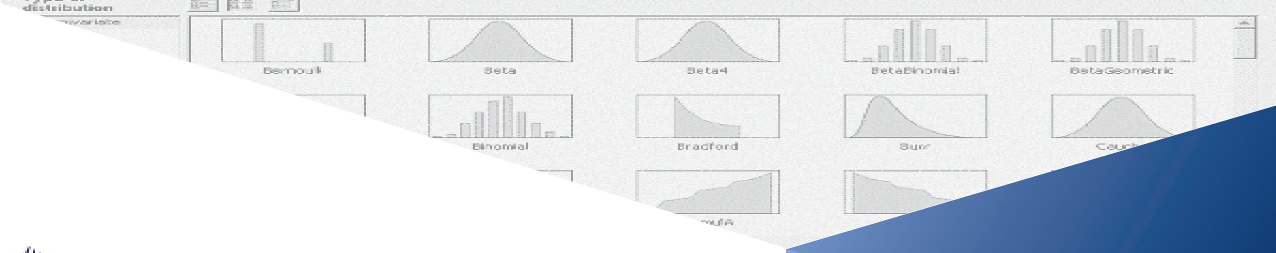
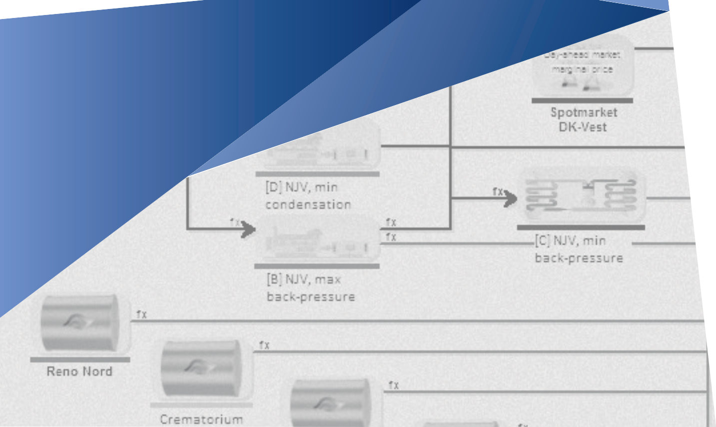


AALBORG UNIVERSITY

MASTER THESIS

Combining energyPRO and Monte-Carlo Simulation - an approach towards sustainable energy planning

Aalborg University - Spring Semester 2016



written by Heinz-Uwe Lewe
Supervisor: Anders N. Andersen

Sustainable Energy Planning and Management

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Synopsis

AALBORG UNIVERSITY
STUDENT REPORT

Combining energyPRO and Monte-Carlo simulation – an approach towards sustainable energy planning

Author: Heinz-Uwe Lewe

Supervisor: Anders N. Andersen

Program: Sustainable Energy Planning and Management

Semester: Spring 2016

A B S T R A C T

A successful transition towards a 100% sustainable energy system requires investments into renewable energy technologies. Public support schemes proved to be successful in stimulating such investments, but the financial burden grows and it puts economic pressure on renewables. To ensure the expansion of sustainable energy technologies, improved energy planning methods and better investment decisions are necessary. Therefore, potential benefits from combining two tools from different fields of studies are explored. EnergyPRO for energy system analysis is combined with Monte-Carlo simulation (MCS) which is usually applied for quantitative risk analysis in finance studies. Possible value creation through this synthesis is explored by using the future district heating system of Aalborg, Denmark's fourth biggest city, as an example. The system was modelled in energyPRO and scenarios were developed to represent different technological investment options. The tool synthesis requires a new definition of input variables for energy system analysis in the form of probability density functions. A method is presented on how to generate these. The results show that the combination of energyPRO and MCS generates output data that is only marginally more valuable. Scenario and sensitivity analysis could reproduce all main results from the previous MCS. The remaining benefit of this tool synthesis are statements about probabilities, which for obvious reasons cannot be generated from sensitivity or scenario analysis. A major drawback is the additional computation time that is caused by the large amount of repetitive calculations in energyPRO. After all, using MCS with energyPRO should only be considered if regular scenario or sensitivity analysis does not generate the required output quality for investment decisions.

THE GREAT TRAGEDY OF SCIENCE - THE SLAYING OF A BEAUTIFUL HYPOTHESIS BY AN UGLY FACT.

Thomas Henry Huxley

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AAK	Aalborg Kommune/Aalborg Municipality
BAU	Business as Usual
CDF	Cumulative Distribution Function
CHP	Combined Heat and Power
COP	Coefficient of Performance
DAH	Day-Ahead Market
DH	District Heating
DSO	Distribution System Operator
EIA	Environmental Impact Assessment
GoO	Guarantee-of-Origin
HP	Heat Pump
IEA	International Energy Agency
LHS	Latin Hypercube Sampling
MCS	Monte-Carlo Simulation
MMT	Million Metric Ton
NHPC	Net Heat Production Costs
NJV	Nordjyllandsværket
NPV	Net Present Value
O&M	Operation & Maintenance
OTC	Over-The-Counter
PDF	Probability Density Function
PEM	Polymer Exchange Membrane
PSO	Public Service Obligation
RE	Renewable Energy
SOEC	Solid Oxide Electrolyser Cell
TSO	Transmission System Operator

1 Introduction

The present chapter follows a spatial course. From a continent with 500 million people down to a single man's research question. The succession starts in Europe, looking at the latest trends in the heating sector and examining the role that district heating (DH) plays in here. Then, we will narrow it down to Denmark, a country in the centre of Europe, occupied by 5.5 million people and having a long DH tradition. Already in 1903, the first DH system was inaugurated in Frederiksberg, which could solve its waste treatment problem at the same time (DBDH 2016). Today, DH is an essential part of Denmark's heat supply system. Chapter 1.2 will give insights into the latest trends, looking specifically at fuel sources and production types. In a next step, Aalborg will get into the focus. The municipality is inhabited by around 200,000 people and located in the northern part of Jutland. The latest development of Aalborg's DH grid is described, both spatially and in terms of gross heat demand. Eventually, the research question, focal point of the previous elaborations, is formulated. Its genesis is explained and delimitations are drawn.

1.1 District heating in Europe

The perceived importance of DH in a future European energy system has increased considerably (Heat Roadmap Europe 2016). While a few years ago official EU Commission documents would expect its future decline, DH became a key factor in the new EU Strategy on Heating and Cooling, published in February 2016. The heating and cooling sector consumed 50% of Europe's final energy consumption in 2012, which made it the biggest of all energy sectors (EU Commission 2016a). It is now an EU priority to make this sector more efficient and sustainable. DH is acknowledged as an essential contribution towards an accomplishment of these goals. The motivation behind this is to reduce the energy import dependency (especially of natural gas), to lower private and commercial expenses and to fulfil the pledges under the climate agreement which was negotiated at the COP21 climate conference in Paris this year. In 2012, 82% of the EU's primary energy supply for heating and cooling was based on fossil fuels (EU Commission 2016a). The largest share (46%) is covered by natural gas (Figure 1.1). With 11% biomass has the largest share among renewable sources.

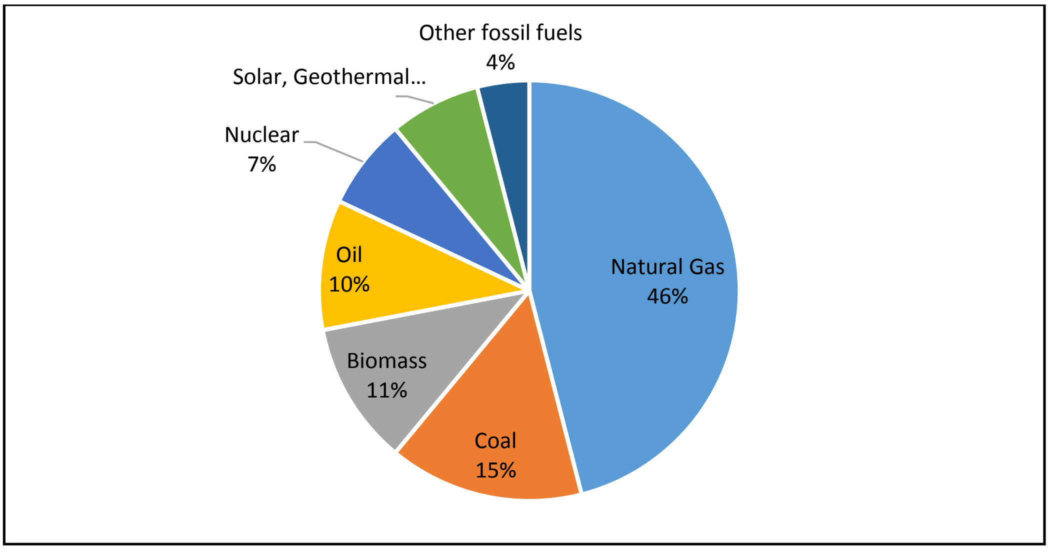


Figure 1.1: The EU-27's primary energy supply for heating and cooling in 2012; based on data from EU Commission (2016a)

According to the EU 2020 goals, 20% of the gross final energy consumption shall come from renewable sources in 2020 (EU Commission 2016c). Each energy sector has different targets, e.g. the transport sector shall only achieve 10%, the electricity sector is expected to have 34% and heating and cooling shall have a renewable share of 21%. Each member state is obliged to develop a national action plan to promote renewable energy (RE) sources. Such plans also state the member's individual targets. Denmark's goal is to have a 30% renewable share of its gross final energy consumption by 2020 (EU Commission 2014b). For its heating sector the target is set to 40%. In 2013, Denmark's RE share of its gross heat demand was already close to 35%. Though, according to the latest EU tracking report, Denmark has just missed its interim targets, but growth rates are still sufficient to achieve the 2020 targets (Spitzley et al. 2015). Generally, most EU member states are on track to achieve their 2020 targets. Only a few have missed their interim targets, but most of these have missed it only slightly.

As mentioned above, the latest EU strategy on heating foresees DH to play a major role in a future, decarbonized and sustainable energy system. Its advantages to integrate renewable excess electricity, waste heat and municipal waste are stated explicitly. Since the importance is now underlined, it is worth having a look at how DH is developed in the different member states. Euroheat & Power, an organization working for the EU and promoting research and development concerning district heating and cooling, provides statistical data on such issues. The latest, freely accessible EU country overview on district heating and cooling was published in 2013, referring to data from 2011. The Baltic and Scandinavian countries have a very extensively developed DH system. In Lithuania and Latvia more than 65% of the private households are connected to a DH grid (Euroheat & Power 2013). Denmark's share is slightly above 60% and Sweden, Finland and Estonia are around or even above 50%. Least developed in these terms are France, Italy, Netherlands, the UK, Norway and Switzerland. All of them have a share below 10%.

This trend is also roughly reflected when examining the share of DH sales with the total heat demand (Figure 1.2). It becomes obvious that there are large differences between advanced and less advanced countries within the EU. While Estonia covers nearly 80% of its total heat demand with DH, Italy does not even cover 4% of it. Similar to the performance in household connections, Scandinavian and Baltic countries reach a generally high share. The relativity displayed in Figure 1.2 should be mentioned here. Germany has the highest total DH sales among all countries (280 PJ), but it also has the highest overall heat demand, which results in a share of only 6%. With DH sales of 102 PJ Denmark can cover 58% of its total heat demand. Only Sweden and Czech Republic show higher values. Finland shows a surprisingly low share (27%), considering that 50% of the private households are connected to DH systems.

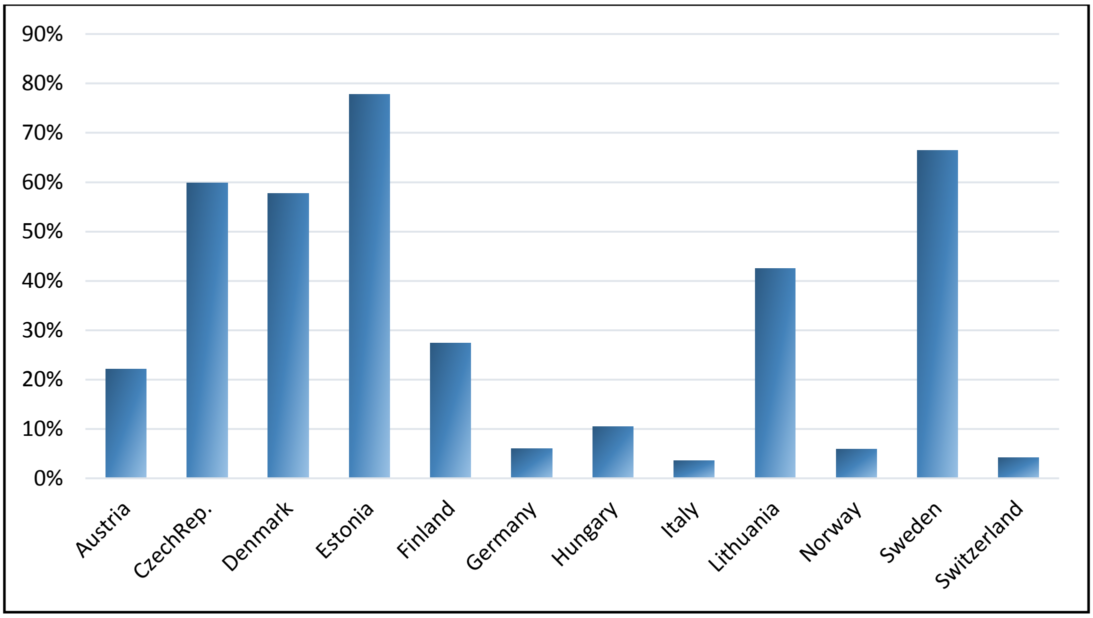


Figure 1.2: Total DH sales as % of total heat demand in 2011; based on data from Euroheat & Power (2013)

1.2 District Heating in Denmark

The present chapter describes the latest trends of DH in Denmark. The Danish Energy Agency (Danish: Energistyrelsen) publishes the national energy statistics at the end of each year for the previous year. In 2014, 63% of all private households in Denmark were connected to a DH system (Energistyrelsen 2015a). This covers both, space heating and domestic hot water. In Denmark, one distinguishes between central and decentral DH areas. The bigger Danish cities comprise six central DH areas which represent 56% of Denmark's total DH supply. The remaining share is supplied by around 400 small and medium-sized DH grids (Energistyrelsen 2015a).

In 2014, 70% of the national DH production could be traced back to CHP production (Energistyrelsen 2015a). Compared to 2005, this share was 83%, but since then it has continuously decreased. It shows that DH production from CHP is slowly decreasing, while other forms without the simultaneous production of electricity are increasing. Generally, DH production can be divided according to its origin into central CHP, decentral CHP, pure DH production and secondary production. The latter one comprises waste incinerators or industrial production. Central CHP production still covers the largest share of Denmark's DH generation, even though it decreased over the last 20 years (Figure 1.3). During the 1990s the production from decentral CHP increased, then it stagnated in the early 2000s and it has dropped since then. Secondary production has increased slightly but steadily. This is straightforward as industrial production or heat from waste incineration does not follow actual heat demand. The other types respond to the actual heat demand which can be clearly seen in 2010 and 2014. While the former year had a cold winter, the latter one had a rather mild winter. In 2014, Denmark's total DH production was 122 PJ, compared to 120 PJ in 2000, showing a stagnation of DH production.

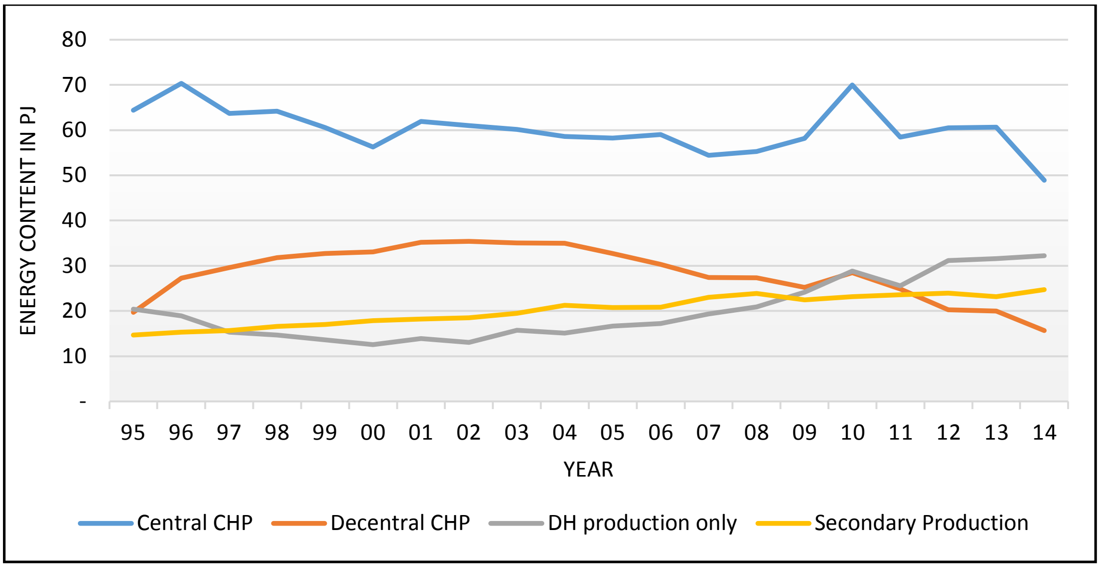


Figure 1.3: DH production in Denmark between 1995 and 2014; based on data from Energistyrelsen (2015a)

Looking at the fuel sources for DH production the last 20 years have shown considerable changes in that matter. Starting in 1995, coal was the dominant fuel for DH production with a share of nearly 40% of total production (Figure 1.4). Both, natural gas and renewable energies had a share of app. 25% and the rest was covered by non-renewable waste and oil. Electricity did not play any role in that matter and this has not changed until now. Besides a few exceptions, coal has steadily decreased since 1995 and covered only 16% of the total DH production in 2014. Natural gas shows a rather constant profile when looking at the last 20 years, but since 2010 it has decreased from 30% down to 24% in 2014. In contrast to that, renewable energies have experienced an ongoing growth since 1995, covering nearly 50% of Denmark's total DH production in 2014. Non-renewable waste had a rather constant development and it maintained a share of around 10%. Oil for DH production decreased considerably. It covered less than 3% in 2014.

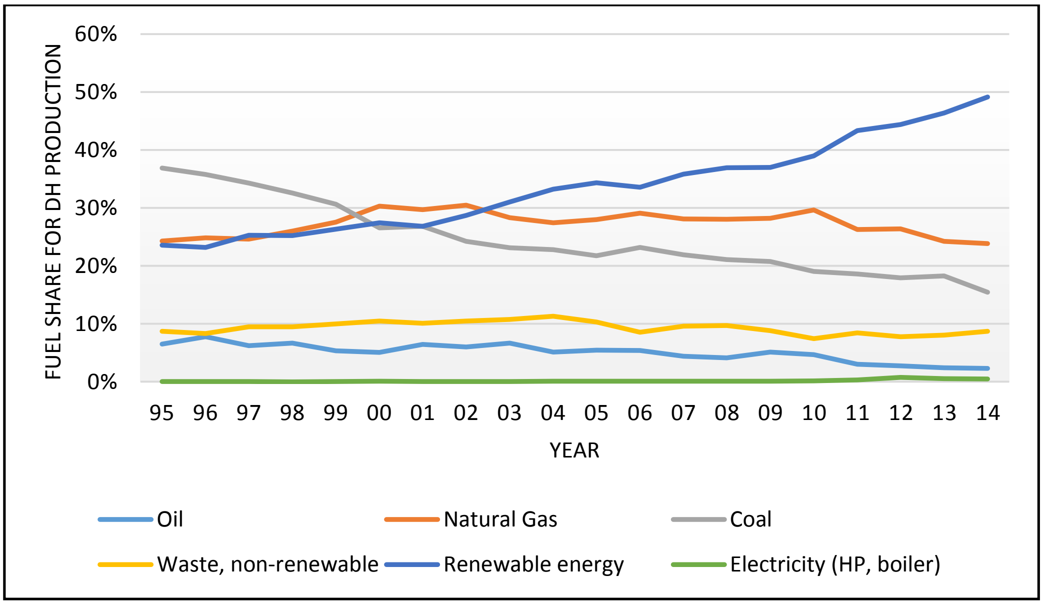


Figure 1.4: Fuel consumption for DH production in Denmark between 1995 and 2014; based on data from Energistyrelsen (2015a)

Covering almost 50% of Denmark's total DH production, it is worth to have a closer look at renewable sources for DH. During the last 20 years, the renewable share has been clearly dominated by biomass. Its annual share has always been above 95% of renewable DH production. Back in 1980, 90% of this biomass share was based on biogenic waste. The remaining share was straw and wood. Until 1990, these two sources had multiplied their share by factor 10 and the total DH production from renewables nearly tripled within 10 years. Until 2000, straw and wood had an almost similar DH production with each 25%. The remaining was covered by biogenic waste. Bio-oil was almost negligible back then (Figure 1.5). In the next 15 years wood increased by factor five, while straw had an increase of only 50%. Eventually, wood became the dominant biomass source for DH production, being responsible for 55% of the total biomass-based DH production.

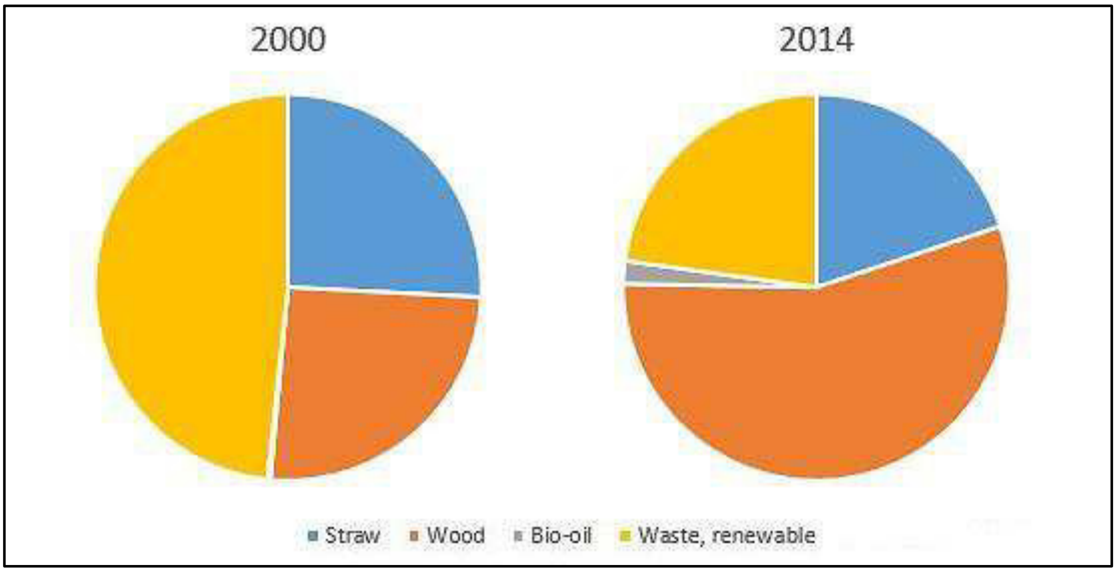


Figure 1.5: Biomass sources for DH production in Denmark; based on data from Energistyrelsen (2015a)

1.3 District Heating in Aalborg

The DH network of Aalborg Forsyning Varme, the local DH supplier, can be distinguished into a centralized and a decentralized grid. Both of them are marked with purple in Figure 1.6. The present thesis considers only the centralized grid. It starts in Tylstrup at the northern border of Aalborg Kommune (AAK), covers most of Nørresundby and Aalborg City and stretches down to Svenstrup in the south. The decentralized grid comprises two smaller villages, Hou and Farstrup-Kølby, which are located at the outer east and west of AAK. In 2014, the centralized grid had around 34,000 meter points with a total gross heat demand of 6,130 TJ (Aalborg Forsyning Varme 2015a). For comparison, the decentralized grid had an overall heat demand of 40 TJ, comprising 470 meter points. Within the central grid area, 99% of the total heat demand is covered by DH. The decentral area has a lower coverage rate of around 75% (Aalborg Forsyning Varme 2015b, 2014).

