregning.” http://skat.dk/SKAT.aspx?oID=2061620&chk=208670.

———. 2013e. “SKAT: E.A.4.4.10.2 Fordeling Af Brændsler Mellem El- Og Varmeproduktion i Kraftvarmeværker.” http://skat.dk/SKAT.aspx?oID=2061647&chk=208670.

Skov, Andreas, and Jens Åge S Petersen. 2007. *Dansk Fjernvarme i 50 År : 1957-2007 / Andreas Skov, Jens Åge S. Petersen*. Edited by Andreas Skov. Kolding: Dansk Fjernvarme and Odense Stadsarkiv.

Sommer, Morten. 2013. “Interview with Morten Sommer”. Fredericia.

Sornn-Friese, Henrik. 2007. *Hvad Er En Virksomhed? : Erhvervsøkonomisk Teori Og Analyse / Henrik Sornn-Friese*. Edited by Henrik Sornn-Friese. Frederiksberg : Samfundslitteratur.

Spees, Kathleen, SA Newell, and JP Pfeifenberger. 2013. “Capacity Markets - Lessons Learned from the First Decade.” *Economics of Energy and Environmental …* 2 (2) (April 1). doi:10.5547/2160-5890.2.2.1. http://www.iaee.org/en/publications/eeeparticle.aspx?id=45.

Stenvei, Michael. 2013. “Energibranchen Efterlyser Politisk Debat Om Forsyningssikkerhed.” *Jyllands-Posten*, September 24.

Stoft, Steven. 2002. “Power System Economics.” http://stoft.com/metaPage/lib/Stoft-2002-PSE-Ch-1-3,4,5,6.pdf.

Svenska Kraftnät. 2010. “OM REGLERKRAFTAFFÄRER.”

———. 2012. “Effektreservsupphandlingen 2012/2013”. Svenska Kraftnät.

———. 2013a. “Effektreserven 2013/2014”. Sundbyberg: Svenska Kraftnät. http://www.svk.se/Energimarknaden/El/Effektreserv/Effektreserven-20112012/.

———. 2013b. “Effektreserven.”

Svenska Kraftnät, and Fingrid. 2008. “Hantering Av Svensk Och Finsk Effektreserv På Nord Pool Spot”. Vol. 1.

The Economist. 2013. “European Utilities: How to Lose Half a Trillion Euros.” *The Economist*. http://www.economist.com/news/briefing/21587782-europes-electricity-providers-face-existential-threat-how-lose-half-trillion-euros?fsrc=scn/fb/wl/pe/howtolosehalfatrillioneuros.

Thrane, Mikkel, Arne Remmen, and Henrik Lund. 2007. *Tools for Sustainable Development*. Edited by Lone Kørnøv. Aalborg: Aalborg : Aalborg Universitetsforlag.

Tingkær, Eva. 2013. “Kraftvarmen i Alvorlig Fare.” http://www.danskenergi.dk/Aktuelt/Arkiv/2013/September/13_09_26A.aspx.

Vries, Laurens J. De. 2013. “The Impact of Renewable Energy on European Electricity Markets.”

Vries, LJ de. 2011. “Mandatory Long-Term Contracts for Renewable Energy: The Best of Both Worlds?” *Energy Market (EEM), 2011 8th International …* (May): 586–591. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5953080.

Østermark Andreasen, Peder. 2013. “Danmark Risikerer Grøn Fremtid Med Røde Tal.” *Altinget*. http://www.altinget.dk.zorac.aub.aau.dk/energi/artikel/danmark-risikerer-groen-fremtid-med-roede-tal.

Nomenclature

Capacity: Is generally applied for electricity generating capacity

CRM: Capacity remuneration mechanism. The concept of offering payment for capacity rather than energy.

DCHP: Decentral combined heat and power plants. CHPs which are relatively small and distributed across Denmark

DH: District heating

DKK: Kr., Danish kroner. 1 DKK = 0.13 EUR

DR: Demand response. Electricity consumers who can alter their consumption according to signals from the system or market

EOM: Energy-only market. A market where electrical energy is traded

EU ETS: European Union Emissions Trading System

EUA: European Union emission allowances. The equivalent of 1 tonne of CO_2 in the EU ETS

EUR: €, Euro. 1 EUR = 7.46 DKK

Load balancing responsible (LBR): makes plans for, and bid in with expected consumption

MW_e: Electricity capacity

MWh_e: One megawatt-hour of electricity

MWh_{th}: One megawatt-hour of heat

MW_{th}: Heat capacity

Nm^3: Normal cubic metre, assumed to have a lower calorific value of 39.6 MJ/Nm^3

PIP: Production-independent payment. The Danish term is produktionsuafhængigt tilskud or grundbeløb

Plant: Power plant

Producers and generators: Is generally used in the same meaning, i.e. electricity producing/generating entities

Production responsible party (PBR): administers the participation of DCHPs on the market

SR: Strategic reserve. The type of capacity remuneration mechanism that is studied in this project

VOLL: Value of lost load. The cost of not meeting the requirements for electricity-supply for the consumer. Also, the point where the consumer is indifferent if its demand for electricity is not met

VRE: Variable renewable energy. Energy from renewable sources which is variable due to the dependency on wind or sun

DCHP

decentralised combined heat and power

SR

strategic reserves

CRM

capacity remuneration mechanisms

EOM

energy-only market