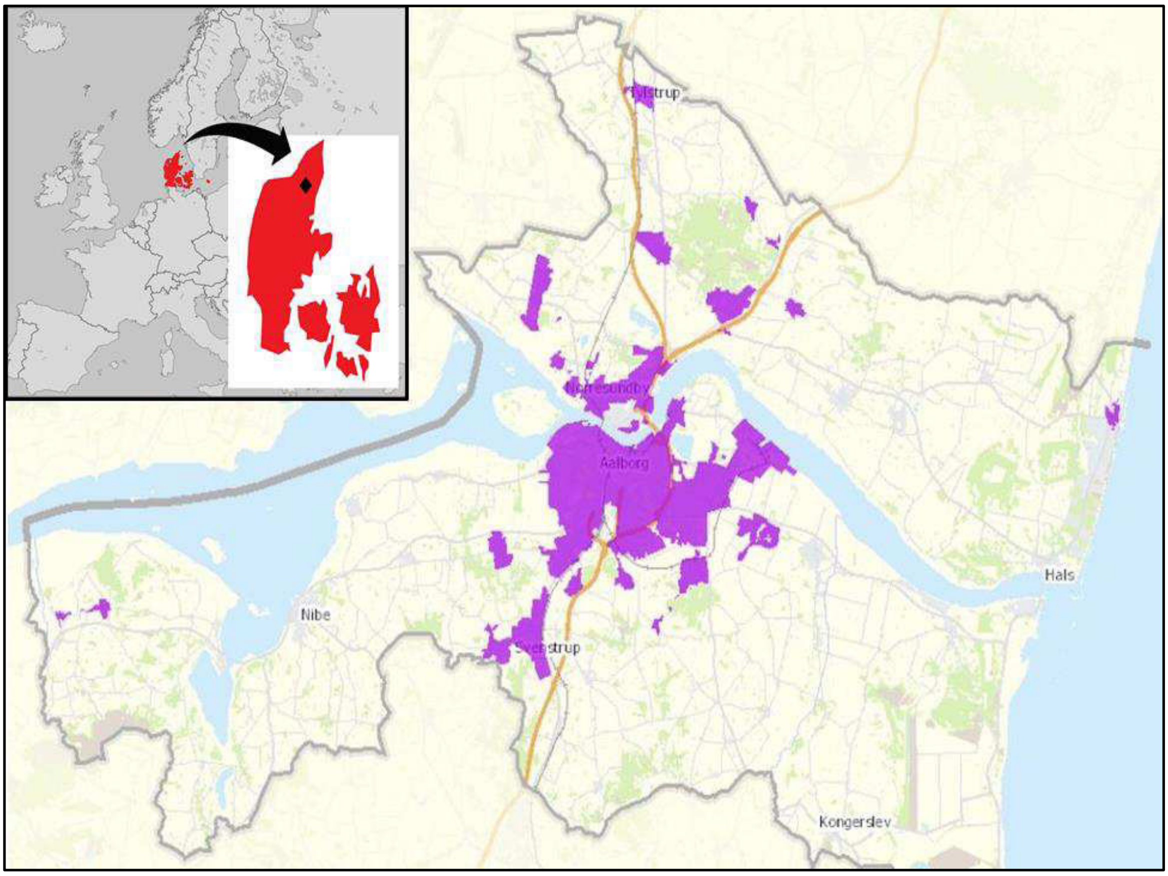


Figure 1.6: DH supply area of Aalborg Forsyning Varme; based on Aalborg Forsyning Varme (2016)

The centralized grid is mainly supplied by three large producers, i.e. Nordjyllandsværket (coal-fired CHP plant), Reno-Nord (waste incinerator) and Aalborg Portland (cement production). Together they cover more than 95% of the annual gross heat demand. Besides these three production units, there are several smaller producers, which deliver heat, e.g. the crematorium or the sewage treatment plant. Aalborg Forsyning also maintains 12 reserve and peak-load production units which secure heat delivery in case of outages or extreme temperatures. Chapter 2.2.1 provides more information regarding production units within the centralized grid.

Looking at the historical development of Aalborg's central DH grid, two major trends are obvious (Figure 1.7). First, during the last 10 years the number of customers has increased steadily. The system has experienced a growth of nearly 20%. With 29,000 connected meter points in 2004, the central grid is now connected to more than 34,000. The latest strategy plan foresees a continuation of this growth process, ending up at app. 37,300 meter points in 2019 (Aalborg Forsyning Varme 2015b). On the other hand, the annual gross heat demand stayed rather constant when one neglects the variations due to weather fluctuations. One explanation could be that the increasing demand from newly connected customers is offset by heat savings and grid loss reductions. In order to verify that it would be necessary to examine the degree-day normalized heat demand against the number of meter points. Unfortunately, the former data was not available and as a consequence this rough and visual conclusion is the best estimate for now.

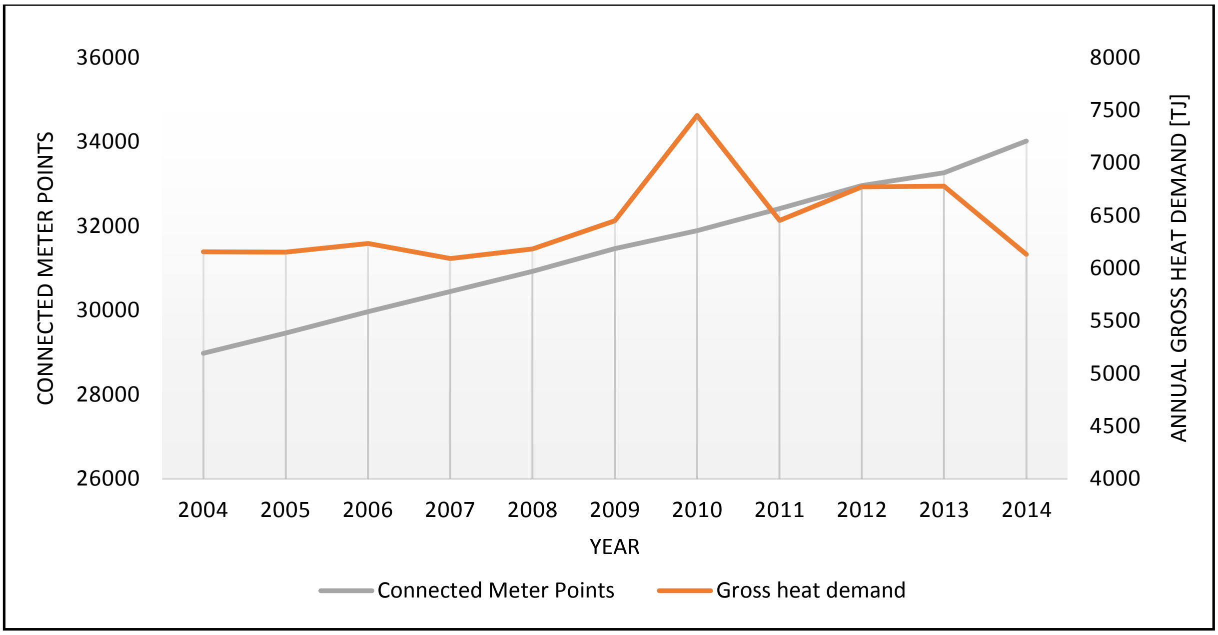


Figure 1.7: Annual gross heat demand against the number of meter points in the centralized DH grid; based on internal data from Aalborg Forsyning Varme

1.4 Developing a research question

The project started with a three-month internship at Aalborg Forsyning Varme. During the internship the focus was put on getting familiar with the local DH system, acquiring data and developing an energyPRO model of Aalborg's central DH system. At the same time the planning department of Aalborg Forsyning started a process to develop a so called *Forsyningskatalog* (English: supply catalogue). This catalogue shall give the politicians of Aalborg's city council guidance and recommendations for a future investment decision. It is an extensive assessment of alternative, renewable sources for Aalborg's future DH supply. Despite the just recent purchase of Nordjyllandsværket (NJV), the by far largest supplier of Aalborg's DH demand, it is planned to erect another DH production plant based on renewable energies in the near future. This is a reaction to Danish national legislation and planning. It is expected that by 2035 fossil fuels are no longer needed for power and heat generation in Denmark. Further, coal and oil shall already be phased out by 2030 (KEBmin 2013). In order to follow national requirements, AAK assess the possibilities of different renewable heat sources for its future DH system. The latest strategy plan mentions increased excess heat utilization, biomass, large-scale HP, geothermal and seasonal heat storage explicitly (Aalborg Forsyning Varme 2015b). The *Forsyningskatalog* is not entirely developed by the planning department of Aalborg Forsyning Varme itself, but the most well-known and biggest Danish consultancies will also contribute to it. The energyPRO model which was started during the internship is supposed to be used in the *Forsyningskatalog* as well.

Investment possibilities should be seen against the goal and vision statements of Aalborg Forsyning Varme (Aalborg Forsyning Varme 2015b). Among others, Aalborg wants to decrease its environmental impact from DH production. It is mentioned that security of supply is also a very important aspect, which implies to maintain a certain reserve and peak-load capacity. Aalborg Forsyning aims at making a great contribution to the national sustainability transformation. In other words, having a 100% RE DH system by 2035. The focus is put on a holistic approach, which means to integrate the different energy sectors. Further, the goal is to be among the best three DH suppliers within the national benchmark system, which compares the six largest Danish cities in terms of economic performance. Inevitably, the questions arises how one can give an appropriate recommendation in regards to

Aalborg Kommune's future investment decision? Or, from another point of view: How should Danish national energy planning be implemented in its fourth biggest city?

At the beginning, it was tried to establish a systematic approach towards this issue. Giving answers to future investment decisions can be done on different levels (Figure 1.8). From a broader perspective, one would probably conduct a socio-economic analysis in order to evaluate the impact on a national or at least regional scale. Socio-economic studies assume that the current economic system (legislation, fees, taxation, etc.) is not optimal for the implementation of technological change (Hvelplund, Lund 1998). The neo-classical approach would assume that the *invisible hand* will regulate market conditions to an overall, preferable state. Instead, socio-economic studies conduct a critical assessment of the current institutional context. Therefore, such studies often have a very long time horizon. They analyze the links between current legislation and a project's economic feasibility. Implementing new taxation schemes or abolishing old ones are typical steps in a socio-economic analysis. Since the project is done on a municipality level and Aalborg Forsyning has to give account primarily to its customers, the socio-economic perspective does not seem very suitable in this context.

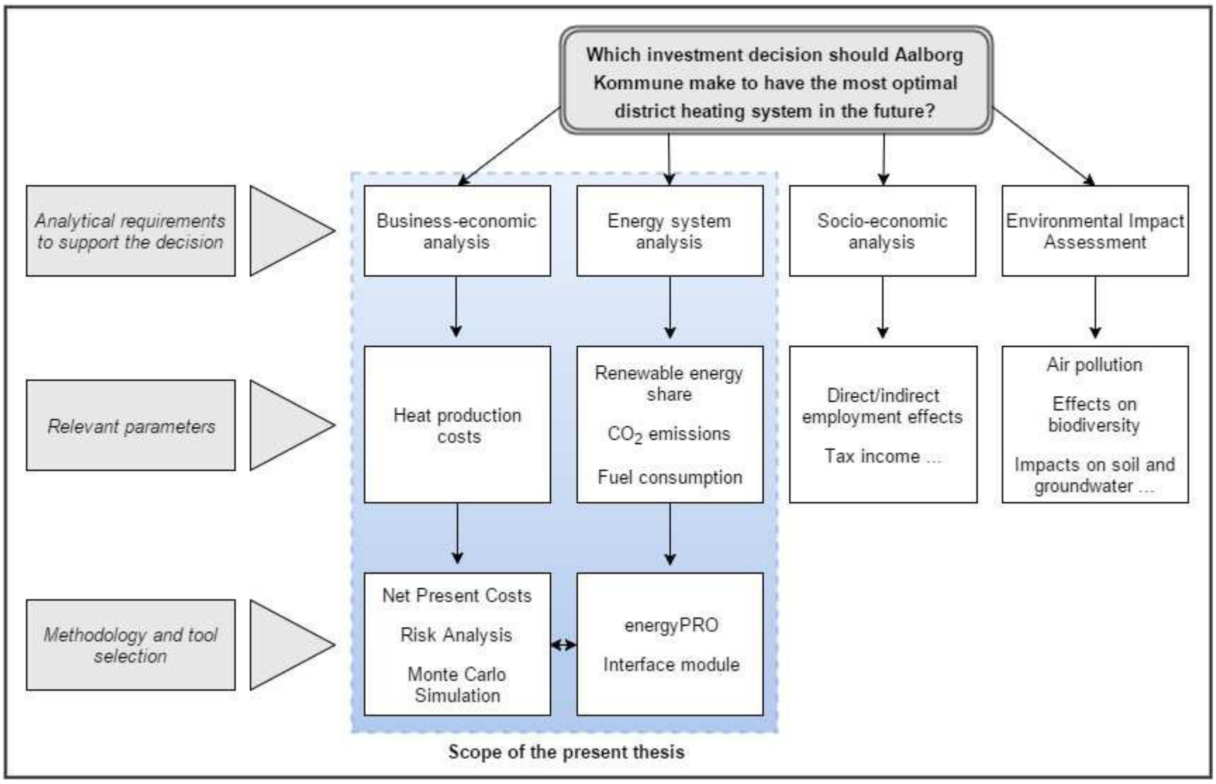


Figure 1.8: Analytical requirements overview and thesis delimitation (own graphic)

Another option to assess a project is to carry out an Environmental Impact Assessment (EIA). Optimally, an EIA reveals a project's effect on the environment before it is authorized and conducted (EU Commission 2016b). This ensures that environmental implications are taken into account before the final decision is made. In Europe, the basis for this is the EU-Directive 2011/92/EU. It regulates whether it is mandatory, voluntarily or not at all necessary to conduct an EIA for one's project and especially how such an EIA has to be carried out. This perspective does not seem to be suitable for the present thesis either. First, it would go beyond the focus of the master program within which this thesis is written. Second, AAK will review the necessity of conducting an EIA anyway, since it is a legal requirement.

Eventually, given the present context, a business-economic analysis with an energy system analysis seems to be an appropriate perspective. In contrast to a socio-economic study, the business-economic perspective assesses a project’s feasibility within the current legal and economic framework. It is not the aim to evaluate whether a certain tax should be abandoned or not, but whether the project is profitable for a single entity. One of the main parameters for Aalborg Forsyning are heat production costs. Obviously, other factors, such as security of supply are also relevant, but they are eventually measured against the resulting costs. Besides economic aspects, Aalborg Forsyning has formulated goals and visions for its future activity, which were described previously. These should be taken into account by doing an energy system analysis, which can assess CO_2 emission reductions, RE shares, etc. In the present context, energyPRO was selected as a tool for this analysis. A detailed reasoning for this decision is given in chapter 2.1. A business-economic analysis could make use of the Net-Present-Cost method or quantitative risk analysis, e.g. Monte-Carlo simulation (MCS). At the same time, energyPRO becomes a prerequisite to generate output data which are necessary for any subsequent business-economic study. Eventually, a combination of both tools could be beneficial for a thorough analysis and generate more valuable output data. This supposition leads to the core research question of the present master thesis:

How can Monte-Carlo simulation and energyPRO for energy system analysis be integrated to give recommendations for an investment decision?

This question shall be answered within the framework of AAK’s future DH system. In fact, this will lead towards two essential questions. One part focuses on the methodological aspect, examining in how far quantitative risk assessment can be integrated with techno-economic energy system analysis. What value-added results does it generate and in how far does it supply results for a better investment decision? This is described in the research question above. The other part will focus on a more practical aspect, i.e. giving an answer to the question which investment decision would be most favorable for AAK, based on the present methodological approach.

The motivation behind this research question is based upon the continuous economic and political pressure that RE technologies are facing. A successful transition towards a 100% renewable energy system cannot be taken for granted and it requires investments to overcome the current, fossil-dominated system. RE investments have received public support in various forms and their supply share has grown considerably. Such support schemes often reduce the investment risk as they guarantee revenue streams in form of feed-in tariffs, market premiums or the issuing of Guarantees of Origin (GoO). The expansion of RE capacity has also led to an increased financial burden which forces public decision makers to review support schemes. The Danish government has just recently proposed to cut subsidies for RE projects by EUR 2.7 billion until 2040 (Montel.no 2016b). Also the UK and Germany have made recent cuts on their RE subsidies (Carrington 2015; Franke 2016). In addition to that the German government plans to change its public support scheme for RE from market premiums and feed-in tariffs into an auctioning scheme (Montel.no 2016c). To a certain extent this is development comes natural, because RE technologies have steep learning curves and generation costs are falling. Nonetheless, renewable investments are facing smaller margins, which requires more robust investment decisions. This necessity calls for new approaches in the field of renewable energy planning. An integration of tools from different fields, i.e. energyPRO from energy system analysis and MCS from finance and econometrics, could enhance the quality of investments. Eventually, a good investment is nothing else than an efficient allocation of resources, which can only be in the interest of a transition towards a 100% RE system. The current project tries to contribute towards making better investment decisions in the renewable energy sector.

2 Methodology

The present thesis comprises two main methodological frameworks: techno-economic energy system analysis and risk analysis. For the first part energyPRO is chosen. It is a widely used software for energy system analysis. Its characteristics and the decision process for this tool are described in chapter 2.1. After that, the set-up of the reference model is presented and a validation assessment is carried out comparing the model's output data with historical data. The reference model served as a frame for designing four scenarios (cf. chapter 3). While three of them incorporate one additional DH technology, representing one possible investment opportunity for AAK, the other one represents a Business-As-Usual (BAU) case, where no investment takes place.

Eventually, the field of risk analysis is discussed, both from a theoretical and a practical point of view. Starting with the more theoretical part, the term risk is reviewed before the chapter moves on to risk analysis, especially in regards to renewable energy systems. After that, the Monte-Carlo method, a tool for quantitative risk assessment, is presented. It follows a presentation of ModelRisk, a software for applied MCS, which was chosen for the present thesis. The chapter ends with a brief introduction into the typology of scenario design.

2.1 EnergyPRO as a tool for energy system analysis

EnergyPRO is a module-based software for in-depth energy system analysis. It offers combined techno-economic optimisation and analysis of co- and trigeneration projects (EMD International A/S 2016). It is now commercialized by EMD International A/S, having its main office in Aalborg. It is an integral part of the master programme *Sustainable Energy Planning and Management* at Aalborg University. More than 50 versions have been released in the last 20 years (Connolly et al. 2010). Potentially, energyPRO is able to model all kinds of thermal generation units (except nuclear power) and most renewable energy technologies. Though, it was initially developed for the optimization of a single thermal or CHP power plant within smaller energy systems (Connolly et al. 2010). The software is based on the design module, which optimises the techno-economic performance of the energy system model within a defined time period. Usually, this period is one year. EnergyPRO follows a deterministic approach, which is based on user-defined inputs, such as time series, fuels, energy conversion units, taxes, etc. Such time series can e.g. reflect a DAH power market and energyPRO would optimize the energy system by dispatching its power producing and/or consuming units in line with the defined DAH market. Storages add flexibility because energyPRO can then decouple present supply from actual demand and thus find a more optimal operation schedule.

EnergyPRO uses an analytical approach which is extensively described by Østergaard and Andersen (2016). Cornerstone of the optimization is a matrix which contains the total of production units on one axis and the total of time steps on the other axis (in this case 8760 hours) for each planning period. Each cell is defined by a priority number, which is stated in the operation strategy tab. One can either choose to minimize the net production costs and energyPRO will automatically calculate those priority numbers based on algebraic formula. The final number depends on which type of demands need to be satisfied and which costs were allocated to the respective unit. As an alternative one can also insert user defined priority numbers. The lower the priority number, the higher the actual priority in the energy system. In a system where it is only required to satisfy heat demand, the priority number is equal to the Net Heat Production Costs (NHPC). Figure 2.1 shows how this is graphically presented in energyPRO. In this case NHPC are shown with spot prices. The two reserve units have a horizontal NHPC line, since their priority is not depending on spot prices. Opposite to that, [B] NJV shows decreasing NHPC with increasing spot prices. Both, the compression HP and [C] NJV have increasing NHPC with increasing spot prices. The intersection points indicate at which spot prices a unit becomes cheaper or more expensive than the other one. In energyPRO it is also allowed to define whether a plant can flow its production to the storage unit and whether partial load is allowed.

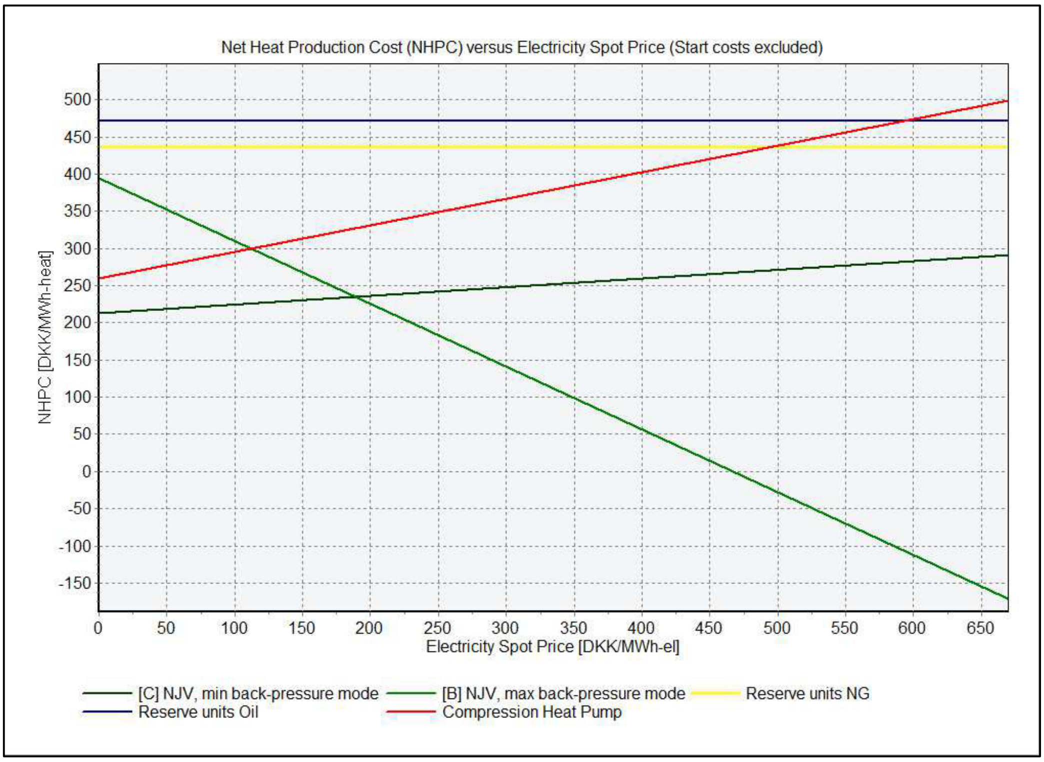


Figure 2.1: Graphical presentation of the production priority order in energyPRO; extract from the HP scenario

Having all priority numbers calculated for each cell in the matrix, energyPRO will start the production allocation in a non-chronological way (Østergaard and Andersen 2016). It starts by selecting the plant in the hour with the lowest priority number. Then, it controls whether there are any restrictions in terms of storage capacity or transmission congestions and after that it continues to the second lowest priority number in the matrix. This way, energyPRO schedules the annual production plan.

In the present analysis, energyPRO is configured in a way that it can foresee the exact spot price and dispatch production units accordingly. Hence, the system might be too perfectly optimized, which leads to results that would not be possible in reality. It is acknowledged, that energyPRO offers the possibility to use planning prices for the operation scheduling. In this case one would apply an interval function that flattens the real spot price curve depending on the share of extreme hours that one wants to take out for the prognosis. Østergaard and Andersen (2016) point out two reasons why it is nonetheless reasonable to apply perfect spot price forecasts: 1) Incorporating the prognosis function increases the computation time considerably, which in this case would have been a huge drawback. 2) The approach in energyPRO is similar to actual behaviour of plant operators. Also, from the author's own experience as a short-term power scheduler at an energy trading company it seems that the real settings are not that entirely different. All major European spot exchanges allow participants to submit their DAH schedule in form of a bid matrix with a considerable amount of price steps. Besides, just-in-case bids are also common practice in the industry. Together with highly advanced spot price prognosis this brings the present optimization method very close to real-life situations.

Other modules are built-up on the design module. The finance module supports economic analysis, which can cover the entire lifetime of a project. Given that the necessary input is provided, it can also calculate investment key parameters, such as payback time or Net Present Value (NPV). The Interface module is of outmost importance in the present thesis. This module allows the user to perform repetitive calculations in any energyPRO model. It uses an excel spreadsheet to define the desired changes in a specific energyPRO file. Then, it creates an xml file which is processed by energyPRO and the simulation is conducted based on the parameters that were predefined in the excel spreadsheet. The user determines which output data should be generated, e.g. cash flow, annual energy conversion, environmental performance, etc. After that, one can read each report individually or one uses the Interface spreadsheet to collect specific parameters from each report. With the Interface module it is possible to run several 100 simulations in one model without changing each and every single parameter manually. Eventually, this makes it possible to perform MCS with energyPRO.

In the last years, energyPRO has been widely used among energy researchers. Connolly et al. (2010) found energyPRO to be one of the tools for energy system analysis with the highest number of users worldwide. Kiss (2015) modelled the energy system of Pécs, a Hungarian city with app. 160,000 inhabitants and analysed impacts of the municipality's energy strategy. Østergaard (2012) investigated the impact of different storage technologies in a 100% RE scenario for Aalborg using energyPRO. Fragaki and Andersen (2011) assessed the economic profitability of aggregated CHP plants with direct market access and thermal storage. There are numerous other examples which show the wide range of applications of energyPRO. Besides its popularity, there are more reasons which make it an appropriate tool for the present study. First, energyPRO was introduced in the first semester of the above mentioned master programme and the author had used it in his first semester project. Thus, energyPRO had the advantage that the author could draw on some experience with this software. Besides energyPRO, the only other programme that would have such an advantage was energyPLAN. This software was used during the second semester project. It was found that its usage applies preferably to large-scale projects, e.g. at least regional or even national or supra-national. It also provides less detailed modelling opportunities, especially in regards to production units. Consequently, energyPLAN was disregarded. Another reason which favoured energyPRO was the fact, that the planning department of Aalborg Forsyning Varme also uses this software. They had already developed a basic model of the central DH grid, even though NJV was not considered as an integral part of this system. Until the acquisition in 2016, it was purely a heat supply unit. Still, it was possible to build up on this model for the current analysis, which made energyPRO an attractive option. During the course of this project, Aalborg Forsyning Varme decided to hire EMD International A/S for consultation purposes. Eventually, this made energyPRO the most reasonable tool for this thesis.

2.2 The reference model in energyPRO

In the previous chapter the reasons for choosing energyPRO were explained. In a next step its suitability to model Aalborg's central DH grid is assessed. During a three-month internship, real data of Aalborg's DH system was collected in order to design a reference model, representing the genuine, current DH system. This model is extensively described in the following chapters. In a continuous process, this model was adjusted until its output data would correspond as close as possible to the real characteristics of Aalborg's DH system (cf. chapter 2.2.3). Eventually, the model generates annual heat distribution shares which deviate less than 1% from actual data. Then, based on this model, three scenarios are developed, which cover different, presently available technologies, i.e. geothermal heat, large-scale compression heat pump and solar thermal. In addition to that a BAU scenario represents the option of making no investment. Other technologies were deliberately neglected, which is explained in chapter 3.4 - 3.6.

The heat demand of Aalborg's central DH network is modelled with an hourly time series. In the reference model, the actual heat demand from 2013 was used, as the total annual heat consumption of this year is nearly identical to a normal year's consumption. A normal year's heat demand is defined by the planning department of Aalborg Forsyning Varme as a year with a nearly average heat demand of the last 10 years. The demand in 2013 varies between 32 MJ/s and slightly less than 570 MJ/s. Aalborg's central DH system had a gross heat consumption of 1.88 TWh (6,778 TJ) in 2013 (Aalborg Forsyning Varme 2015a). This demand was mainly covered by three large heat suppliers, i.e. NJV (63%), Reno-Nord (20%) and Aalborg Portland (16%). These generation units are fuelled by coal and a mix of different waste resources. Besides, there are several smaller suppliers, such as the crematorium, the sewage treatment plants (biogas) and several reserve plants. There are two large-scale thermal stores in the system, each with a capacity of app. 1,000 MWh. A visual presentation of Aalborg's DH system in energyPRO is shown in Figure 2.2.

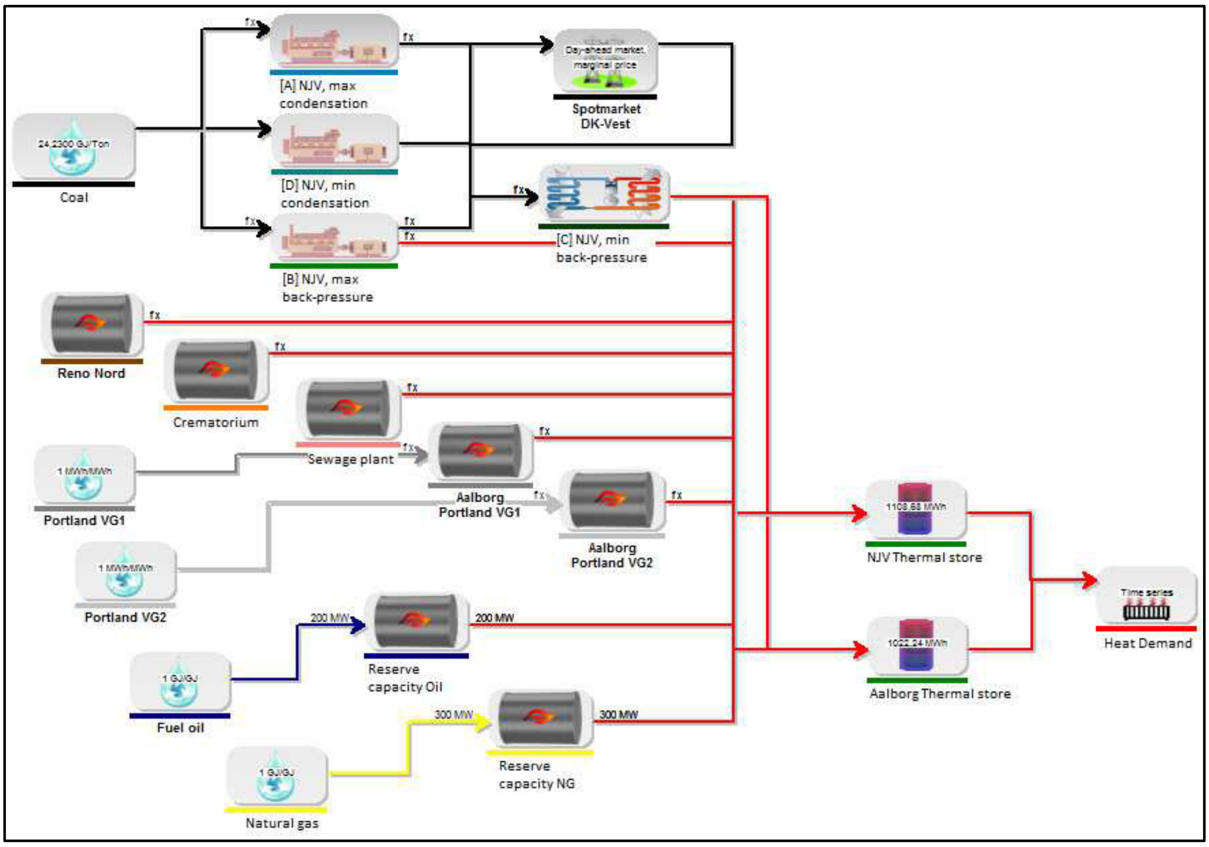


Figure 2.2: Aalborg's central DH system in energyPRO

2.2.1 Main production units

In the following, the different production units of the reference model are described. If it is not mentioned further, these units, as they are described below, have the same properties in all scenarios (cf. chapter 3).

Reno-Nord

Reno-Nord is a CHP waste incinerator, operated by the company I/S Reno-Nord which is indirectly owned by AAK. The generation unit comprises two incinerators: line 3 and line 4. The former one was erected in 1991, capable of burning 10 t waste per hour. This refers to a DH capacity of 18 MJ/s. Today, line 3 is only used for reserve purposes. Line 4 was commissioned in 2005 with a capacity of 22.5 t/h, an equivalent of 45 MJ/s heat capacity and 18 MW electric capacity (Reno Nord I/S 2016).

For the energyPRO model, only the heat output from Reno-Nord is considered, while the electricity production is of no interest here. From a DH-model perspective Reno-Nord is primarily a DH supplier, receiving compensation from Aalborg Forsyning for the energy delivered. The available amount of waste for heat production is limited to around 115 TJ per month. Since Aalborg Forsyning Varme has no direct influence on the heat production of Reno-Nord, it produces according to its historical production profile from 2013. Thus, energyPRO cannot use Reno-Nord's heat capacity for optimization purposes. Obviously, the monthly waste streams can vary, e.g. Christmas causes an increase, while during the summer holidays the waste stream decreases. Untreated waste, which incorporates a wet, organic fraction, is subject to immediate treatment. If stored without further treatment, the production of methane, leachate water or odour would follow. Therefore, municipal waste needs to be burnt instantly. Otherwise, waste would remain unused and storage would become necessary. Under the given conditions, long-term storage is not possible, although theoretically different options exist, such as Residual-Derived-Fuel (Gendebien et al. 2003; Münster 2009).

Nordjyllandsværket

NJV is a coal-fired CHP plant, formerly owned by Vattenfall, but recently purchased by AAK. Commissioned in 1998, it is supposed to be one of the most efficient coal-fired CHP plants in the world (Vattenfall A/S 2010; Santoianni 2015). At full back-pressure mode it has a DH capacity of around 400 MJ/s and an electric capacity of app. 300 MW (Vattenfall A/S 2010). It is assumed that NJV has an annual non-availability period for maintenance during the whole month of July. Due to confidentiality, exact parameters of NJV's operational possibilities are not mentioned here.

At first, NJV's energy output was modelled by a linear function starting at the minimum electric capacity and 0 MJ/s thermal capacity (condensation mode). Linearly increasing, it reached its maximum electric and thermal capacity at full back-pressure mode. In other words, this modelling approach assumed that for any electricity production between minimum and maximum electric capacity (at full back-pressure mode) there is only one heat production value possible. It was clear that this represented an over-simplification of NJV's actual operational possibilities. The approximate real range is represented by the striped area shown in Figure 2.3.

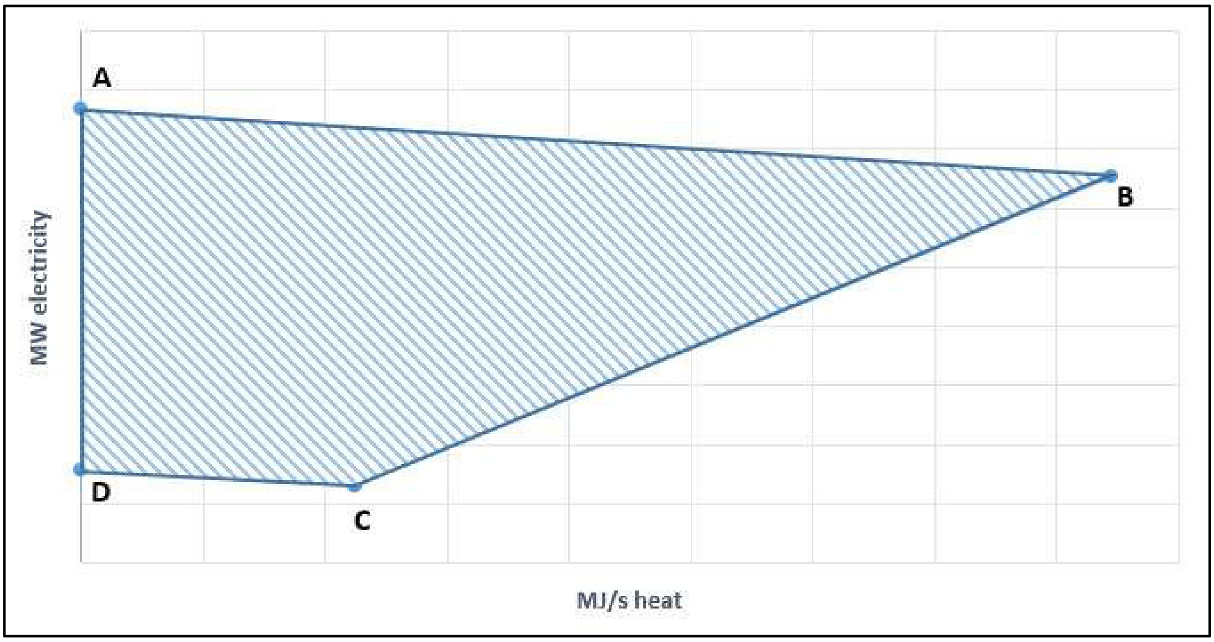


Figure 2.3: Operational range of NJV (adapted from Energistyrelsen (2015c))

NJV can operate at any point within this area. It implies that for an arbitrary electricity output between minimum electric capacity in condensation mode and maximum back-pressure mode, there is a range of possible heat outputs. The initial modelling could only reflect an energy output equal to a straight line between point D and B, even though the actual range lies within this area. When EMD International A/S got involved in the Forsyningskatalog project, the modelling of NJV could be improved considerably. The intellectual credit for the final design of NJV in energyPRO goes clearly to their consultation and input. In order to simulate NJV's operational range more accurately, four units are set up. They comprise two purely power producing units, one CHP unit and one electrical heat pump (Figure 2.4). While the former two units represent the operation at point D and A, the CHP unit is allocated at point B and the heat pump at point C. The operation of unit A, B and C is dependent on unit D, which needs to be active, before any other unit can start its operation.

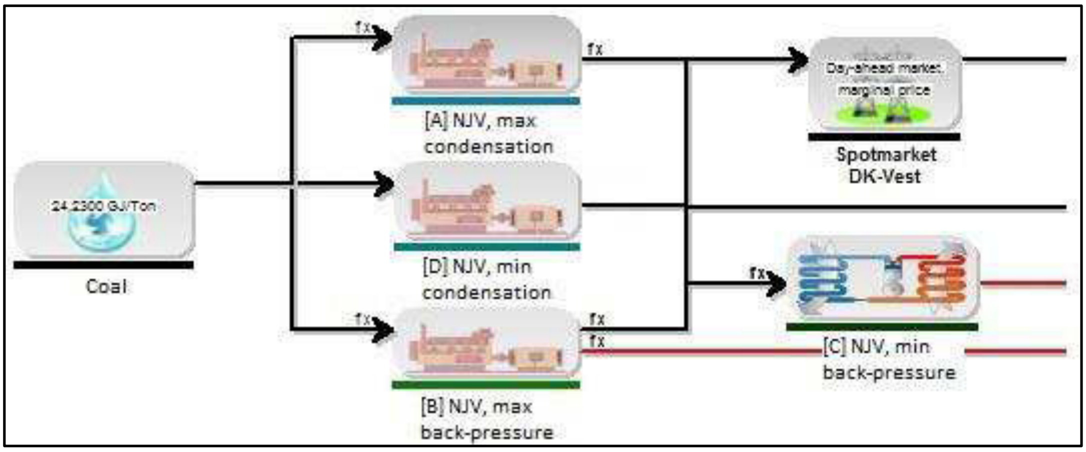


Figure 2.4: Advanced modelling of NJV's operational range in energyPRO

Unit D produces only electricity in condensation mode with an efficiency of 40%. Efficiency follows indications from Energistyrelsen (2015c) for an average, large-scale, coal-fired CHP plant. If unit D is operating, unit C can start. It is a heat pump with a certain heat output equal to point C and it basically illustrates the line between D and C. At maximum output, it has an electric load equal to the difference in electrical output between D and C, but simultaneously it generates a certain heat output. In a next step, CHP unit B allows NJV to operate along the line between C and B. Eventually, at all points between D-C and C-B, unit A can produce power with partial load, which will lift the operational mode perpendicular towards line A-B. In order to ensure that unit A does not exceed line A-B, a coal input limit is set. Coal fuel input against heat and electricity output at full back-pressure mode (B) reflects an overall efficiency of 91%, corresponding to statements from Vattenfall A/S (2010). For unit A it is economically only reasonable to operate when the DAH price exceeds the marginal production costs for 1 MWh of electricity. Therefore, a bidding price is modelled which simulates the marginal production costs. In case the DAH price exceeds the bidding price, unit A will start operation. The bidding price comprises the current coal price, NO_x tax, SO_x tax, variable O&M costs, CO_2 quota costs and a small feed-in-tariff which needs to be paid to energinet.dk, the Danish Transmission System Operator (TSO).

According to Danish taxation law, any CHP plant shall declare how much of its fuel consumption is either appointed to power or heat production (Skatteministeriet 2009). These shares are the basis for a CHP plant's payment of environmental and energy taxes. CHP plants can choose between two methods to calculate their output specific fuel consumption, i.e. the so called v- or e-formula. In this case v refers to heat (Danish: Varme) and e refers to power (Danish: El). The crucial part in this case is how much fuel is appointed to power production, because fuel for power production can be exempted from the Energiafgift and the Danish CO_2 tax (PwC 2015). One can be exempted from the latter tax, when the plant is subject to the European CO_2 quota system, which is the case for NJV. Based on the v-formula, fuel consumption for power production F_{el} is calculated as follows (Skatteministeriet 2009):

$$F_{el} = F_t - P_h/v$$

F_t is the total fuel consumption, P_h refers to final heat production and v = 1.2. The latter part P_h/v defines the fuel consumption for heat production. Though, the law prescribes that F_{el} has a maximum threshold value, equal to:

$$F_{el,max} = P_{el}/0.35$$

Here, P_{el} is equal to the CHP plant's power production. It limits the amount of fuel which is free of taxation. The law prescribes that one shall always apply $F_{el,max}$ when $F_{el} > F_{el,max}$. Besides the v-formula, it is also possible to apply the e-formula which is defined as:

$$F_{el} = P_{el}/e$$

In this case, e is defined as 0.67. From the formulae above one can deduct that the higher the heat production in relation to the total fuel consumption, the more likely it is that the v-formula would give the most profitable tax declaration. In other words, the v-formula would define a higher fuel volume which is appointed for power production and thus free of taxation. On the contrary, the higher the power production share in relation to the total fuel consumption, the more probable it is, that one should apply the e-formula for its tax declaration. Without any in-depth analysis on which formula would be more favourable for NJV, it was decided to apply the v-formula in the current energyPRO model. Both Energiafgift and Danish CO_2 tax are only applied to the heat production of NJV.

Start-up and shut-down period, start-up costs, fixed and variable operation & maintenance (O&M) data were defined according to indications from Energistyrelsen (2015c).

Aalborg Portland

Aalborg Portland is a cement factory in the east of Aalborg and Denmark's single biggest energy consumer (Alberg Østergaard et al. 2010). It consumes app. 2.4% of the total primary energy demand in Denmark. It is part of the Cementir Group, an Italian holding company. The cement production generates a vast amount of excess heat. Part of this excess heat is delivered to Aalborg's central DH grid through two different generation units. Similar to Reno-Nord, the heat production from Aalborg Portland is independent from heat demand and therefore both units are modelled with their production profile from 2013. According to these profiles, Portland VG1 has a maximum heat capacity of 46 MJ/s with an annual average of 23 MJ/s. Portland VG2 can deliver up to 27 MJ/s and showed an annual average of 11 MJ/s. Aalborg Portland covers app. 20% of its energy demand with renewable fuels, such as industrial waste, slaughter waste or dried sewage residues. The remaining energy consumption is supplied by coal, pet coke or oil (Aalborg Portland A/S 2015).

Reserve plants

The reserve plants comprise 12 boilers and 3 CHP plants. As the name already indicates, they are operated either for backup in case of outages or for peak load situations. The reserve plants are fuelled with natural gas or oil. Their contribution to the annual gross heat demand of Aalborg's central DH grid was less than 1% in 2013 (Aalborg Forsyning Varme 2015a). For simplicity reasons the 15 units are bundled in two boiler units, with 300 MJ/s and 200 MJ/s capacity respectively, differentiated by their fuel input. The amount of reserve capacity is determined according to a worst-case scenario in which the two biggest district heating suppliers fail in a peak load hour during winter season.

Small-scale production units

These units comprise the crematorium and the two local sewage treatment plants. They have a capacity of less than 4 MJ/s and contribute with less than 1% to the annual gross heat demand (Aalborg Forsyning Varme 2015a). Since operation is independent from Aalborg's heat demand, operation is modelled according to their 2013 production profile.

2.2.2 Modifications in energyPRO for MCS with Interface

In order to conduct a MCS by using Interface for energyPRO it was necessary to make some adjustments in regards to the initial reference model. First, the heat demand was modelled with an hourly time series that showed real gross demand values of Aalborg's central DH grid. The MCS does only generate random values for the annual heat demand, but not for every single hour during the year. Thus, it was decided to take out the time series and use a fixed annual heat demand instead. EnergyPRO allows to define a dependent fraction of the fixed heat demand, which in this case was set to 65%. Following a rough estimate, one can assume that 20% of the demand in an average DH system are due to transmission losses. Domestic hot water demand accounts for another 20% and the remaining 60% refers to space heating (Østergaard and Andersen 2016). Different shares between 50-80% were tested and 65% was found to be the most accurate, using visual comparison (Figure 2.6). In a next step, one can specify a formula to determine the dependent fraction. In this case it was decided to apply the degree-day method which is pre-installed in the heat demand section. By default, energyPRO uses a reference temperature of 17 °C. If the outdoor temperature in a given hour exceeds 17 °C, the dependent fraction is 0. If it is below the reference, the difference between 17 °C and the actual outdoor temperature is multiplied with a factor in MW/°C and a constant factor is added to that. The factor depends on the fixed heat demand and the dependent fraction. Finally, the independent fraction is added to this.

Besides outdoor temperature, consumer behavior plays a decisive role for the hourly heat demand. Looking at actual daily profiles, one can see two peaks which occur in the early morning and the late afternoon. In order to reflect this, one can create a fixed daily profile in energyPRO (Figure 2.5). It allows to redistribute the daily heat demand by defining ratios for certain hours. The daily demand around noon and during the night is only 68% of the demand during the two peak periods. Obviously, this is not the most precise profile, but it roughly reflects the behavior which was found in several samples from the actual hourly heat demand. It was found that the ratio of minimum and maximum heat demand during the day can go up to 80% on a cold winter day and down to 60% during a mild spring day. Therefore, 68% for the current profile was found to be an acceptable value. It also seemed to be more accurate to use a rough daily profile instead of using no profile at all. Comparing actual hourly heat demand with hourly temperature showed clearly that correlations exist on a long-term basis, but on a daily basis the consumer behavior is much more decisive than temperature fluctuations.

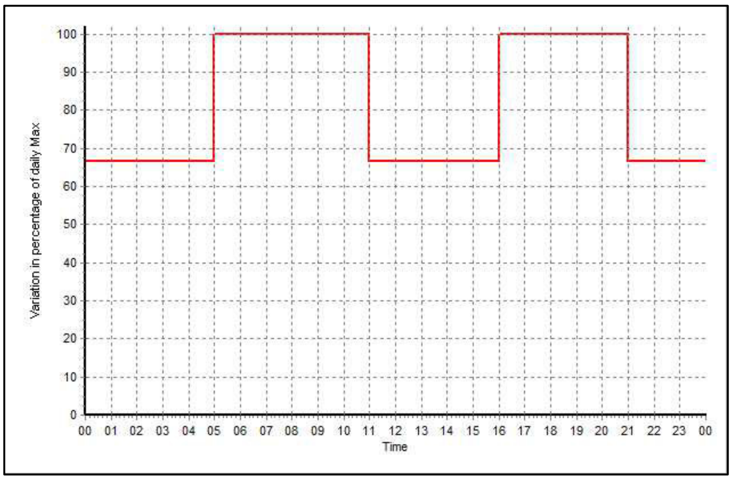


Figure 2.5: Daily profile of the newly modelled heat demand

Overall, it was found that this method generates an annual profile which is fairly close to the real profile (Figure 2.6). Both show an absolute peak load end of January at slightly over 550 MJ/s. The general profile course is relatively similar. The highest demand can be observed from mid of January until beginning of April. After that it falls down to a low plateau level. Between July and September demand fluctuates somewhere between 50 and 100 MJ/s. The newly modelled demand profile has an absolute minimum which represents the remaining independent fraction in each hour. By early September, demand increases again.

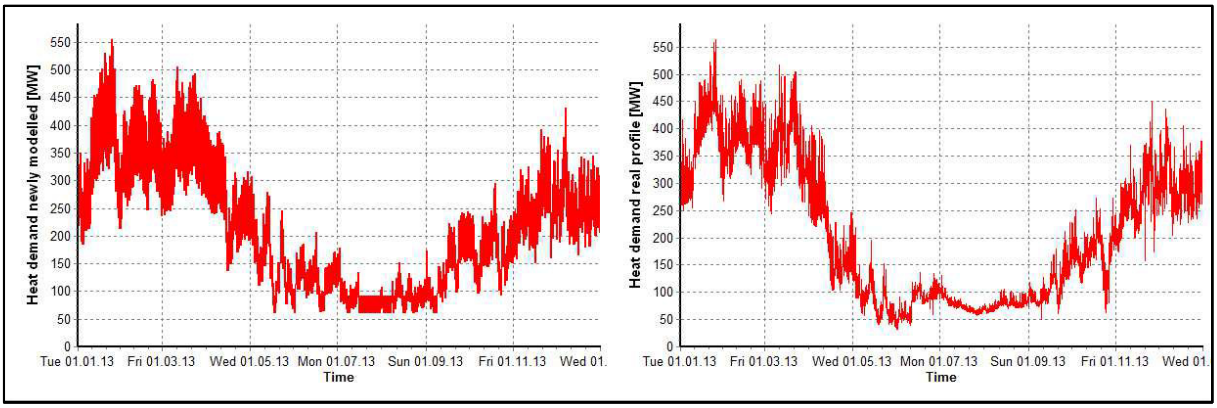


Figure 2.6: Comparing annual heat demand profiles – the actual time series and the new modelling approach

Similar to the heat demand, hourly DAH price values are modified in the MCS via a single annual spot price. Even though Interface allows the user to replace whole time series, it seemed more favorable to keep the basic profile from 2013 and adjust hourly values by a variable factor. Since the heat demand profile is based on 2013, it seems reasonable to keep the 2013 DK1 DAH price profile for reasons of uniformity. Further, a certain correlation between outdoor temperature and spot price setting is assumed which automatically recommends to use profiles of the same year. Eventually, it is less complex to appoint a variable based on annual spot prices to one single time series instead of creating one thousand new time series and feed them into Interface. In 2013, the average annual DAH price in DK1 was 282 DKK/MWh. The energyPRO model was modified in a way, so that the hourly 2013 DAH prices are multiplied by factor, which equals the randomly generated annual DAH price from MCS divided by 282 DKK/MWh.

2.2.3 Model Validation

The model's validity is assessed in two different ways. One way is to compare the model output data with actual data from 2013. Another way would be to examine the operation profiles and conduct a plausibility check. Both approaches are presented in the following.

As a key characteristic of the current model the annual heat production shares were compared with each other. It was found that the historical data and the data generated by the reference model show a very high degree of conformance. In absolute terms, the deviations are less than 1% of the total heat production. There are no differences between the two different operation strategies in energyPRO, both resulted in equal production shares. It should be mentioned that there is a small deviation between the total heat demand according to the Green accounting catalogue of Aalborg Forsyning and the provided hourly data. The total heat demand based on hourly data is 3% below the value specified by Aalborg Forsyning Varme (2015a). For now, it cannot be explained what causes this deviation. The reserve plants show a higher relative deviation, considering that their generation share in the model is only 40% of what it was according to actual data from 2013 (Table 1). This could be explained by the fact, that the actual maintenance period of NJV was longer than 4 weeks. According to the reference model, reserve plants are mostly producing during the non-availability period of NJV. Thus, if the maintenance period was extended, then the reserve plants' operation hours would increase. Besides planned maintenance, there are obviously also unplanned outages, which would require reserve unit production. These unplanned outages have not been incorporated in the reference model at first. In order to reflect unplanned outages in the future scenarios, two "unplanned" outages each lasting 24 hours were randomly implemented. With those two outage days included the reserve plant's production share gets very close to what actual data provides. Otherwise, it might also be the case that Aalborg Forsyning has internal guidelines which foresee an annual minimum operation time for each reserve plant to assure its functionality. This would not be represented in the model.

	NJV	***Reno-Nord***	***Aalborg Portland***	***Reserve plants***
Actual Share 2013*	63.1%	20.3%	15.7%	1%
Reference Model	62.6%	21.1%	15.8%	0.4%

*Table 1: Comparing the annual heat production share between simulated and historical data. *according to Aalborg Forsyning Varme (2015a)*

EnergyPRO provides a graphical presentation of the operation profiles in combination with other time series, such as spot prices or heat demand. From these it can be easily seen which production units are operating in any given hour and how this corresponds to other parameters. Figure 2.7 shows the production profile for three days in March comprising spot prices, heat and electricity production and the thermal storage content. In the upper profile one can observe the daily price peaks, which occur around noon and 6-8 p.m. On Thursday, these peaks are most notably. The heat profile shows that Reno-Nord and Aalborg Portland are running almost constantly during all hours. Unit C [NJV] runs nearly evenly as well, but it is interrupted by hours of high spot prices, where it is not feasible to run a unit, which converts power into heat. Unit B [NJV] operates on top of unit C, sometimes exceeding heat demand in order to fill up the thermal storage. Similar to B [NJV] it runs primarily during hours with lower spot prices. The electricity profile shows that D [NJV] is running constantly, which is reasonable, as start-up costs for NJV are high and short-term shut downs would not be plausible. It is also straightforward that A [NJV] only runs during hours with high spot prices and during most of these hours C [NJV] is not running. This reflects situations where NJV is running in full condensation mode to profit from maximum electricity sales at the spot market. The storage is utilized actively to cover those hours where A [NJV] is running and heat supply is below demand. The graphic shows that at full storage content it is easily possible to allow full condensation mode for 10-11 hours, given the specific heat demand during these days. Of course, with a changing heat demand this time window will change as well.

Figure 2.7: Operation profile of the reference model between 16-03 and 18-03

2.3 Risk analysis

The concept of risk is first explained from a broader, more theoretical perspective. During the following sub-chapters, this perspective is narrowed down. After looking into existing approaches of risk analysis for renewable energy systems, the focus moves to quantitative risk analysis and later MCS in particular. The risk analysis methodology ends with a brief introduction into ModelRisk, a software for MCS, which was chosen for the present thesis.

2.3.1 What is risk?

The following chapter discusses the concept of risk. First, the author explains his own understanding of risk. What does this term imply? In which contexts can it be used and what is the opposite of risk? After these questions are answered, the understanding of risk is extended through literature input. How do other authors conceptualize risk? Are there contradictions to the initial explanation or have certain aspects been neglected? Therefore, the risk concepts of Vose (2008) and Aven (2008) are examined with a special focus on aspects which are relevant for risk analysis.

Giving an answer to “What is risk?” leads to the question of how risk is actually created. In other words, what is the origin of risk and where does it come from? Intuitively, one relates risk to the future, because it is full of uncertainties. It is not possible to foresee the future with 100% certainty. After decades of advanced weather forecasts, every report still incorporates a certain level of uncertainty. Contracts are made to avoid risk and to be sure that one can expect a precise outcome in the future, nonetheless every contract can be breached. Plans can fail, strategies go wrong and arrangements flop. A recent study published by the Hertie School of Governance, Berlin showed that public, large-scale projects in Germany were on average 73% more expensive than estimated (Kostka, Anzinger 2015). In this study 170 large infrastructure projects between 1960 and 2014 were analysed. Likewise, large-scale projects in the energy sector show an average cost increase of 136%. Though, there are big differences within the energy sector. Especially nuclear power projects show high cost overruns in comparison to other energy technologies. Large offshore wind parks were only 20% more costly than originally planned (Kostka, Anzinger 2015).

If it is assumed that every action which will happen in the future incorporates uncertainties, then any event in the future must always include risk. Though, this temporal aspect alone is insufficient for a comprehensive explanation. There is another level, which is an inevitable prerequisite for the creation of risk and this is the aspect of expectations. A future event can have various possible outcomes and thus consequences and still, these might not be perceived as a risk. This is due to a lack of expectations in regards to the future outcome. Expectations do not exist when one is not directly affected by a certain outcome or when one is indifferent towards it. Climate change gives a good example in this case. If climate change is defined as a risk increase of natural disasters in certain regions, then the ones who are not affected by these disasters are less likely to perceive climate change as a severe risk. Simultaneously, one could be indifferent towards the risk of climate change, when one has sufficient adaptation capacity, i.e. resources to avoid the negative consequences.

The opposite of risk is opportunity. Normally, risk is perceived as a negative and possible outcome of any future event. Though, also the opposite can take place. When projects can become more expensive than initially calculated, it is theoretically also possible that they will be cheaper than expected. This would be a chance or as said earlier, an opportunity. The commonly known proverb “No risk, no fun” shows that risk depends on the perspective. A classic example is betting. The risk of losing money is a necessity to be able to earn money (opportunity). As another example one could explain housing construction as an interplay of different risks and opportunities. Taking a loan to build a house is a risk and an opportunity at the same time. While the bank has an initial opportunity to earn money with the loan, i.e. the interest rates which are paid later on, the loan-taker has the risk in regards to the house construction. The house could be badly built or external events might cause a value reduction. From the opposite perspective, the bank takes the risk that the loan-taker is not capable of paying back the loan, which eventually finds its quantitative expression in the interest rate. Simultaneously, the loan-taker has the chance to build a house and thus create something which has more value than the initial loan.

After all these considerations, it can be summarized that defining risk takes place on three levels, i.e. temporal dependence, expectations and risk perspective. A definition which incorporates all three aspects could be as follows: *Risk is an existing possibility that besides an expected outcome, other outcomes can also take place which, based on the perspective of the affected subject, are less desirable*. In a next step this initial definition will be extended by other concepts. Therefore, two authors who are well known for their expertise on risk analysis were chosen. Their approaches are introduced in the following.

Aven (2008) uses a rather practical approach towards risk. He defines risk as something which is related to future events (A), which will have consequences and outcomes (C). As the future is unknown, the occurrence of both A and C is subject to uncertainty (U). The probability (P) is a way to quantify the likelihood that A and/or C will take place. P is based on the knowledge (K) which is available in regards to A and C. K can include historical data, personal experience, expert opinions, etc. It is possible to add C*, which tries to predict the consequences, i.e. the real-life value of it. Further, Aven (2008) emphasizes the aspect of vulnerability in connection to risk and risk analysis. He argues that one should understand vulnerability as the product of C and U, given that the event A took place. A high vulnerability describes a state where C multiplied with U is high and thus the probability of a negative outcome is high as well. In regards to the initial definition, Aven’s approach adds the aspects of probability and background knowledge to the concept of risk. Probability becomes a tool to describe and compare future uncertainties of events and consequences. The background knowledge defines the quality of our probability calculations. The more knowledge one has, the more precise probabilities can be assigned to the occurrence of certain events. Aven (2008) does not define whether risk has a purely negative or positive connotation or whether one should distinguish between risk and opportunity. He argues that one should focus purely on uncovering possible consequences and how they should be assessed and probabilistically described.

Contrary to that, Vose (2008) makes a clear distinction between these two points. His approach is explained as follows. Future events can either be classified as a risk or as an opportunity. The former one has a negative impact and is composed of three elements: the risk scenario, the chances that it will actually occur and the magnitude of the impact (Vose 2008). An opportunity involves the same three aspects, but its consequences are positive. As the same event can be considered as both, risk and opportunity, it is suggested, that when the impact is negative and the chances are below 50%, then one should call it risk. If the chances of this risk exceed 50%, then it will be incorporated in the basic scenario and it is an opportunity when it does not take place. In addition to uncertainty and probability which are interlinked with risk, Vose (2008) introduces the term variability in relation to risk, which allows a more precise definition. Variability is an effect of randomness which is inherent to any physical system. In contrast to that, uncertainty relates to incomplete knowledge of the assessor. In other words, by gaining more knowledge about a certain system, one can reduce the level of uncertainty, but one cannot change its variability. The variability can only be altered when the physical set-up of the system is changed. The combination of both, variability and uncertainty results in the so called *total uncertainty*. It is the sum of our inability to foresee future events. Vose (2008) defines the previously used term probability as a numerical evaluation of the chances of an occurrence in the future. Probability and the values of the potential occurrences represent the variability of a system.

The following example shows how one can distinguish between variability and uncertainty: When tossing a perfectly fair coin, one has a probability of 50% to hit either head or tail. Repeating this 10 times, one would get a binomial distribution and the probability to hit the head five times would be highest (Figure 2.8).

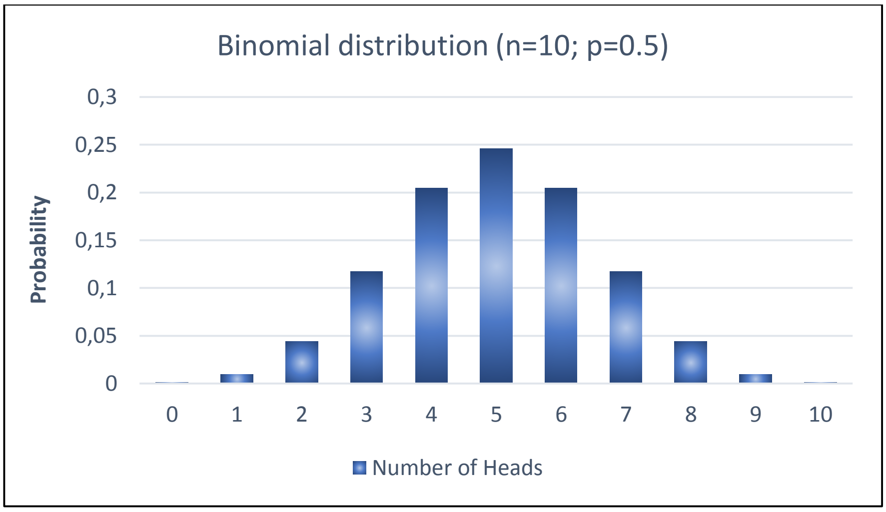


Figure 2.8: Binomial distribution for tossing a coin (adapted from Vose (2008))

The distribution illustrates a variability of a stochastic system. It reflects the level of randomness, because tossing a coin is not a completely controlled event. Factors such as the time it stays in the air, the number of rotations, the angle when hitting the ground, etc. make it impossible to predict which side of the coin one will hit. At the same time, it is assumed that all parameters of the system are perfectly known, i.e. the number of tosses and the fact that it is an absolutely fair coin (p = 0.5). Thus, there is no uncertainty in this system and the only reason why the outcomes of this system deviate, lies in the existence of randomness. Thus, if one wants to decrease the total uncertainty of this system, it will be useless trying to gain more knowledge about this system, because the uncertainty is already decreased to a minimum. On the other hand, one can only change total uncertainty by changing the variability, thus changing the physical system itself. In this case it would mean to manipulate the coin so that it will show either heads or tails with a higher probability.

Vose (2008) emphasizes to keep variability and uncertainty separated when conducting risk analysis. This is often difficult, because both are illustrated by distributions which have the same appearance and behaviour. It is nonetheless crucial to keep them separated in order to retain information about what part of the distribution is due to randomness (variability) and which part is due to insufficient knowledge. This information can tell the assessor in which field he should try to make improvements in order to reduce the total uncertainty.

In order to keep variability and uncertainty separated in a risk analysis model, Vose (2008) recommends to follow a so called *second order*. It means that in step 1, the variability model shall be constructed, including different probabilities for different parameters. In step 2, one can implement uncertainties about parameters into the model. It is possible to use the coin example again in order to illustrate this principle: at first, the probability of the number of heads has been calculated using a binomial distribution with a given probability p = 0.5 (step1). Then, it might be possible that one is not certain any longer, whether the coin is perfectly fair. As a consequence the initial probability p = 0.5 could be replaced by a distribution which only estimates the probability p (step 2). In this step we have included uncertainty into the risk analysis model.

The previous chapter gave a theoretical presentation of how risk can be conceptualized. Focus was laid on the terminology and how different sub-aspects of risk differentiate from each other. Figure 2.9 gives a graphical overview about the previous discussions. It represents a synthesis of the concepts illustrated above, even though *Vose's* approach is dominating.

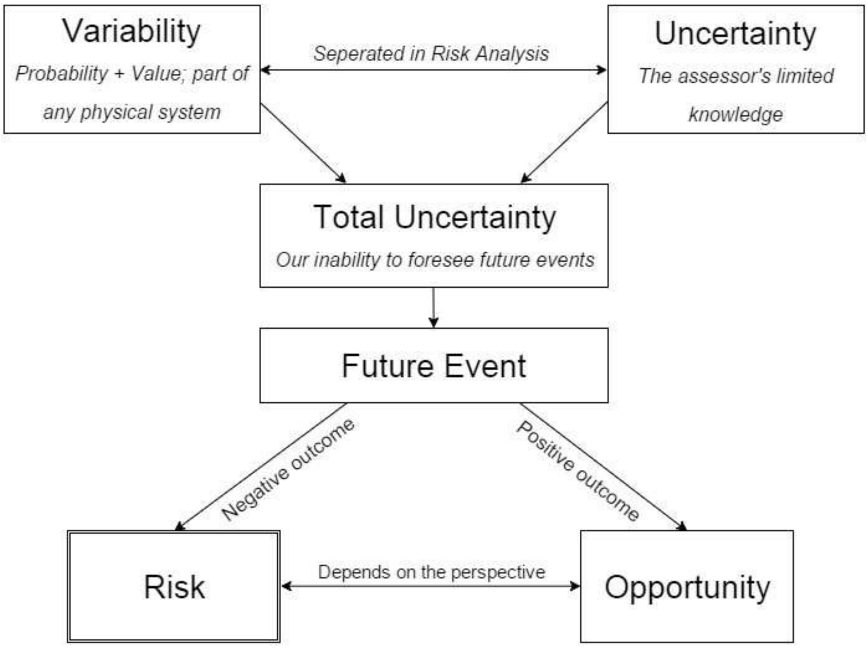


Figure 2.9: Graphical overview of the conceptualization of risk (own graphic)

2.3.2 Risk analysis for renewable energy systems

Even though renewable energy systems are progressing fast, this does not happen as a matter of course. Financial, technical and regulatory obstacles have to be taken. Arnold and Yildiz (2015) emphasize that renewable energy systems have relatively high upfront capital costs compared to conventional power generation investments. The costs of financing are crucial to any project and they are determined by several factors, e.g. the borrower's credit worthiness or available securities. In particular, the aggregated project risk is of outmost importance for the interest rate. Investors will define their return on investment depending on the project risk. Thus, proper risk analysis is an important requirement for a project's economic feasibility.

As the importance of risk analysis is now underlined, the focus moves to the question: what is risk analysis? Aven (2008) points out that it is a tool to support decision making. It describes risk and presents an informative risk picture. Vose (2008) states that the core of risk analysis is to determine the total uncertainty which lies in every project. Though, risk analysis in the energy sector can have a broad range of applications. To illustrate this, searching for *renewable energy* in the international, peer-reviewed journal *Risk Analysis* gives 63 results in total. The majority relates to nuclear power issues, Carbon Capture and Storage (CCS), power outages or climate change. Other terms such as *energy system*, *renewable energy system* or *energy system modelling* reveal similar results. Though, the present thesis focuses on a renewable energy project and therefore, a more case-specific risk analysis concept is introduced in the following. It will elaborate a risk analysis scheme, which is specially developed for renewable energy projects.

On behalf of the International Energy Agency (IEA), Graf et al. (2011) developed a guide for renewable energy specific risk assessment. The incentive behind is to improve the management and quantification of risk. Eventually, this helps to reduce the costs for capital acquisition for renewable energy projects. It becomes more relevant as renewable energy technologies become mature and their public support systems are reduced successively. As this leads to a reduced revenue security for investors, focus is laid on thorough risk analysis to make investments feasible and attractive. Graf et al. (2011) suggest a five step procedure, which includes:

1) Project identification and requirements
2) Risk identification
3) Risk evaluation
4) Risk control
5) Risk feedback

In the first step a detailed description of the planned project needs to be completed. This should cover all investor-relevant aspects. Special attention should be paid to less mature technologies, as delays during the construction or operational outages are more likely to happen. Also, the permission process can be more sophisticated than expected and it often includes hidden costs. In the next step, risks need to be uncovered and organized. There are several, renewable energy specific aspects which require special attention. The intermittent power output needs to be integrated into the existing grid, which was designed for a centralized and non-intermittent power production system. Grid reinforcement can be a time consuming process and curtailing renewable energy production is not always avoidable. Besides biomass and geothermal energy, most renewable energy forms are immediate weather sensitive, which generates a risk on the forecasted revenue streams. The economic feasibility is nearly always depending on long-term public support schemes. These can change according to the political environment and the government which is in charge. Public resistance is a commonly known aspect which requires consideration as well. Especially wind power projects have experienced considerable resistance from citizen groups (Krohn, Damborg 1999; Ek 2005). The acquisition of all necessary permissions can be time consuming and costly and does often lead to project delays. The supply chain can become a crucial risk factor as well. Although wind and PV became rather mature, other technologies are still at an early stage. A rapid demand growth can lead to supply shortages, especially in less developed technologies. Different techniques exist on how to identify risks. Among others, brainstorming with relevant stakeholders is a commonly known technique. Expert interviews, checklists and in some cases even databases are available for risk identification.

After all risks are revealed and organized, they need to be evaluated. Graf et al. (2011) distinguish between quantitative and qualitative methods. To begin with the latter, a qualitative approach is a less-complex way to get an overview about different risks at stake and gives opportunity to prioritize them. In a qualitative assessment, risk is examined according to two levels, i.e. probability of occurrence and magnitude of consequences (impact). Risks which have consequences in terms of project costs, duration and future revenues are especially important to consider. A qualitative assessment finds its expression in a risk matrix. Probability and impact are each assigned one axis and every risk finds a position within the matrix. This position is determined by the judgment of stakeholders which can be asked to state their risk evaluation during workshops or in individual questionnaires.

A quantitative assessment is a complex, probabilistic analysis. It evaluates the likelihood and impacts of a set of chosen risks and thus their effect on certain output parameters, e.g. total costs or project duration. Graf et al. (2011) suggest to create a risk register which lists all risks included in the quantitative assessment and the applied distribution types and assumptions behind. The result of such a quantitative assessment are probability distributions. It gives information about the confidence to which the project can achieve a certain value. E.g. from a cumulative probability distribution for the project's NPV one can deduct how probable it is that the NPV is at least 0. A quantitative analysis replaces fixed/numerical parameters with probability distributions. These are then combined in a stochastic model, which generates randomly several hundred or thousand values from the probability distributions. This makes it possible to calculate numerous combinations of different parameter constellations and the respective model output. Thus, this risk assessment method is more sophisticated and delivers stronger arguments compared to common best-case, base-case and worst-case scenario analysis. Whereas a scenario analysis covers only a few parameter constellations, a probabilistic approach covers up to several thousand constellations. A common tool within the field of quantitative risk assessment is the MCS, which will be explained in detail in the following chapter. Cornerstone of every MCS are probability distributions which are explained below.

A distribution is either classified as continuous or discrete, depending on what kind of parameter they refer to (Figure 2.10). The triangular distribution describes a parameter where a most-likely value exists and the best and worst cases are defined. With high certainty the outcome will not exceed the minimum and maximum value. Typically, one would assign costs to this type of distribution. The uniform distribution refers to a case where there is no value which is more probable than any other value. This can be the case, when e.g. experts cannot agree on a most-likely outcome and therefore it is assumed that all possible values between the agreed minimum and maximum are equally probable. Factors such as long-term supply cost increase or project delay from permission processes are normally assigned to such a distribution. Curved distributions are applied when there is sufficient data available from comparable cases or when a lot of data exists in general. There are symmetrical distributions, e.g. the normal distribution (Figure 2.10) or asymmetrical distributions, e.g. log normal or beta distribution. Chapter 2.3.5 includes a more extensive discussion on that. Weather patterns or equipment reliability are usually described by those distributions. The triangular, uniform and normal distribution are considered as continuous distributions. If one wanted to model decisive moments which can either occur or not, a discrete distribution would be appropriate. Here, single point events with a certain outcome are allocated according to their likelihood. Examples can be changes in public support systems or permission refusal.

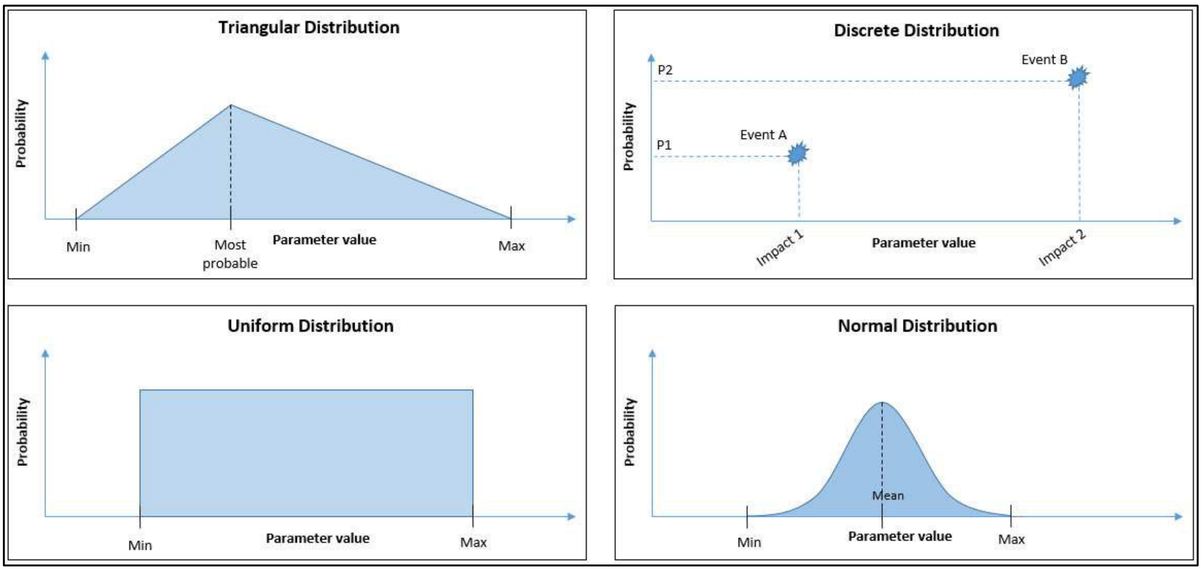


Figure 2.10: Distribution types for quantitative risk analysis (adapted from Graf et al. (2011))

After the risk evaluation has been completed, risk control takes place. Risk management plans are allocated to different stages of the project. Continuous reporting is done by the responsible actors. Finally, risk feedback is given after the project has been finished. At this stage, the initial risk analysis is compared with the actual project development. A final review summarizes deviations from earlier expectations and assumptions. In an optimal case these reports are added to a data base for future risk analysis.

2.3.3 Quantitative risk analysis – introducing Monte-Carlo simulation

The MCS is a method to assess risk quantitatively. One can explain what it is by showing its advantages compared to ordinary analysis, such as scenario or sensitivity analysis. An analysis which is based on the output comparison of several scenarios is limited as it can only show results for the number of designed scenarios. Every scenario equals one constellation of different, uncertain parameters which determine the model output. In case there are three scenarios, then one can only obtain results for three different parameter constellations. In a next step, sensitivity analysis focuses on a single parameter and its impact on the model output. This gives more detailed information about a model's behavior, but it lacks comprehensiveness. While the input for one parameter is changed, all other parameters stay constant. In contrast, MCS computes model outputs while changing all chosen parameters. One could say that MCS adds another dimension to sensitivity analysis, because not only one parameter is altered at a time, but all input variables are altered simultaneously. Besides the fact that MCS generates a higher quantity of results, it has another advantage from a qualitative perspective. While scenario and sensitivity analysis allocate the same probability of occurrence to each scenario/input variable, MCS considers probability density functions (pdf) for variables. Thus, input is not chosen randomly, but based on probability distributions. Therefore, the increased number of results does not exhibit a wider range, but the output variety becomes more accurate. MCS generates result structures which are much closer to reality than those from simple scenario analysis (Vose 2008). In the following, the operation principle of MCS is explained in depth.

The starting point of any MCS is a random number generator. These random numbers are used to create random samples of the model input variables. As it was mentioned above, not every variable is equally probable. Each variable has a specific pdf (cf. chapter 4) and the random sample should reflect the respective probability function. To understand how a random sample for a MCS is generated, one needs to understand the correlations between pdf, cumulative distribution function (cdf) and the inverse cdf (Figure 2.11).

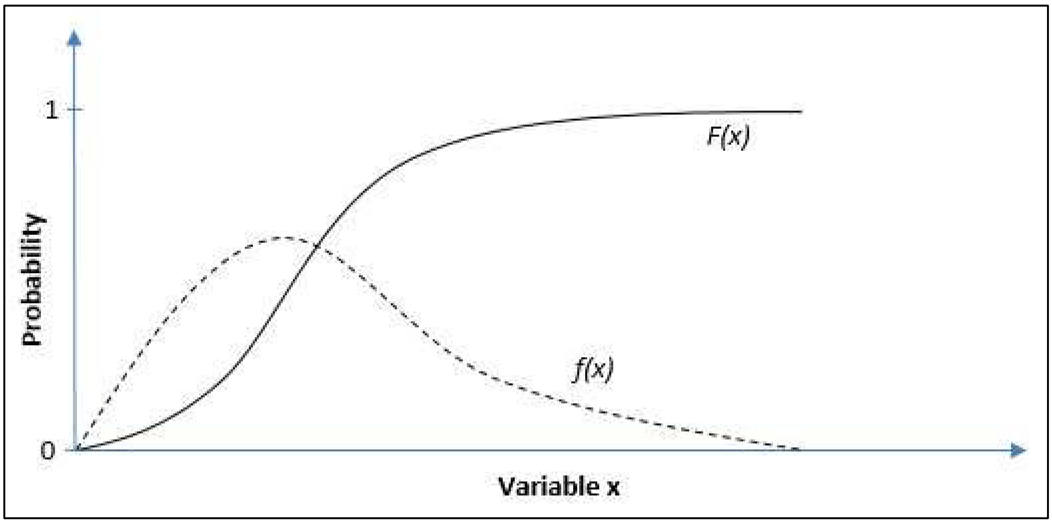


Figure 2.11: Probability density and cumulative distribution function (adapted from Vose 2008))

The pdf $f(x)$ defines the probability of occurrence for any possible value of x. The cdf $F(x)$ defines the probability P that a variable X will be less or equal to the value x. In other words, it defines the area below $f(x)$ which is delimited by a vertical line at the respective value x.

$$F(x) = P(X \leq x)$$

$F(x)$ can range between 1 and 0, where 1 defines a probability of 100% that X will be less or equal x or simply that all values are within the possible range. The present cdf starts with a value on the x axis and finds the respective probability on the y axis. The inverse cdf changes this direction and in this case it would look like this:

$$G\big(F(x)\big) = x \quad \text{or} \quad G(P) = x$$

The inverse function is required to generate a random sample of the original pdf. $G\big(F(x)\big)$ starts at the y-axis with a certain probability and from that point it defines the respective variable x. There is only one step missing to complete the whole process of random sample generation and this is the introduction of the previously mentioned random number generator. This random number r can range between 0 and 1, the same range as for $F(x)$. It has a uniform distribution (cf. Figure 2.10). Replacing $F(x)$ in the inverse function $G\big(F(x)\big)$ with a random number creates the random sample for the input variable x.

$$G(r) = x$$

The s-shape of $F(x)$ makes it easy to understand why this inverse function in combination with r generates a random sample of x which reflects the initial pdf. Along the y-axis, r can be any arbitrary number between 0 and 1. This number on the y-axis defines a value on the x-axis, the input variable x. Due to the s-shape there is a certain interval around which the x values will accumulate and this is where $F(x)$ is most vertical. The more vertical $F(x)$ is shaped, the denser the accumulation of x values around a certain value. If one imagined that $F(x)$ had a vertical interval, then it would generate only one x value for a range of possible r values.

There is one problem with this method of random sampling. The MCS is too random which might sound paradox at the beginning. Due to the absolute randomness of Monte Carlo it will naturally over and underrepresent certain intervals of the distribution. The lower the amount of repetitions, the bigger this problem will become. The basic idea behind the random sampling process is to generate a most accurate copy of the initial pdf, based on random numbers. Now, MCS does not necessarily generate such a precise copy because some intervals will be either under or overrepresented, due to pure randomness. Vose (2008) proved this disadvantage and suggests to apply the Latin Hypercube sampling (LHS) instead. Also Brandimarte (2014) mentions the LHS as a strategy to reduce the inherent variance of Monte Carlo methods. The LHS is not purely random, because it memorizes what it has already done and therefore any repetition is depending on the previously observed outcomes. The cdf for any given variable x is split up into a certain amount of intervals i which is equal to the number of repetitions. Each interval has the same probability (same length on the y-axis) and is graphically illustrated by a horizontal bar (Figure 2.12).

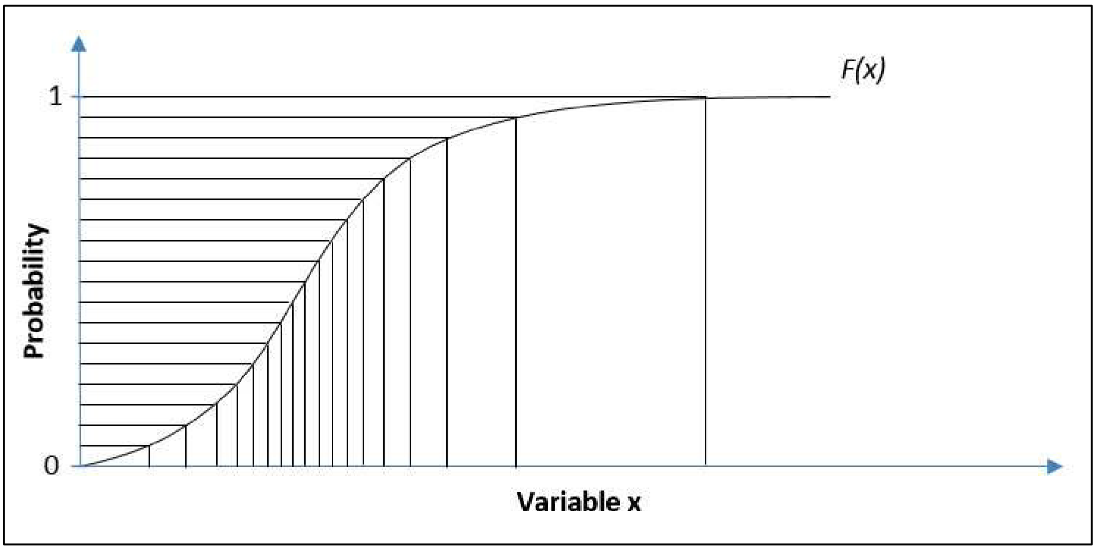


Figure 2.12: Illustration of the Latin Hypercube Sampling (adapted from Vose (2008))

The LHS starts by choosing randomly one of the intervals from the y-axis with the aid of a random number generator. Then, a second random number is created and it defines the exact value of $F(x)$ within the previously selected interval. As mentioned above, by using the inverse of $F(x)$ one can compute back to the actual variable x, which is the desired input parameter for the model. For the next repetition, the LHS remembers that it has already selected an interval and it will not choose this interval again. At this moment, LHS gives up on a 100% randomness but it gains more accuracy in reproducing the initial distribution. The process is repeated i times and since the number of repetitions equals the amount of intervals, each interval is only selected once. Eventually, the randomness of the LHS is limited to the value of $F(x)$ within the interval. Therefore, this sampling method has a higher degree of reproducibility compared to MCS. This can be advantageous when one changes the pdf or other characteristics of the model in order to see the effects of these changes. With the MCS sampling the chances are higher that output differences are due to randomness, while for LHS it is more likely that differences can be traced back to the modifications.

Finally, the reproduction of parameter distributions is put into the energyPRO model (Figure 2.13). It is the basis to conduct a large number of simulations. Due to the high quantity of model output data one can present a distribution of results and use standard statistical terms (mean, variance, etc.) to describe the result structure. The MCS could be described as a layer surrounding the energyPRO model. It adds a probabilistic dimension to the deterministic model.

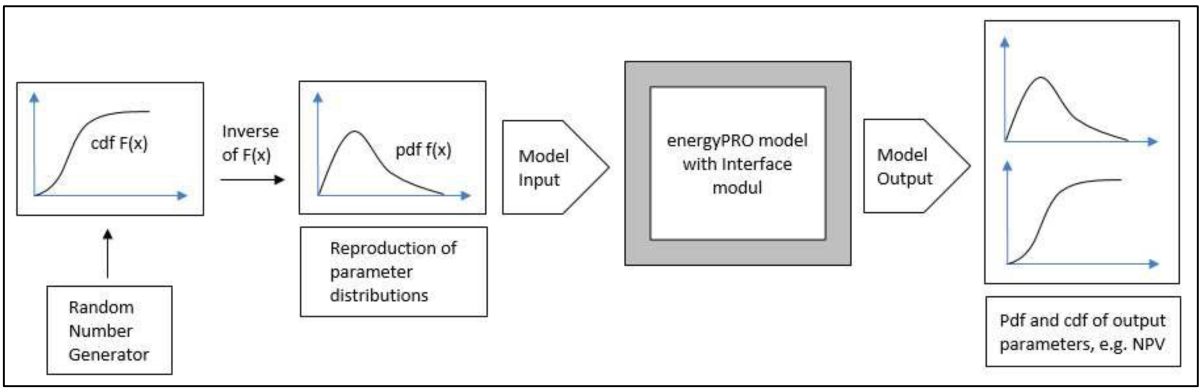


Figure 2.13: Relationship between energyPRO and Monte-Carlo simulation (own graphic)

2.3.4 From variables to distributions – fitting data into theoretical distributions

One of the core challenges of quantitative risk analysis is to generate distributions which adequately represent the parameters within the model. According to Vose (2008) one can distinguish between parametric and non-parametric distributions. The former type refers to a mathematical function which defines the distribution by different parameters. Examples of such distributions are normal, log-normal, beta distribution, etc. One disadvantage of these distributions is that the parameters are not intuitive and most of them have no direct correlation to the pattern of the distribution. It requires a certain level of statistical expertise to understand directly how such parameters shape distribution curves. Additionally, parametric distributions depend on a certain amount of available data. Vose (2008) illustrates that even 20 data points might not be sufficient to derive a clear distribution type. Often, there are several 100 data points necessary to depict a distribution with a reasonable accuracy. Parametric distributions seem rather appropriate for variables which represent technical or natural systems, where a large amount of data is available. Thus, in the present study this is not feasible for most of the parameters as they constitute price and demand forecasts for which only a few data sets exist. In this case, non-parametric distributions would be more appropriate. They can include uniform, discrete or triangular shapes (cf. Figure 2.10). The advantage lies in their intuitiveness and visual simplicity. That is why Vose (2008) uses this type to generate distributions from expert opinions. As opposed to parameters which are almost exclusively determined by their variability (natural and technical systems), there are often parameters in risk analysis which include a high degree of uncertainty and that makes expert opinions inevitable. This can be the case when such data has not been analyzed in the past, when historical data is not appropriate due to political or technological change and when data availability is scarce anyway. The parameters in the present thesis fulfill such criteria which make expert opinions necessary. One could think of the future spot price forecast from energinet.dk as one expert opinion, while the forecast from Danske Energi is another opinion. Therefore, it was decided to apply non-parametric distributions for the model's input variables.

2.3.5 Non-parametric distributions for input variables

As mentioned in the previous chapter, there are uniform, triangular and discrete distributions. Vose (2008) also presents relative and cumulative distributions, but both are neglected at this point. The former one is a fully customized distribution. The idea behind is that an expert can directly shape the distribution graphically and thus express his best guess of how the variability could look like. Since there are no "real" experts who could be consulted, this method is not relevant. The cumulative distribution was neglected because it is described as extremely sensitive towards minor shape changes. Secondly, its main purpose is to show variables which can vary around several orders of magnitude, such as bacteria populations. Since this is not expected to be the case in the present thesis, it is considered irrelevant. The uniform and discrete distributions were introduced in chapter 2.3.2 and since their complexity is not too challenging they are not mentioned again. Instead, focus is laid on triangular distributions and two modifications of the same.

Starting with the basic triangular distribution, it is characterized by the most probable value p, which defines the peak. The minimum a and maximum c are indicated by the triangle's end on the left and right side. The mean and standard deviation can be calculated as follows (Vose 2008).

$$Mean = \mu = \frac{(a + p + c)}{3}$$

$$Standard\ deviation = s = \sqrt{\frac{a^2 + p^2 + c^2 - a * p - a * c - p * c}{18}}$$

As it can be seen from the formula for the mean value, all three criteria that define the triangular shape have an equal impact on the mean. Depending on how the maximum value was determined, this could be problematic. Often, there is a maximum value, which is theoretically possible and there is one which is reasonably possible. The former one often exceeds these practical limits and would therefore push the mean to a higher value than it would actually be realistic. The so called *Trigen* distribution can be a suitable alternative to avoid this bias (Vose 2008). Basically, it replaces minimum and maximum values by reasonable minimum and maximum limits and it adds a probability range, for the case that those limits could be surpassed (Figure 2.14). The blue areas in the right and left corner represent the probability (5%) that the minimum and maximum values could be surpassed.

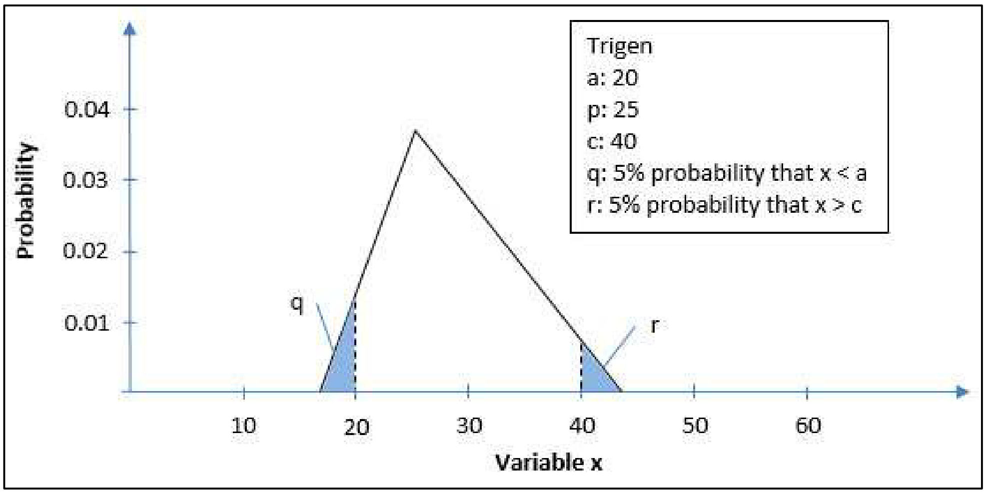


Figure 2.14: Trigen distribution (adapted from Vose (2008))

The advantage lies in the avoidance of theoretical maximum and minimum values, but one might still not be satisfied with the final extensions. Additionally, one might wish to put more emphasis on the most probable value, since this might be the criterion which is best known or predictable. In this case, the PERT distribution could be useful. Even though it is not shaped as a triangle, it does still cover most of the area that a triangle would cover as well. In fact, the PERT distribution is a type of beta distribution, but it only requires the same three criteria as a normal triangular distribution (a, p and c). It is defined as follows (Vose 2008).

$$PERT(a, p, c) = Beta(\alpha_1, \alpha_2) * (c - a) + a$$

With:

$$\alpha_1 = \frac{(\mu - a) * (2p - a - c)}{(p - \mu) * (c - a)}$$

$$\alpha_2 = \frac{\alpha_1 * (c - \mu)}{(\mu - a)}$$

$$Mean = \mu = \frac{a + \gamma * p + c}{\gamma + 2}$$

The PERT distribution's mean value is more robust towards extreme minimum and maximum values, which can be seen in the last formula. The most probable value p is multiplied by a factor γ, making it the dominant part of the fraction. Normally, a factor of 4 is applied for standard PERT. It is also possible to use higher or lower numbers. This allows to adjust the level of uncertainty one wants to have reflected in the distribution. The higher the number, the more it will peak around the mean and the less uncertainty there is. Figure 2.15 shows two different PERT distributions and their standard triangular equivalent. Clearly, the PERT distributions are more centered on the mean value. Consequently, PERT distributions have a lower standard deviation compared to triangular distributions.

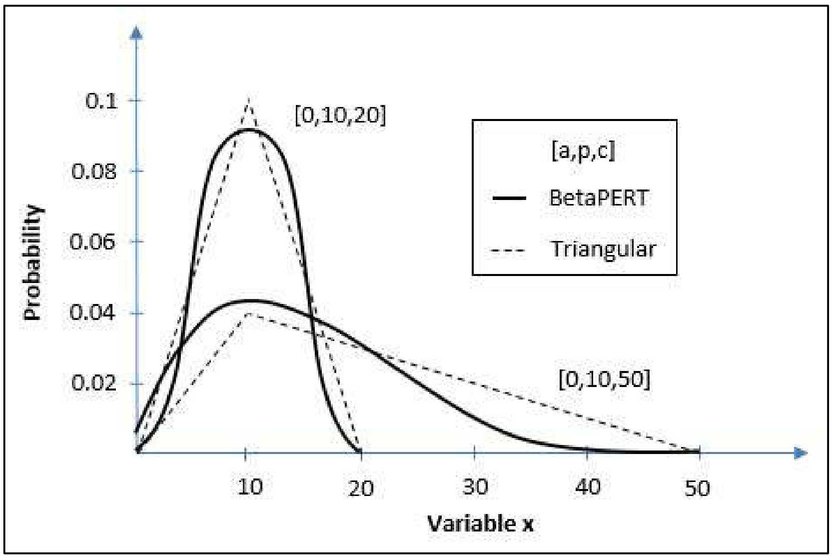


Figure 2.15: PERT and Triangular distributions (adapted from Vose (2008))

2.3.6 The ModelRisk software for Monte-Carlo simulation

In the present thesis ModelRisk by Vose Software is used to conduct MCS. It is a built-in tool for Microsoft Excel spreadsheets and appears as an additional tab in the usual excel ribbon. As a core feature it provides a wide range of distribution types. The graphical interface gives a preview of each distribution according to the defined input parameters (Figure 2.16). The software can also define correlations between various variables and it allows to fit an existing data set into a most accurate distribution type. ModelRisk can run MCS from 100 up to 10,000 simulations.

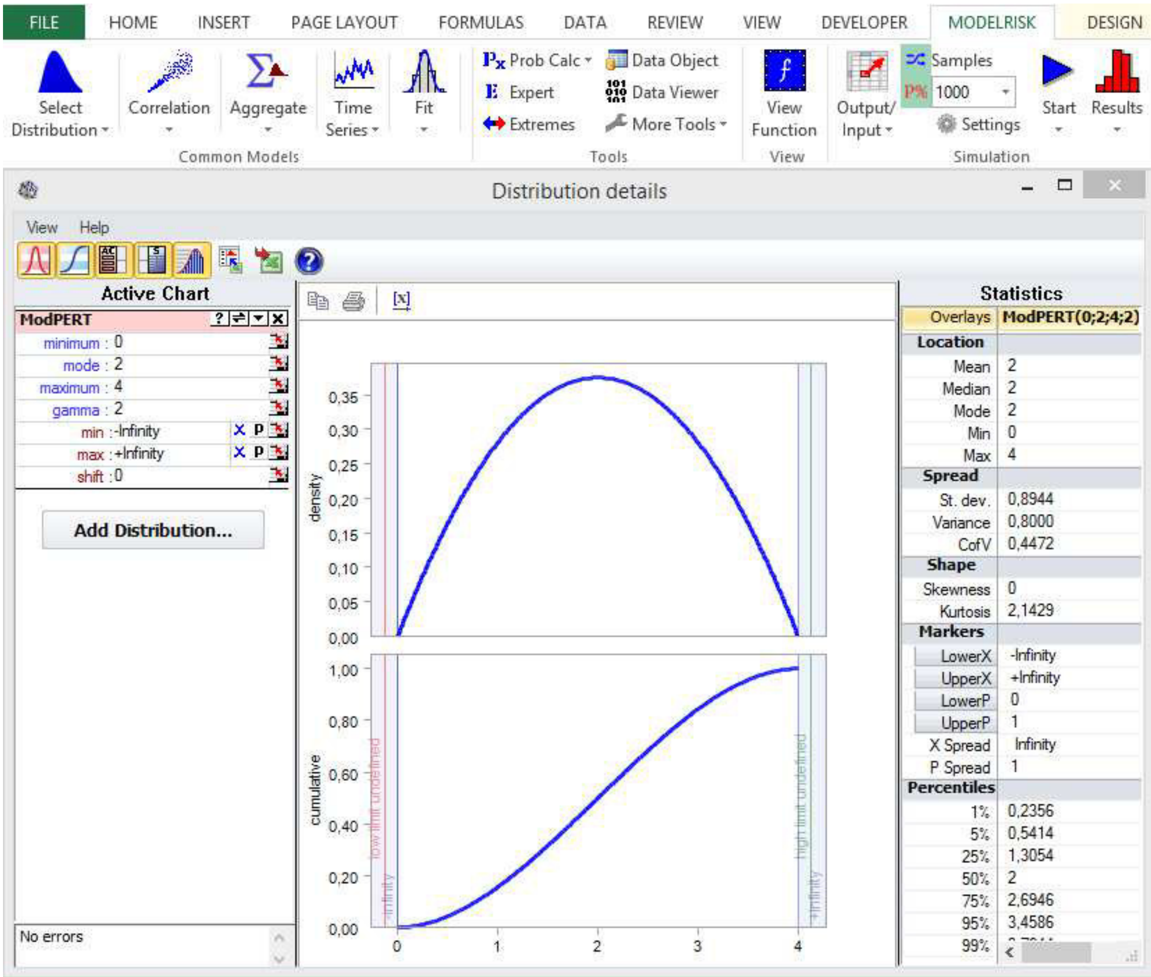


Figure 2.16: ModelRisk within a normal excel sheet - modelling a ModPERT distribution

ModelRisk does not use LHS for random number generation. Instead, it uses the Mersenne Twister algorithm. Even though both are pseudo-random number generators, there are several reasons which favor Mersenne Twister over LHS. One of them is the speed and memory use of the simulation. As it was explained in chapter 2.3.3, the LHS stratifies a distribution and generates sample values for each stratification before the actual simulation start. Depending on the number of distributions and desired samples this can easily add up to several 100,000 numbers which need to be generated in advance. Vose (2015) argues that the LHS method is simply outdated since computers are much faster nowadays than in the 1980s when LHS was the state-of-the-art method. Back then, computers were slower and it was of great advantage that LHS could achieve great accuracy with only a few samples and distributions. Though, nowadays computers can easily handle several 1000 iterations. With an increasing number of samples, the generated data get very close to the initial distribution and thus, the main advantage of LHS becomes negligible.

Besides ModelRisk there are other programs for MCS available, of which the most common are @Risk and Crystal Ball. Since Aalborg University does not hold a license for any of them, the software had to be purchased privately. A student version of Crystal Ball costs EUR 320 and was found to be too expensive for the present purpose. Even though @Risk is slightly cheaper than ModelRisk, it was decided to purchase the latter. While writing the methodology chapter about risk analysis the main source was the scientific text book from David Vose (2008). After reviewing several textbooks about quantitative risk analysis, his book was found to be the most comprehensive and relevant for the present thesis. Since David Vose is also the CEO of Vose Software which retails ModelRisk it is straightforward that most of the examples in the textbook refer to his own software. Therefore, it seemed reasonable to decide for ModelRisk. Additionally, the software is used by various well known academic and commercial institutions. Among its users are the Danish Agriculture & Food Council, KPMG, Pricewaterhouse Coopers, the World Bank, the World Health Organization and Aarhus University (Vose Software 2016).

2.4 Theory of scenario design

Before the scenarios are described in detail, a more general approach towards scenario studies is presented. It shall bring the present study in line with a more fundamental, methodological context. Therefore, the scenario typology of Börjeson et al. (2006) is applied. They have reviewed the nine most prominent scenario typologies in scientific literature and created a synthesis which classifies scenario studies into three different categories: Predictive, Explorative and Normative (Figure 2.17). Predictive scenarios answer the question: "What will happen?" This is done based on forecasts or what-if scenarios. Forecasts describe what will happen given that the most probable development will evolve. This gives reference results which can be accompanied by results from high and low scenarios, which limit the range around the most probable development. A what-if scenario tries to figure out what will happen in case that some event of considerable impact will take place. Such events can theoretically relate to external effects or internal decision making.

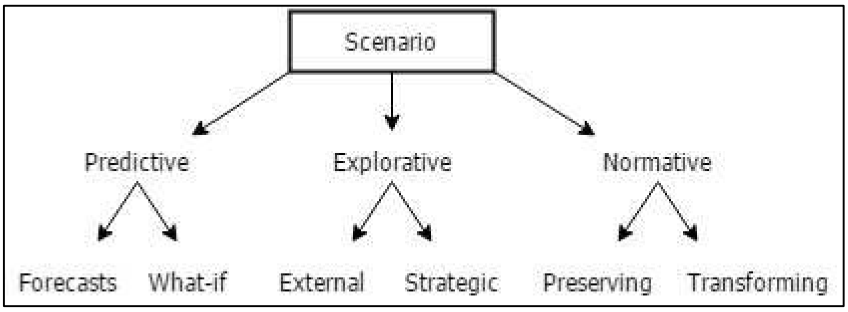


Figure 2.17: Scenario typology according to Börjeson et al. (2006)

Explorative scenarios give an answer to the question: "What can happen?" Börjeson et al. (2006) distinguish between two types of these scenarios, i.e. external and strategic scenarios. The former one puts its emphasize on factors which are out of the influence area of the respective actor. Such scenarios would typically guide decision-makers in how to develop and assess their policies and strategies. A strategic scenario portrays possible impacts from strategic decision making. Both, internal and external factors are considered and it basically illustrates how a decision can have different consequences depending on how the future will develop. The distinction towards what-if scenarios is small and it could be argued that explorative scenarios incorporate a range of what-if scenarios. Though, the difference here is that explorative scenarios have normally a longer time frame and they allow to integrate more general and fundamental changes in the system. These could be changes in tax and public support regimes.

Finally, normative scenarios answer the question: "How can a specific target be reached?" This can be done by either preserving or transforming scenarios. As the name already indicates, the preserving scenario focuses on how a goal can be achieved, given the system structure is unaltered. Opposite to that, the transforming scenario assumes that the defined target cannot be achieved under the current regime and fundamental, structural changes are inevitable. The current system is perceived as part of the problem and marginal alterations are not sufficient for the accomplishment.

At this point the question arises which of the discussed concepts fits the present scenario approach best? The normative concept does not seem to apply here because the strong focus on structural changes for transforming scenarios does not match the present business-economic framework. A typical example of transforming scenarios is back casting and this does definitely not apply here. One could argue that a preserving scenario would be closer to the conditions of business-economic studies. This is probably valid, but the reason why a preserving scenario might not be entirely appropriate is that it requires a prior normative target. This could be a certain share of renewable energy or a pre-defined emission reduction. While those normative targets exist for Aalborg Kommune on the long run, the present project did not define such normative goals, at least not that it came to the attention of the author. Regarding explorative scenarios, one can definitely exclude the external concept, since the present scenarios comprise factors which are indeed in control of the relevant actor, i.e. the decision which technology to invest in. A strategic scenario seems relatively appropriate, given that consequences of strategic decisions are of a major concern in the present project. Though, its focus on policy impacts and the wide time horizon which foresees structural changes seems to make it more appropriate for socio-economic studies. At last, predictive scenarios are supposedly the most accurate concept for the present study. Their focus on what will happen given that event X or Y takes place, resembles the initial situation of AAK. Börjeson et al. (2006) state that likelihood is closely connected to the idea of predictive scenarios, which matches the integration of probability distributions into the present study. Predictive scenarios are commonly applied by investors and planners and this matches the present conditions as well.

3 Scenario design

The reference model was set up and extensively described in chapter 2.2.1. Its behavior was found to be plausible and output data are sufficiently matching historical data (c.f. chapter 2.2.3). In a next step, three scenarios were designed based on the reference model. These scenarios cover the current technological possibilities for sustainable DH production, i.e. HP, geothermal and solar thermal. During the course of this thesis, it was announced that AAK has decided to investigate the possible erection of an electric boiler in close proximity to NJV (Dansk Fjernvarme 2016a). This decision would change the research design as previously an electric boiler represented one scenario alternative, while now it seems more than probable that it must be considered as an integral part of the reference model. Eventually, it was decided to keep the reference model without an additional electric boiler. The reasoning behind is explained thoroughly in chapter 3.4. Further, the present study does not include biomass and electrofuel technologies, which is justified in chapter 3.5 and 3.6. The beginning of this chapter shows an overview with the main, techno-economic details of each scenario. Later on, each scenario is extensively described, providing details about underlying assumptions, technical and economic characteristics. Then, environmental data which are incorporated in all scenarios are presented. The chapter ends with a summary of economic key data that are used throughout all scenarios. In most cases, indications from the Energistyrelsen (2015c) were used for economic assessments.

	Heat pump	***Geothermal***	***Solar thermal***
Heat Output [MJ/s]	84	92	81
Elect. Capacity [MW]	30	20	-
COP	2.8	4.6	-
Applicable taxes	Elafgift: 383 DKK/MWh elect.[1)] PSO: 261 DKK/MWh elect.[2)] TSO grid fee: 82 DKK/MWh elect.[2)]	Elafgift: 383 DKK/MWh elect. [1)] PSO: 261 DKK/MWh elect. [2)] TSO grid fee: 82 DKK/MWh elect. [2)]	Electricity consumption and related taxes are already included in the plant's O&M costs
Active markets	DAH market	DAH market	-
Additional remarks	No DSO grid fee	79 MJ/s geothermal heat input required; No DSO grid fee	113,000 m² solar collector area; 24,000 m³ extra storage volume
1)	(Skatteministeriet 2016)		
2)	(energinet.dk 2016)		

Table 2: Scenario overview with techno-economic key data

3.1 Heat pump scenario

There are various reasons which promote the utilization of HPs in a 100% RE system. Among others, they can reduce the production of excess, intermittent renewable power (Mathiesen and Lund 2009). Further, Connolly and Mathiesen (2014) consider the establishment of small and large-scale HPs as an integral part of a renewable energy transition. From a more general perspective, the future energy system will probably experience a higher degree of electrification (Brito and Sousa 2014). HPs could then play an important role to facilitate the integration between the power and heating sector.

In the present scenario the HP operates only at the DAH market. It was decided to neglect participation at the balancing market. This has three reasons: First, operational flexibility of a large-scale HP is still unclear, which raises doubts whether it can fulfil the requirements in terms of start-up times and minimum capacity offer. Though, these concerns were of relative little importance for this decision. Second, it is more decisive that from personal communication with Morten Blarke (Energianalyse.dk) it was found that additional revenue streams from the balancing markets are negligible in an investment assessment for HPs. Third, since the beginning of 2015, a large part of the primary reserve and all secondary reserve capacity for DK-1 is supplied by the Danish-Norwegian interconnector, *Skagerrak 4* (energinet.dk 2014). This reduces the market volume for frequency-stabilizing services considerably. Tertiary or manual reserve would theoretically be a possible income source, but there are HP-specific drawbacks to it. Downward regulation is only applicable when the HP increases its power consumption, e.g. when it starts operation. Since it is supposed that HPs will function as base-load units with 6,000 – 8,000 h/a, there won't be many hours, where a HP can offer downward regulation (Clausen et al. 2014). Also, upward regulation is only applicable to a limited extent. It is theoretically possible to shut-down a HP on short notice, but this could result in a cold start later on, which generates additional costs. These costs are uncertain, since the start-up time can vary considerably between several hours and during the cold start-up time the HP does not produce any heat for DH. The bidding price for upward regulation should include these expenses, but it would be difficult to model these accurately. Further, it is considered to be questionable, whether a long-term investment decision in a municipal context should be based on a market which is relatively unsteady. Therefore, it was decided to solely operate on the DAH market, which provides a more robust decision basis.

The Coefficient of Performance (COP) is set following an indication from Energistyrelsen (2015c), giving a COP = 2.8. This relates to moderate pessimistic expectations. It is taken into consideration that the COP can increase when excess heat or ground-source heat is utilized, but for the present study it was decided to use the minimum COP first. Electric capacity is set to 30 MW, resulting in a maximum thermal output of 84 MJ/s. Short-term marginal costs are comprised by electricity prices at the DAH market, grid fees and taxes. Currently, the Danish legislation charges a so called *Elafgift* (electricity fee) and a Public Service Obligation (PSO) tariff for large-scale HP (Detlefsen, Koch 2014). The latter one is a surcharge paid by all electricity consumers to cover feed-in tariffs for RE producers and to finance research projects. At the moment, PSO equals 261 DKK/MWh el and the Elafgift is 383 DKK/MWh el. Grid fees to the distribution and transmission operators are identical to what is stated in chapter 3.8. O&M costs 3.4 MDKK per year and the initial investment costs are expected to be 426 MDKK incl. grid connection. For the MCS, investment costs are distributed uniformly between 325 MDKK and 526 MDKK, following expectations from Energistyrelsen (2015c).

3.2 Geothermal scenario

Geothermal energy is a promising, renewable energy source and it is expected to cover a considerable share of the Danish DH demand in the future (Mathiesen et al. 2010). In a recent sustainability assessment of different heat and power technologies, Dombi et al. (2014) have shown that geothermal DH can be an advantageous option. Especially in regards to land demand, ecological impacts and job creation the technology showed a better performance compared to biomass or solar thermal.

At the moment there are three active geothermal DH plants in Denmark, i.e. Thisted, Copenhagen and Sønderborg. All of them use an absorption heat pump, because the temperature of the geothermal fluid is not high enough for direct heating purposes. The drilling depths vary between 1.2 km and 2.6 km, where they reach geothermal temperatures between 45 - 74 °C (Dansk Fjernvarmes

Geotermiselskab 2016). On average, the geothermal temperature gradient in Denmark is around 25 - 30 °C per km (Vangkilde-Pedersen et al. 2012). Besides absorption heat pumps, it is also possible to use compression heat pumps in combination with geothermal heat. Both solutions can add flexibility to the existing system. A compression heat pump can adjust its electricity consumption to a certain extent, which would allow a higher integration of fluctuating renewable sources. Østergaard and Lund (2011) have shown that absorption HPs in combination with suitable CHP plants can also increase flexibility. In that case, steam is extracted from a CHP's turbine and used as a high-temperature source for an absorption HP instead. Obviously, the CHP's electric and thermal output decreases, but additional heat output from the HP compensates these losses by far. Flexibility is created, because the amount of steam, which is extracted from the CHP unit, can vary and thus allow better integration of intermittent renewable sources.

In the present scenario, a compression HP is used in combination with the geothermal unit. One main reason for that decision lies in the assumption that the future energy system will become increasingly electrified. This makes a compression HP more favourable, as it allows the integration between different energy sectors. Normally, an absorption HP is fed with steam from a boiler, which uses natural gas or biomass as a fuel. Natural gas is a fossil fuel, which is supposed to be excluded from the Danish heat and electricity system in 2035. Though, the new government has already announced that it could abandon this goal (Dansk Fjernvarme 2015). Still, it was decided to exclude natural gas in this case and follow the original political approach. Biomass is a limited resource, which should be rather used for transport or material production. Waste would remain an option to produce steam, especially since waste incineration units are not very flexible. Steam extraction would add flexibility as it was described above. Though, flexibility can also be achieved by implementing storage systems ahead of waste incineration and this might be a more favourable way to gain flexibility.

Regarding the COP, it was decided to follow an indication presented by Energistyrelsen (2015c). It states in an example, that the total system (geothermal pump, HP and heat exchanger) can have a COP = 4.6. Electric capacity is set to 20 MW, resulting in 92 MJ/s maximum thermal output. Based on this example, the system would require a geothermal input of 79 MJ/s, which relates to an investment of app. 942 MDKK. O&M costs excl. electricity consumption sum up to 22 MDKK per year. Grid fees and taxes which apply to the HP operation are identical to what is described in chapter 3.8. For the MCS, it is expected that total investment costs can range between +/- 30% of the initially expected costs. Between these limits investment costs are uniformly distributed.

3.3 Solar thermal scenario

As the previous two scenarios are all to a higher or lower degree exposed to fluctuating electricity prices, the last scenario offers a technology which is hardly depending on spot prices. Besides an electric load for pumps the only input in this case is solar radiation. The risk that solar radiation will decrease beyond its natural fluctuations is considered to be nearly zero. In other words: if the sun disappeared, then the world would have other problems than sustainable DH production.

To begin with, it was assessed whether a solar thermal unit could provide a similar heat output capacity as the previously introduced scenarios. In this respect, it was questioned whether the required solar collector area is within a reasonable range. As a state-of-the-art reference the solar thermal production unit in Dronninglund, a few kilometres north-east of Aalborg was chosen. It is one of the biggest units of this technology in Denmark with a max. heat output of 27 MJ/s (Solvarmedata.dk 2016). In 2014, the facility was erected with a net solar collector area of around 38,000 m². Considering clearances and pathways between the modules one might estimate the total required area to be around 50,000 m². Based on that, a max. heat output of 81 MJ/s would require an area of app. 150,000 m², which is slightly less than 400 x 400 meter. Considering the mostly rural area around Aalborg and NJV this space requirement seems possible.

In energyPRO the solar thermal scenario includes a flat-plate solar collector with a net area of 113,000 m². For the aggregated solar radiation data from the Danish Reference Year 2013 were used, i.e. Zone 1 – Nordjylland. Collector specifications were taken from the Arcon HT-HEATstore (Solar Keymark Database 2015).

Having such an amount of solar thermal capacity installed, it is straightforward that there will be excess heat. While having the lowest heat demand in the summer, the heat output from solar thermal is highest during exactly that season. The heat generation can be 8x as high during the summer as it is in winter (Energistyrelsen 2015c). Therefore, a seasonal heat storage can be a viable option to minimize these losses (Kerskes 2011). Having 113,000 m² of solar collector area installed, it would require a seasonal storage volume of app. 140,000 m³ when one wants to achieve a solar coverage share of around 40% (Energistyrelsen 2015c). This volume equals a bit more than two times the size of the seasonal storage which is installed in Dronninglund. Initial simulations have shown that such a coverage rate, purely based on storage volume over collector area ratio does not apply in the case of Aalborg. The coverage rate in Aalborg's DH system would be much lower, which is supposed to be related to the overall high heat demand. Opposite to the case of Dronninglund, solar heat production during the summer period does not exceed heat demand significantly. It was also tested whether this is due to the newly modelled heat demand, but this presumption turned out to be negative. As a consequence, additional storage volume was reduced to 24,000 m³, which corresponds to a final storage capacity similar to the already existing stores, i.e. 1,100 MWh. Thus, instead of a seasonal pit storage the scenario comprises an additional steel tank.

The latest examples of solar heating in combination with seasonal storage also include a heat pump in their system (Jensen 2014). A heat pump makes it possible to utilize storage heat from low temperature layers and to reduce heat losses of the storage (Marstal Fjernvarme 2016). Considering the absence of a seasonal storage as described above, this option was neglected.

O&M costs are set to 4.2 DKK/MWh heat production incl. electricity consumption, following indications from Energistyrelsen (2015c). Regarding investment costs, data from the Dronninglund example are applied. In this case one can expect 2,800 DKK/m² net collector area, which gives 340 Mio DKK in total including 27 Mio DKK for the thermal storage tank (Energistyrelsen 2015c; Solvarmedata.dk 2016). For the MCS, it is estimated that total investment costs can range between +/- 30% of the initially expected costs, which are uniformly distributed.

3.4 Electric boiler scenario considerations

AAK decided recently to examine the possibilities of an electric boiler next to NJV. While low spot prices put economic pressure on NJV, an electric boiler can exploit these to produce more economic DH (Dansk Fjernvarme 2016a). Besides, a growing RE capacity and the inevitable intermittency of these energy sources increase the frequency and magnitude of DAH price spikes (Milstein, Tishler 2015). After AAK has purchased NJV, this perspective became increasingly relevant for the municipality. The motivation behind an electric boiler takes this development into account and presumes that NJV will experience an increasing amount of hours where its electricity sales won't be profitable due to low prices at the DAH market. Simultaneously, start-up costs are high, which makes it unattractive to shut down NJV for short-term periods. An idle operation mode, where the boiler is simply kept at a minimum temperature is possible, but this option is neither efficient, nor does it contribute to a more flexible energy system. An electric boiler in close proximity to NJV, with a capacity that could cover the minimum electric load, would solve these issues. This would be equal to point C in Figure 2.3. In moments of short-term price drops, NJV could continue to run in this operational mode and transmit its power production to the electric boiler. Thus, it avoids expensive start-ups and at the same time a certain heat demand is covered through the boiler. Also, the power plant's turbine would benefit from an electric boiler as a reduced number of start-ups can increase its operational lifetime. Besides, the combination of NJV and an electric boiler has an increased potential to offer balancing services to the TSO, which can be another revenue source. It should also be noted, that the design of an electric boiler is relatively simple, meaning low O&M and investment costs (Energistyrelsen 2015c). It has a short start-up time and it is easy to regulate.

The advantages of an electric boiler have been elaborated. Now, the next paragraph discusses the question how such a unit would be modelled, if it was decided to do so. Following data from Energistyrelsen (2015c), efficiency can be set to 99%, thus heat and electric capacity are almost identical. As explained previously, the electric capacity should be between 65 – 85 MW. To begin with, one could set up two equal electric boilers in energyPRO, in order to represent the possibility to operate on two different markets, namely DAH and downward balancing market. They are both exclusive to each other, meaning that only one of them can run at a time. One of them is connected to DAH market prices, while the other one refers to downward balancing market prices (in Danish: Balancekraftpriser, Nedregulering). Depending on the achievable prices on the two markets, the electric boiler with the lowest NHPC will be activated. It was found that under this setting the boiler would run app. 250 h/a and during 2/3 of this time it was activated on the balancing market. From personal communication with Aarhus Forsyning it was known, that their electric boiler runs between 500-600 h/a. The difference could be explained by considering special downward regulation volumes in DK1. In 2015, there were nearly 1,200 hours with a demand for special downward regulation with more than 80 MWh/h (Nordpool Spot 2016).

A main difference between special and regular downward regulation is the auction scheme. Regular downward regulation is paid-as-cleared, which means that every unit that is activated receives the price of the last unit which was activated. Thus, one often receives a price which is more attractive than the price which has been initially submitted to the TSO. Contrary to that, special downward regulation is paid-as-bid. Thus, market actors can only receive the price which they have submitted. For both auctions only one bid is submitted to energinet.dk which counts for both balancing markets. Over the time market actors have learned to predict the need for special downward regulation and thus, they have changed their bidding strategy. In hours where special downward regulation is expected, it is more profitable to submit a very low price. Of course, with a very low price one is more likely to be disregarded for regular downward regulation by energinet.dk. Though, when activated for special downward regulation one profits from the very low price one has submitted earlier. It could be argued, that the paid-as-bid auction scheme for special downward regulation led market participants to lower their bids beyond their actual marginal price points in order to increase profits.

Special downward regulation is a reaction of the Danish TSO to a demand from northern Germany where wind production often exceeds transmission capacity towards southern Germany. Thus, at the interconnector between DK1 and the German TSO Tennet there is a demand for negative balancing service to account for excessive wind production. Therefore, one could include a third electric boiler which operates at this market. Using a *Z-function* in energyPRO the boiler would be modelled in a way that it could only be activated when the others are not active in the spot or the regular balancing market. The main modelling challenge in this respect is the achievable price for special downward regulation. As mentioned previously, the paid-as-bid auction scheme does not provide hourly prices as it is the case for paid-as-cleared auctions. The only available information is the hourly volumes which were requested by energinet.dk (Nordpool Spot 2016). To solve this, one could set a threshold value to a certain volume demand. If the required special downward regulation in a given hour is below that threshold, the boiler in the model wouldn't be activated. If it exceeds the threshold, then it is assumed that the boiler gets activated. The submitted price could be set to 100 DKK/MWh below the regular downward regulation price in that hour. Certainly, this model design would have various drawbacks. First, the bidding price for special downward regulation is highly speculative and so is the threshold value for activation. A more accurate modelling would require market insights, which the author does not possess. Further, it is possible to get partly activated for balancing power, but the model would only distinguish between 0 and full capacity. It could be considered to implement a three-step threshold system which allows to tier the activated capacity according to how much demand for special downward regulation there is in total. The model might also be too precise in respect to the amount of hours where the boiler will be activated. No market participant knows precisely when there will be demand for special downward regulation. Thus, one would always miss certain hours, but in energyPRO the production is optimized in a way that one gets the maximum amount of hours, which is not realistic as well.

Despite these possibilities to model an electric boiler, it was decided to exclude it. The reasons for that are explained in this paragraph. Departure point for the argumentation is the temporal availability of the balancing and special downward regulation market. It was found, that the more markets one includes, the more operation hours an electric boiler will have, thus the more significant it becomes for the system. Now, the question arises, how long these markets will continue to exist in regards to their current volumes and prices. There are good reasons to assume that the special downward regulation market will cease to exist in the next years. Also, the regular downward balancing market might decrease in volume and price attractiveness. Especially the former one has its origin in the fact, that the expansion of installed RE capacity, e.g. in Germany, proceeded much faster, than the high-voltage grid expansion took place. As a consequence, bottlenecks occur, dispatching becomes more frequent and congestion costs level up (ENTSO-E 2014). 50Hertz, one of the four German TSOs, has just recently announced that its congestion costs in 2015 tripled compared to the previous year (Montel.no 2016a). Total redispatch volume increased to 9 TWh, a fourfold jump compared to 2014. Additionally, 50Hertz had to curtail app. 1.5 TWh of wind generation in 2015, costing EUR 150 Mio. These numbers put pressure on German TSOs and politics to advance the grid expansion process. Even the EU Commission has criticized the German government for its delayed progress in that matter (Bauchmüller, Mühlauer 2015). Especially the energy-intensive part of southern Germany shows strong and frequent local resistance against high-voltage transmission lines. Though, the latest developments show a positive turn in that matter (Auer et al. 2015). A long lasting dispute with the Bavarian state government could be solved last year and the German parliament has just recently voted for an amendment of the existing laws which regulate the expansion and planning procedure for high-voltage transmission lines (Saathoff 2015). One cornerstone of the new law provides that underground cables will be the preferential consideration for DC high-voltage transmission lines. This provision is expected to increase costs, but it is also presumed that it will reduce local resistance and eventually speed up the planning process.

From all these points one can assume that the causes for the current state of the regular downward balancing and special downward regulation market will vanish in the next couple of years. Without these two markets, an electric boiler would operate less than 100 h/a in the present model. It was therefore decided not to adjust the model according to the latest planning decisions of AAK. Instead, it seems more appropriate to focus on the actual core of the present thesis, i.e. the synthesis between energyPRO and MCS for energy system analysis.

3.5 Biomass scenario considerations

A major economic advantage using biomass for DH is that there is currently no taxation, as this is the case for electricity or other fuels (Energistyrelsen 2014). In the last years, several cities in Denmark have invested in biomass fuelled CHP plants. In 2014, the city of Aarhus started constructing a 110 MW straw and wood chip fuelled CHP unit (Nielsen 2016). *Amagerværket* in Copenhagen (580 MJ/s heat output) will shift from a coal-fired to a woodchip and wood pellets-fired unit. Completion is expected in 2020 (HOFOR 2015). Also on a smaller scale, the number of new biomass boilers is increasing.

There are several reasons which led to the decision to exclude a biomass scenario from the present study. First, biomass is considered as a valuable and limited resource. In a future, fully renewable energy system, its potential (when not used for food purposes) shall be primarily used for transportation, material production or industrial processes (Mathiesen et al. 2009; Mathiesen et al. 2012). Therefore, biomass fuelled heat and electricity production should only be seen as an intermediate option on a path to a sustainable energy system. During the last 15 years the import of wood pellets has exceeded domestic production by far (Thrän et al. 2005; Flach 2013). In 2012, Denmark imported app. 2,000 Million Metric Tons (MMT) wood pellets, while having a domestic production of 150 MMT. This corresponds to only 7% of its total wood pellet consumption (Flach 2013). This import is mainly covered by production in Eastern Europe and Canada. It is reported that in 2012 a new trade route has started between Ghana and Denmark. Wood chips from old rubber tree plantations are now transported to Denmark (Stelte et al. 2015). All these circumstances are considered controversial in terms of sustainability, especially the Ghana case. It is also contradictory to AAK's sustainability goals which were officially ratified by the city council (Odgaard 2011). It states explicitly that biomass consumption shall not surpass local biomass potential and importing large amounts of biomass from neighbouring or third-world countries is considered to be not sustainable. Summarizing all arguments, it would be inappropriate to make larger, long-term investments, which are based on biomass.

The only thinkable approach would be to utilize already existing infrastructures and limit biomass usage to the outmost. The recent acquisition of NJV offers potential for co-firing. The necessary investments for co-firing depend on the characteristics of the substitute fuel. Wood pellets are regarded as the cheapest option, while wood chips or straw would cause more extensive modifications and thus higher investment costs (Energistyrelsen 2015c). Another aspect that should be considered here refers to utilizing the remaining ash from biomass, which can be used as fertilizer. In a direct co-combustion process, both ashes from biomass and coal are mixed, thus only usable for cement production, road works etc. If both ashes shall stay separated, a biomass gasifier could be a viable option. In this case biomass gasification produces syngas which can be burned with coal in the existing boiler and the biomass ash remains separated from coal ash. Even low-grade biomass, such as straw, is applicable with certain gasification technologies (Dong Energy 2016). Usually, the co-firing share ranges between 5-30% (Ciolkosz 2010). Biomass gasification for co-firing would present an option with a rather low overall biomass consumption. It uses primarily local biomass resources (straw) and retains biomass minerals for a subsequent utilization as fertilizer. Still, it was decided to neglect a biomass scenario in the present study. Main reason is that the arguments against biomass overweigh the potential feasibility of such a production. Further, the fact that Dong Energy has recently closed down its pilot plan for low-grade biomass gasification lowers the relevance of such a scenario as well (ENDS 2014).

3.6 Electrofuel scenario considerations

Besides such well-known technologies that were described above it was considered to design another scenario which contains a more futuristic technology. An electrolyser in combination with an electrofuel plant could be an interesting option. Ridjan (2015) defines electrofuels as liquid or gaseous fuels which are generated during a production process which consumes electricity via electrolysis and uses coal, biomass or CO_2 as a carbon source. As a major benefit, such a system could integrate intermittent renewable electricity production into the transport sector. Replacing fossil transport fuels by using excess electricity and carbon from CCS becomes an interesting option in a sustainable, 100% renewable energy system. The IDA 2050 climate plan emphasised that in such a scenario, biomass cannot supply the entire energy demand in the transport sector (Mathiesen et al. 2009). This is especially the case, as a certain share of the biomass production will be required for sustainable material production. Consequently, cross-sectoral integration of intermittent renewable sources becomes inevitable.

Despite these reasons which would make it interesting to include such a technology into the current analysis, it was decided to exclude an electrofuel scenario. After an initial review of current electrofuel technologies, three main technology types were found: Solid oxide electrolyser cell (SOEC), Polymer exchange membrane (PEM) and alkaline electrolyser (Mathiesen et al. 2013). SOECs operate at around 850 °C with a comparably high efficiency and thus producing nearly no waste heat (Ridjan et al. 2013). Another drawback of SOECs is that they are still in the R&D phase and both, economic and technological data are still very uncertain (Mathiesen et al. 2013). PEM and alkaline electrolyser operate at lower temperatures, i.e. 50-90 °C (Ridjan 2015). Both types are commercially available, even though the capacity range of PEM is considerably lower than that of alkaline electrolysers. The largest, existing alkaline electrolyser is to be found in Egypt with a total capacity of 160 MW (Smolinka et al. 2011), while the largest, planned PEM project has a size of 20 MW (Siemens 2014). Still, also these two technologies were not included in any scenario, because there is no data available on how much potential waste heat one could extract from these processes (Ridjan 2015; Mathiesen et al. 2013). Since this is a key factor in the present study, it does not seem reasonable to include it, when the most important technological parameter is currently not known.

3.7 Environmental data

By default, energyPRO includes three different emission types, i.e. CO_2, NO_x and SO_2. More emission types can be added easily, the only requirement is that emission factors for the various fuel types are known. It is acknowledged that NO_x and SO_2 emissions are important factors for a comprehensive EIA, but in this case it is decided to focus mainly on fossil CO_2 emissions. Only in regards to the operation of NJV, NO_x and SO_2 emissions are considered in order to reflect the resulting taxes which eventually define the bidding price. NO_x emissions are taxed with 0.5 DKK/GJ fuel input and SO_2 emissions with 11.7 DKK/kg SO_2 in flue gas. The SO_2 emission factor for coal combustion at NJV is set to 9 g/GJ fuel input, following data for average Danish, large coal-fired power plants (Nielsen et al. 2014). Otherwise, NO_x and SO_2 emissions are not included here. On the one hand this is done for simplicity and time reasons and on the other hand it is not within the scope of this thesis to analyse environmental consequences in depth (cf. Figure 1.8). CO_2 emissions are allocated to coal, natural gas, oil and electricity consumption. Coal emits 95 kg CO_2/GJ and natural gas 56 kg CO_2/GJ (Umweltbundesamt 2006). The emission factor for electricity in Denmark was 230 g CO_2/kWh in 2015, which is based on the 200% method (energinet.dk 2015b). A large share of Denmark's power production is based on central CHP plants and this requires a distribution of emissions between power and heat. Energinet.dk supplies values for both, the 125% and the 200% method. These methods assume that heat from CHP production is produced with an efficiency of 125% or 200% respectively. The 200% method that is applied here generates higher CO_2 emission factors. Since heat is produced with a higher efficiency compared to the other method, more fuel and consequently CO_2 is allocated to power production. For comparison, the 125% method would indicate an emission factor of 192 g CO_2/kWh in 2015 (energinet.dk 2015b).

It is decided to allocate no CO_2 emissions to excess heat delivered from Aalborg Portland. Even though CO_2 emissions are largely based on fossil fuels in this case, the aspect that it is excess heat prevails. The cement production planning does not depend on DH demand, respectively the compensation for DH delivery. Therefore, CO_2 emissions from Aalborg Portland should be allocated to the cement only. Waste burned in Reno-Nord contains a biogenic and a fossil share. Average Danish waste is supposed to be 55% renewable and 45% non-renewable (Danish Energy Agency 2014). In this case, the former 55% would be considered to be CO_2 neutral. Waste incineration in Denmark is supposed to have a fossil CO_2 emission factor of 37 kg/GJ waste (Nielsen et al. 2014). Since heat production from Reno-

Nord is non-adjustable, so are the CO_2 emissions and consequently it is decided to neglect them in the model.

3.8 Economic data

In order to reflect the investment costs for new production units in a single year's simulation period, the Present Value Annuity Payment was calculated. It is a periodic payment which is due at a date in the future. If one decides to amortize a loan based on an annuity payment, the Present Value Annuity Payment reflects the amount which is due after the first period. Given that the interest rate stays constant and that the payment does not change, the annuity payment stays constant during the whole payback time (Fight 2005). The interest fees decrease over the years, because the remaining debts become smaller with every term. At the same time the instalment increases and thus the overall annuity payment stays constant. The following formula, adapted from Fight (2005), describes the amount which is used for comparing the different investments in a one year simulation.

$$AP = \frac{r * PV}{1 - (1 + r)^{-n}}$$

AP is the annuity payment which depends on the interest rate r, the present value of the total investment PV and the number of periods n where payments are due. For the present study an interest rate of 4% and a period of 20 years was determined.

Aalborg Forsyning purchases a large part of its energy from external suppliers and the invoicing is done per unit of heat delivered, i.e. DKK/GJ. This is the case for Aalborg Portland, Reno-Nord and small-scale units. Since these generation plants are not owned by Aalborg Forsyning, only the final price for heat delivery is of interest. Thus, economic modelling is limited to these purchase prices. Since their prices are confidential, the exact costs cannot be mentioned here. Table 3 gives an overview about economic key figures that are used in the reference model and the subsequent scenarios.

Cost component	***Value***	***Unit***	***Distribution Type***	***Source***
AAK DH units				
NJV O&M variable	14.9	DKK/MWh el	-	Energistyrelsen (2015c)
NJV start-up costs	200,000	DKK/start-up	-	Own estimate
HP Investment	325-526	MDKK	Uniform	Energistyrelsen (2015c)
HP O&M total	3.4	MDKK/year	-	Energistyrelsen (2015c)
Geothermal Investment	659-1225	MDKK	Uniform	Energistyrelsen (2015c)
Geothermal O&M total	22	MDKK/year	-	Energistyrelsen (2015c)
Solar Thermal Investment	238-442	MDKK	Uniform	Solvarmedata.dk (2016)
Solar Thermal O&M Total	4.2	DKK/MJ heat	-	Energistyrelsen (2015c)
Fees and Taxes				
Energy tax (coal)	54.9	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
NO_x tax (Coal)	0.5	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
SO_2 tax (coal)	11.7	DKK/kg SO_2	-	Dansk Fjernvarme (2016b)
CO_2 Tax (Coal)	16.2	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
Feed-in-tariff	3	DKK/MWh el	-	energinet.dk (2016)
Grid fee TSO	82	DKK/MWh el	-	energinet.dk (2016)
CO_2 quota	40-174	DKK/t CO_2	ModPERT	energinet.dk (2015a), Meibom et al. (2014)
Elafgift	383	DKK/MWh el	-	Skatteministeriet (2016)
PSO fee	261	DKK/MWh el	-	energinet.dk (2016)
Energy tax (Gas)	52	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
NO_x tax (Gas)	0.2	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
CO_2 Tax (Gas)	13.8	DKK/GJ fuel	-	Dansk Fjernvarme (2016b)
Other costs				
DK1 DAH market Annual Average	116-410	DKK/MWh	ModPERT	energinet.dk (2015a), Meibom et al. (2014)
Coal price	17-30	DKK/GJ	ModPERT	energinet.dk (2015a), Meibom et al. (2014)
Natural gas price	44-83	DKK/GJ	ModPERT	energinet.dk (2015a), Meibom et al. (2014)

Table 3: Overview over cost components used in the scenario design

4 Probability distributions

After four different energyPRO scenarios were designed, their input parameters need to be fitted into a MCS. The underlying methodology was extensively described in chapter 2.3.4. It is decided to apply a ModPERT distribution for coal, natural gas, CO_2 quota and DK1 spot prices. Investment costs for new production units are uniformly distributed, following an example from Bustreo et al. (2015). A ModPERT distribution is a modification of the previously described BetaPERT distribution (cf. chapter 2.3.5). Its advantages is that the parameter γ can be adjusted according to the estimated uncertainty. In a standard PERT distribution, γ would be set to 4. Increasing γ leads to a higher emphasis on the most likely value for the resulting mean of the distribution (Figure 4.1). Here, a ModPERT distribution with minimum = 5, most likely value = 7 and maximum = 10 is displayed. It can be seen that the higher γ, the more concentrated the distribution will be around the most likely value and simultaneously the lower the standard deviation. Decreasing γ will lead to a flatter distribution, reflecting a higher degree of uncertainty. The ModPERT distribution is supposed to be the most appropriate approach for modelling expert opinions, as it is very intuitive and easy to define. One can compare a distribution with the same three basic parameters while changing γ and evaluating the resulting distribution curve which would best match the expected uncertainty. A brief literature survey showed that the application of distribution types varies considerably. Bustos et al. (2016) use a Beta distribution to model the electricity prices in their system. Brouwer et al. (2016) use a log normal distribution for their natural gas-to-coal price ratio. A Bradford distribution was applied by Pereira, Edinaldo José da Silva et al. (2014) who generated values for electricity prices. Eventually, the literature study could not clarify whether there are distinct distribution types which ought to be used in relation to e.g. coal or spot prices. Thus, it was decided to keep the ModPERT distribution.

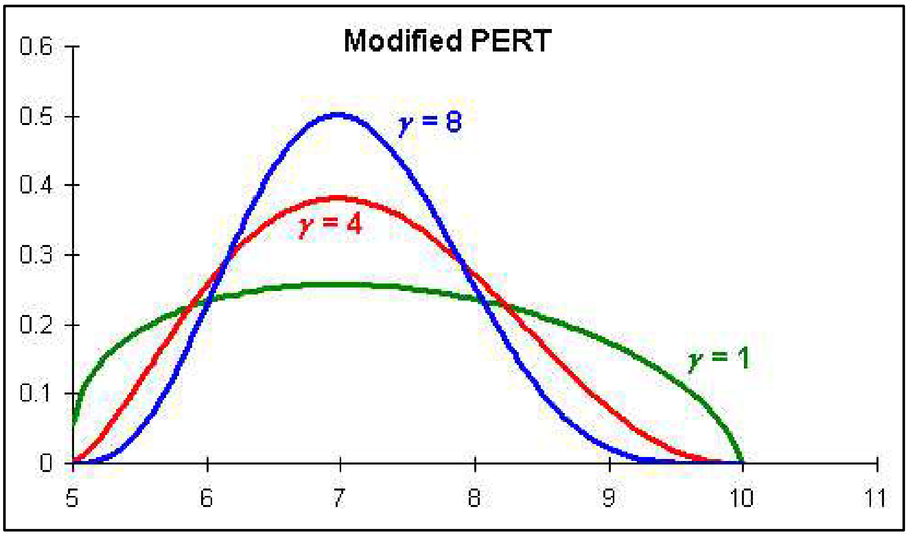


Figure 4.1: ModPERT distributions (5, 7, 10) with different γ values; excerpt from ModelRisk

The annual heat demand is modelled with a normal distribution and the heat output from Aalborg Portland is modelled with a discrete distribution. For the latter case it is straightforward to use a discrete distribution, because the event of interest is whether Aalborg Portland could stop operation and consequently deliver DH or not. Thus, there are two events which can take place and each of them is assigned a specific probability of occurrence. Time constrains did not allow for an extensive expert consultation in order to define how probable it is that Aalborg Portland shuts down within the next years. Based on own estimates, the probability that Aalborg Portland will stop operation is set to 20%, which is modelled with a Bernoulli distribution.

The annual heat demand is determined by the number of connected customers, system efficiency and the temperature variations. As discussed in chapter 1.3, the gross annual heat demand is mainly influenced by annual temperature variations. Even though the number of connected customers has increased steadily during the last decade, a corresponding increase in heat demand could not be observed. It is assumed that efficiency measurements offset the increased amount of customers. Underlining the suitability of using a normal distribution for the heat demand, Allcroft et al. (2001) showed that weather variables are generally best described by normal distributions. Also the Intergovernmental Panel on Climate Change (IPCC) bases mean temperature statistics on normal distributions (IPCC 2001). It is assumed that this institution whose work has a considerable impact worldwide, makes thorough decisions on their data modelling. Thus, it seems reasonable to apply a normal distribution. Figure 4.2 shows the resulting normal distribution for Aalborg's annual gross heat demand, which is based on data from 2004 – 2014. According to this the mean is equal to 6450 TJ, having a standard deviation of 420 TJ. The graph ranges from the mean +/- triple standard deviation, covering 99.7% of the possible data set.

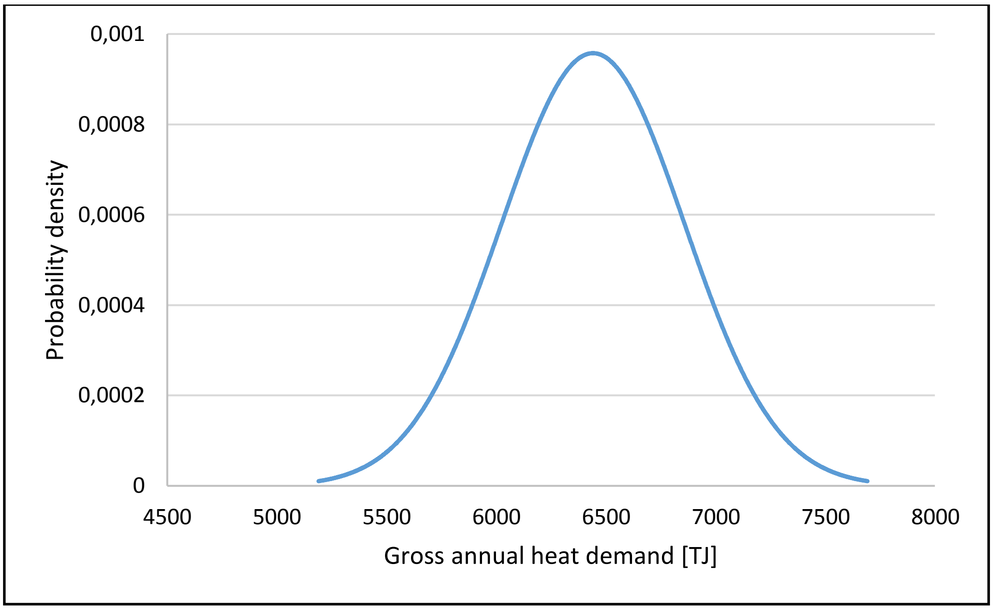


Figure 4.2: Normal distribution to simulate Aalborg's gross annual heat demand

Suitable distribution types for the input variables were selected. In a next step, the parameters that define ModPERT distributions need to be determined. As mentioned above, literature surveys do not give a clear picture on these issues. Further, searching for *energyPRO* in combination with *Monte-Carlo simulation* in the most common databases, such as Web of Science or Science Direct did not show results which could provide the methods that are needed here. Therefore, two new approaches were developed to determine the required parameters for a ModPERT distribution, i.e. the most likely value, maximum, minimum and γ.

Approach 1: Point of departure for both approaches are two studies which provide spot, coal, natural gas and CO_2 quota estimates until 2035. The Danish TSO, energinet.dk, publishes a data catalogue which summarizes the key assumptions behind all its prognosis, analysis and models. The price forecasts between 2015 and 2020 are based on a mix of forward prices and prices from the IEA's World Energy Outlook 2014 – new policies scenario. The closer to 2020, the more weight is appointed to IEA prices (energinet.dk 2015a). The other study was conducted by Dansk Energi, a Danish think tank for energy businesses. In 2014, they published an analysis on future spot price scenarios in Europe based on the Balmorel model (Meibom et al. 2014). Similar to energinet.dk's study they used future prices from the ICE and other exchanges until 2017. After that they applied their model to calculate spot prices. An integral part of their study were also future coal, natural gas and CO_2 quota prices, since they have a major influence on the spot price setting. Overall, the study refers to three sources for these price forecasts. One source relates to futures which were derived from the ICE. In this case, prices are fixed after 2019, according to the latest future price. Another source is the Danish energy projection from 2012, published by the Danish Energy Agency (Energistyrelsen 2012). It should be noted here, that the Danish energy projection is also partly based on the IEA World Energy Outlook as it is the case for energinet.dk's forecast. The last data set is based on an EU forecast, made public in 2014. It is an impact assessment analysis of the different pathways towards achieving European energy goals in 2030 (EU Commission 2014a). Eventually, for each parameter there are four different values. One from energinet.dk and three from Dansk Energi. Starting in 2016, the next five years were considered, ending up with 20 values each. The data sets were adjusted to the price level of 2015. Out of these, the maximum, minimum and average value were selected as input parameters for the ModPERT distribution. In this case, the average is supposed to be equal to the most likely value.

Approach 2: Another way to describe the range of possible prices as an input for a ModPERT distribution is by comparing ICE future prices from different years. As mentioned above, the study by Dansk Energi utilized futures to determine expected prices. Coal, natural gas, spot and CO_2 quota futures for 2017 were obtained in September 2014. These prices are compared against 2017 futures, which were recently obtained in April 2016. The absolute spread is then added/subtracted from the future price which was obtained by Dansk Energi in 2014 to determine the maximum/minimum for the ModPERT distribution. The most likely value is set by the 2017 futures from Dansk Energi. Price levels are set to 2015. One advantage of this method is that it allows to incorporate the latest price developments. At the same time it does only consider price fluctuations within one and a half years, i.e. between September 2014 and April 2016. Historical developments of e.g. coal and gas prices exhibit greater variations over several years, which would not be covered by the current approach (Quandl 2016).

Figure 4.3 shows the resulting ModPERT distributions from both approaches for the case of natural gas (Dutch TTF futures). The blue curve shows the probability density for approach 1, while the red curve refers to approach 2. Both distributions are shown for γ = 4. They result in a nearly identical maximum, but the minimum is clearly different. Approach 1 gives a minimum of app. 45 DKK/GJ, while for approach 2 it is slightly below 30 DKK/GJ. This behavior can be explained as follows. Approach 2 incorporates latest prices for natural gas futures, which have considerably dropped during the last one and a half years (Quandl 2016). While 2017 natural gas futures were traded at around 56 DKK/GJ in September 2014, prices in April 2016 were at around 28 DKK/GJ (Meibom et al. 2014; Powernext 2016). Therefore, approach 2 indicates a much lower minimum compared to approach 1. The higher spread also results in a lower peak around the most likely value. While approach 1 reaches a probability of nearly 0.05 at its peak, approach 2 is only slightly above 0.03.

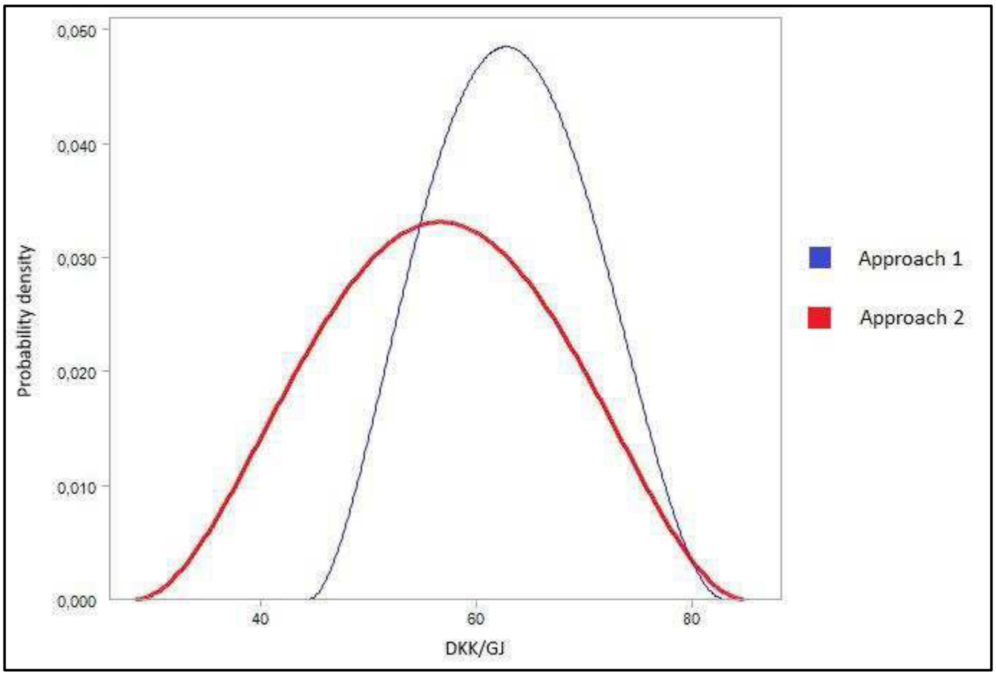


Figure 4.3: ModPERT distributions resulting from two different methods to determine the min, max and most likely value

Finally, it was decided to use approach 1. Even though it lacks a certain level of topicality, as data are reaching back until 2012, the fact that it comprises the expertise and assessment of four different institutions is a strong point. Further, the inclusion of the latest future prices is considered to be of lower importance, because a municipal investment decision normally has a stronger long-term focus. Consequently, it seemed more appropriate to prefer a robust price estimate over a most recent one.

After this, the only remaining parameter γ had to be set. Different values were tested and the resulting shape of the probability distribution was judged against how much impact the average value should obtain. Eventually, it was found that $\gamma = 2$ reflects a curve which does not place too much emphasis around the average value and it is not too uniform at the same time. Deciding on a lower value than standard PERT $\gamma = 4$ acknowledges that the average value of the four different forecast sources is not exactly the same as a most likely value. Though, it is also assumed that the average between these four different predictions points towards a somewhat more likely value than the minimum or maximum values. This is why $\gamma = 2$ seems to be an appropriate compromise between both aspects.

Figure 4.4 shows the probability distributions based on the methods previously described. The DK1 spot price varies between 116 – 410 DKK/MWh. The maximum is determined by assumptions from the EU Impact Assessment and energinet.dk. Based on futures, the expected price would be allocated to the lower end. For comparison, Nordic Power futures for 2017 – 2019 are currently traded at around 135 DKK/MWh (NASDAQ 2016). A recent study by the Swedish utility Bixia assumes Nordic spot prices to increase to 275 DKK/MWh until 2030 (Montel.no 2016). This would approximately reflect the mode for the current DK1 spot price distribution and confirms the suggested scheme. The coal price distribution ranges between 17 – 30 DKK/GJ. Similar to spot prices, the EU assessment foresees higher prices, compared to the other studies. This is also the case for natural gas, which can fluctuate between 44 – 83 DKK/GJ. In relation to current futures for coal and natural gas, both are beyond the distribution's minimum. Coal futures for 2017 (ICE Coal ARA) are currently traded at 11 DKK/GJ and TTF gas futures for 2017 at 28 DKK/GJ (Powernext 2016; ICE 2016). The CO_2 quota assumptions show the largest spread among all four distributions, i.e. factor 4 between minimum and maximum. The latter limit is determined by the Danish Energy Projection from 2012, while the lower end is due to the EU assessment and futures. Contrasting to the previous two parameters, current CO_2 futures (EUA) are fairly close to the modelled probability range. At the moment they are traded at 38 DKK/t CO_2 (ICE 2016b).

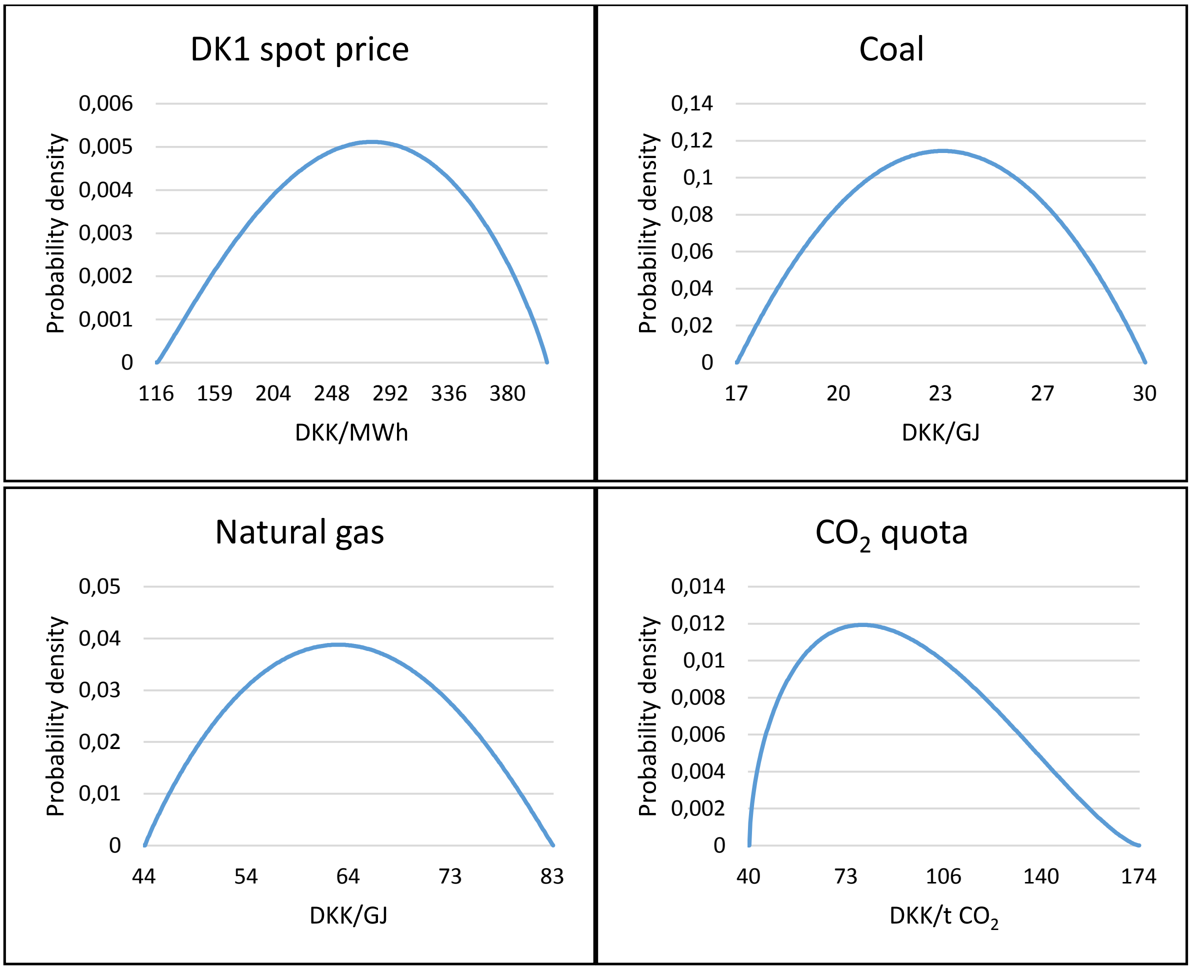


Figure 4.4: Final ModPERT probability distributions to generate input variables for the energyPRO model

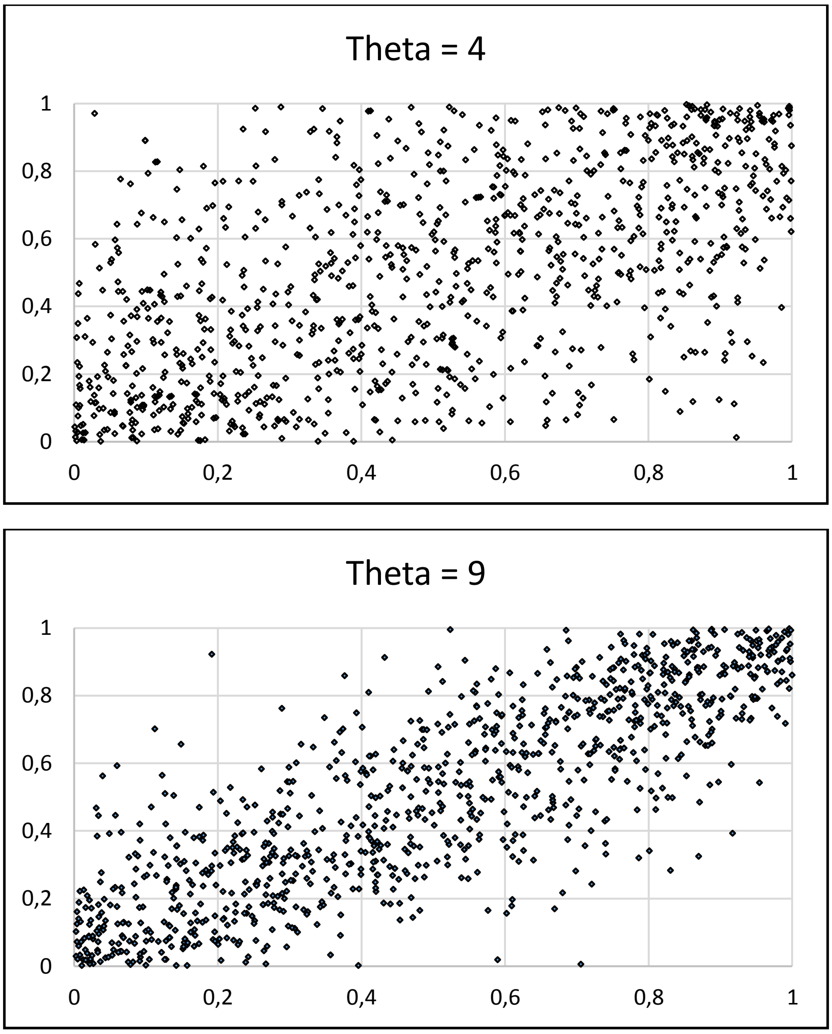
4.1 Implementing correlations and dependencies

A risk analysis comprises a theoretically infinite amount of different parameter combinations. One can be easily overwhelmed by the potential number of those parameter combinations or scenarios that one forgets to check them for sanity. It is not uncommon that one parameter has an influence on another one, e.g. if natural gas prices rise, spot prices will most likely increase as well. Risk analysts distinguish between correlation and dependency. The latter one describes a relation where one has qualitative knowledge about the direction of influence. In regards to the previous example, the coal price has an influence on the spot price, but not vice versa. Talking about correlations means that this qualitative knowledge is missing, but nonetheless a certain pattern is observable. If one parameter goes up, another one rises as well. Or, if one decreases, the other one increases. In this case it is not clear why it happens, but one can make this observation nonetheless.

For the present MCS coal, natural gas and DK1 DAH prices are assumed to be correlated. Ferkingstad et al. (2010) find that Nordic electricity prices are interlinked through gas prices, but correlations between coal and NordPool prices are not confirmed. This could be related to the Nordic fuel mix for electricity which is dominated by hydro generation. Fossil fuels should therefore have a comparably small impact on electricity prices. However, it should be considered that the fuel mix within the

NordPool area is different and that Denmark still has a considerable coal share. Prices could also be influenced by neighboring power markets which are more coal dominated, e.g. Germany. Castagneto-Gissey (2014) finds evidence that there is a relationship between coal and natural gas prices in the NordPool area, whereas coal has a stronger effect on natural gas than vice versa. After all, it seems justified to assume a correlation between coal, natural gas and DK1 DAH prices.

Vose (2008) claims that any scenario which is generated during a risk analysis must be theoretically understandable in real life. It implies that one might want to avoid scenarios where we see high coal and natural gas prices, but low DAH prices. In addition to the reasons named above, this is why the present study uses copulas in order to reflect a correlation between these three parameters. It is possible to correlate two or more random variables while the shape of the distribution is not altered. In this case it was decided to use a Frank copula (Figure 4.5).



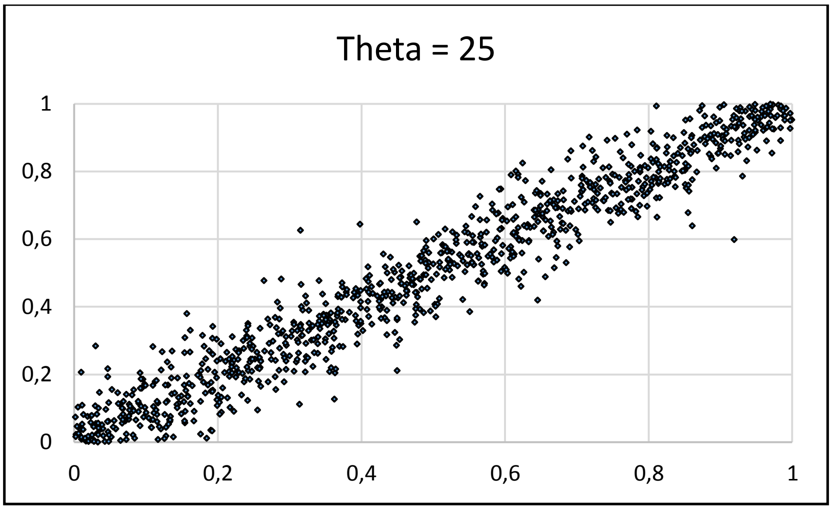


Figure 4.5: Frank copula with different theta values, showing percentile correlations

The theta value determines a copulas correlation density. It can vary between 35 and -35. For negative values the correlation takes a negative shape, i.e. if one value is high, the other value is low. A value of 0 means there is no correlation at all. After examining several copula plots with various theta values it was decided to apply theta = 9 to the correlation between spot, coal and natural gas prices. Such a copula seems to give a reasonable compromise between a desired degree of correlation but it also leaves enough variability for unforeseen future developments. As displayed in Figure 4.5, for a given percentile on the x-axis, there is still a considerable range of possible percentiles on the y-axis. At the same time, very extreme combinations, such as a 0.95 percentile on one axis and a 0.1 percentile on another axis are nearly excluded. Other theta values seemed to be either too loosely correlated or showed a too strong correlation, which would narrow the potential parameter constellations.

It was also considered to include CO_2 quota prices into the correlation modeling. Though, this has not been done because a correlation between natural gas or coal and CO_2 quota prices can hardly be justified. The correlation between CO_2 quota costs and spot prices is relatively straightforward, since CO_2 costs go into the marginal costs of fossil fueled power plants and thus ending up in a price zone's merit order. Without further in-depth correlation modeling, it was only possible to create a positive correlation pattern between all four variables in ModelRisk. In this case CO_2 quota prices would also positively correlate to natural gas and coal prices. This could not be justified, because no obviously logical explanation for such a behavior can be given. Eventually, it was accepted that certain parameter combinations might be rather unrealistic, e.g. an extremely high quota price and a very low spot price. At the same time, quota prices are decoupled from natural gas and coal prices, which seemed more realistic and important than the other way around.

5 Results

This chapter is divided into three parts. Part one presents relative and cumulative frequency plots of the chosen parameters. Four parameters are analyzed in this section, i.e. CO_2 emissions, NHPC, fossil fuel consumption and the production share of the new unit. The first three parameters are presented by histogram plots with relative and cumulative frequencies. The production shares are illustrated by bar charts including standard deviations. The second part presents a correlation analysis showing a selection of scatter plots from the Geothermal scenario. More scatter plots from the other scenarios are found in Annex 1-3. In the last part the results which were generated through MCS are compared with output data from a 3-scenario analysis and a sensitivity analysis. Each chapter starts with a summary of key results.

5.1 Relative and cumulative frequency plots

- *Pure calculation time for four scenarios with each 1,000 samples took almost 3 days.*
- *Geothermal scenario shows lowest CO_2 emissions – 80% of its results have an emission rate of less than 34 kg CO_2/GJ heat while for the other three scenarios this value is around 52 kg CO_2/GJ heat.*
- *CO_2 emission reductions per annual capital costs are also most favorable for the Geothermal scenario. HP and Solar show similar results with only minor differences.*
- *BAU scenario has the lowest NHPC, Geothermal is the most expensive. Difference is less substantial – 80% of the BAU's results are below 65 DKK/GJ heat, but for the Geothermal scenario this value corresponds to 73 DKK/GJ heat.*
- *Only in 4 out of 1,000 events the Geothermal's NHPC are below BAU. This requires low spot prices, high quota prices, the absence of Aalborg Portland and low investment costs.*
- *Fossil fuel consumption frequency plots are very similar to CO_2 emission plots.*
- *Geothermal scenario has by far the highest annual heat production share. The HP scenario shows a relatively high standard deviation for this parameter.*

Running the MCS with Interface for four scenarios with each 1,000 samples took 67 hours pure calculation time. It is possible to speed up the simulation by running two or more programs in parallel, because energyPRO 4.3 does not utilize all kernels by default. Unfortunately, it turned out that running several programs in parallel causes frequent program crashes which slowed down the simulation even more. Eventually, only one program at a time was used for the simulation. Though, it was still not possible to run one simulation continuously, because energyPRO seems to aggregate internal memory until it reaches the limit at one point. Then it stops calculating while giving an error message that it ran out of memory. Recently, energyPRO 4.4 has been released which has an improved kernel utilization. This would decrease the calculation time by 25% for the present case. Eventually, it was decided to keep the older and slower version, because stability and assurance of operability was considered more important at a late project stage.

5.1.1 CO_2 emission factors

Emissions which occurred due to coal, natural gas, oil and the HP's power consumption were summed up and divided by the respective gross heat demand. Thus, fluctuations due to changing heat demands are taken into consideration. Also, variations in annual power production from NJV are integrated in this emission analysis. Fuel consumption for power production was assigned based on the same methodology which was used for determining the Energiafgift (cf. chapter 2.2.1). The respective amount was then subtracted from coal emissions.

The Geothermal scenario shows the lowest CO_2 emissions per GJ heat compared to the other three scenarios (Figure 5.1). While it peaks around 30 kg CO_2/GJ heat, the rest lies between 48 – 52 kg CO_2/GJ heat. Though, the Geothermal profile is less centered around the tip compared to the rest. While its mode reaches ca. 27%, the other profiles surpass 30% clearly. In fact, the BAU, HP and Solar scenarios are relatively similar in their distribution profile. The HP scenario shows a slightly higher peak (35%) and the profiles are distributed along the x-axis with only minor differences, i.e. the BAU profile furthest to the right, followed by HP and Solar. Interestingly enough, all four profiles have a second, weaker peak. Regarding the Geothermal profile this tip is relatively close to the first one, but the other three profiles seem to have a gap between the first and the second tip. A closer look at the data shows that there are at least a few events occurring between them, but with a relative frequency below 1%, thus hardly recognizable. The last peak of the BAU, Geothermal and Solar profile contains around 20% of the results which have a CO_2 emission intensity between 56 – 62 kg CO_2/GJ heat. This probably represents the events in which Aalborg Portland is not available, which was also modelled with a probability of 20%. Also in this case, BAU's peak is shifted more towards the right compared to the others. All events showing CO_2 emissions above 62 kg CO_2/GJ heat are only slightly above this value. The absolute maximum is 62.8 kg CO_2/GJ heat.

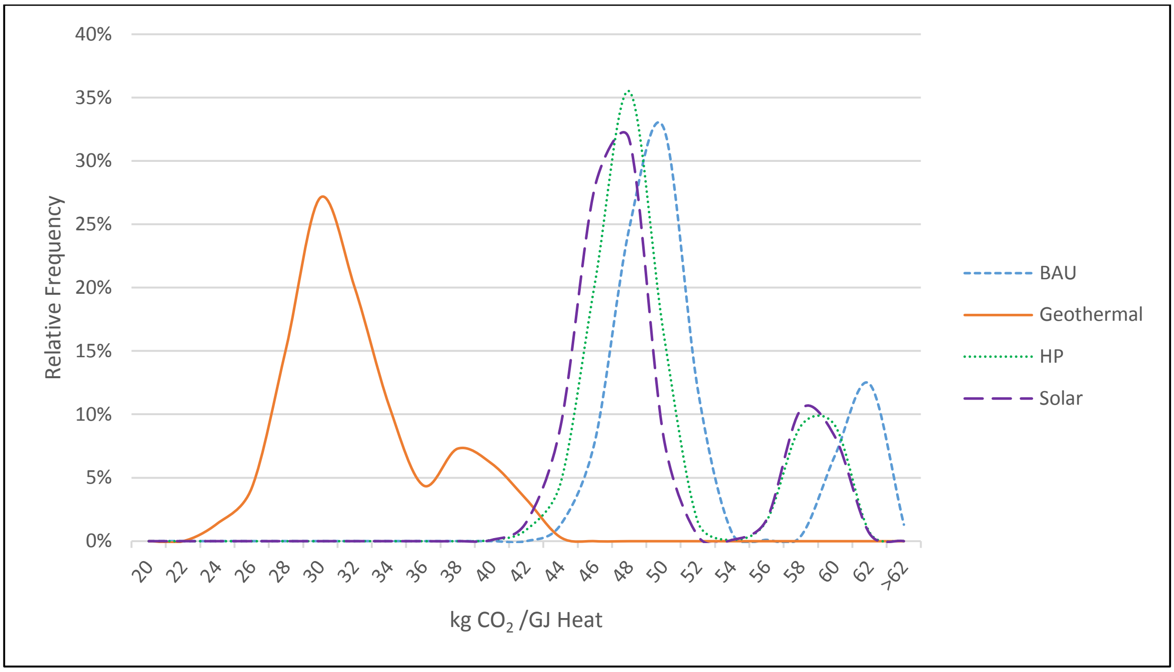


Figure 5.1: Relative frequency plot - average CO_2 emissions from heat production

Figure 5.2 shows the cumulative frequency, i.e. the frequency for a range of values with a given value on the x-axis being the maximum of this range. It is a reflection of the relative frequency graph. The most vertical point of a cumulative frequency graph equals the mode in the relative frequency profile. For the Geothermal scenario around 80% of the results have an emission of less than 34 kg CO_2/GJ heat. The other three scenarios exhibit this threshold at app. 52 kg CO_2/GJ heat. Also, it can be seen that the BAU scenario shows the highest CO_2 intensity as it is shifted furthest to the right.

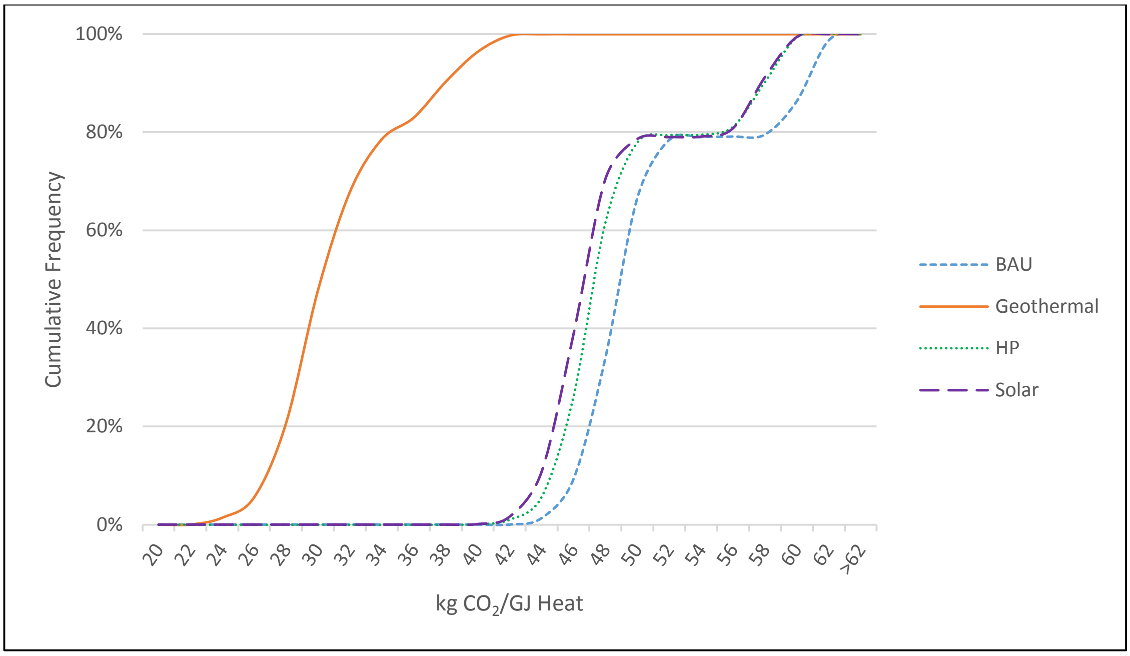


Figure 5.2: Cumulative frequency plot - average CO_2 emissions from heat production

5.1.2 CO_2 emission reductions per annual capital costs

In order to consider the variations in investment and capital costs between the scenarios, the CO_2 savings compared to BAU were calculated against the respective annual capital costs (annuity payment). Figure 5.3 shows the results in form of a cumulative frequency plot. The Geothermal option shows the greatest CO_2 emission reductions per annual capital costs. Considering the previous results, it means that greater CO_2 reductions are not solely caused by higher investment costs in this case. One can expect to save at least 0.2 kg CO_2/GJ Heat*MDKK and 80% of the observed events show reductions of 0.36 kg CO_2/GJ Heat*MDKK or below. Compared to the other profiles, the Geothermal option is the least centred distribution, which is reflected in the relatively shallow gradient. In comparison, the Solar option shows a rather steep gradient, indicating that most of the results aggregate between 0.06 - 0.1 kg CO_2/GJ Heat*MDKK. Even though the 80% threshold value is app. the same for both HP and Solar, there are considerable differences between them. For the HP option one can observe a frequency of app. 40% where CO_2 emission reductions will be below 0.06 kg CO_2/GJ Heat*MDKK. The same event in the Solar scenario has a frequency of less than 1%. Clearly, expected emission reductions from a solar investment are less variable compared to a HP investment.

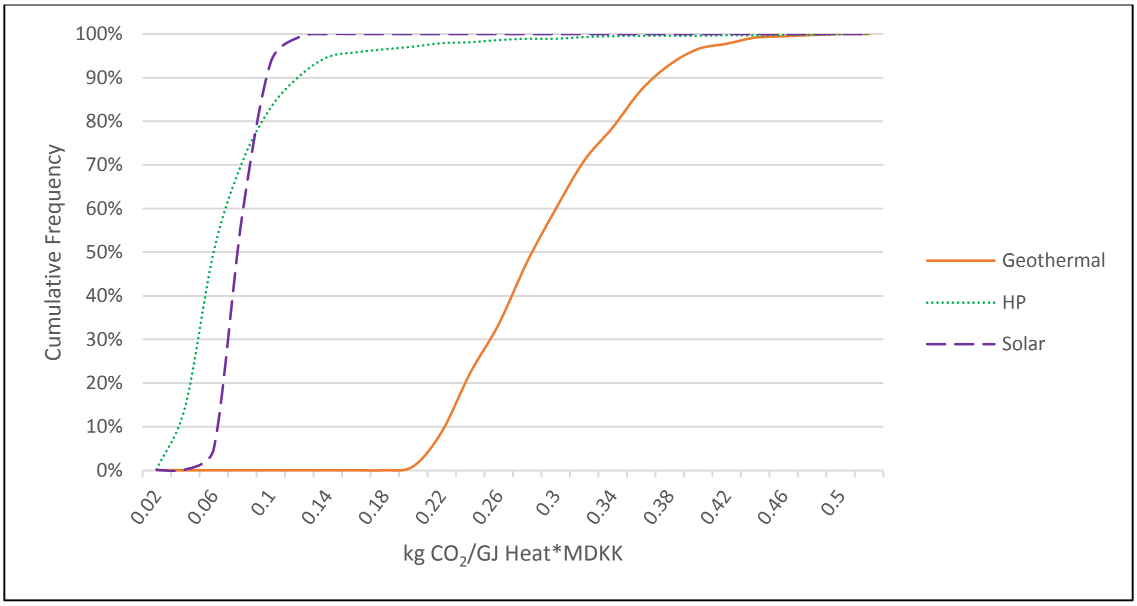


*Figure 5.3: Cumulative frequency plot - CO_2 emission reductions per GJ Heat*MDKK annual capital costs*

5.1.3 Net Heat Production Costs

The following two graphs show the costs per GJ heat production. In this case the costs are limited to generation costs and the annuity mortgage payment where applicable. Other components, such as administration or grid maintenance are not considered here. Thus, the absolute cost values here cannot be used for statements regarding final consumer prices etc. In an average sample, the annual cost structure is dominated by NJV's operation expenditures. Depending on the actual prices, coal purchase is most costly, followed by the Energiafgift and costs for CO_2 quota. Expenses due to external heat purchase, e.g. from Aalborg Portland or Reno-Nord represent only between 10-20% of the total annual expenditures. This share depends a lot on the availability of Aalborg Portland. Annual expenditures for the new generation unit vary between 5% (HP and Solar) and 25% (Geothermal). For the latter one, the annuity payment from the mortgage, Elafgift and PSO tariff are most costly. In the other two cases it is mostly the annuity payment which determines annual costs, though in the HP case this share also depends largely on the operation hours and consequently on Elafgift and PSO as well.

Compared to the previous parameters, NHPC show a rather coherent result structure (Figure 5.4). The difference between the Geothermal scenario and the rest is smaller, but in reversed order. While the former one peaks at around 70 DKK/GJ heat, the other scenarios do this at app. 60 DKK/GJ heat. There is no second peak in the distribution as it was the case previously. It is also worth mentioning that the modes for NHPC are lower than what could be observed for CO_2 emissions. While the latter one reaches modes around 30%, the profiles for NHPC aggregate at app. 15%. This implies that the results are more spread and less likely to occur around one value.

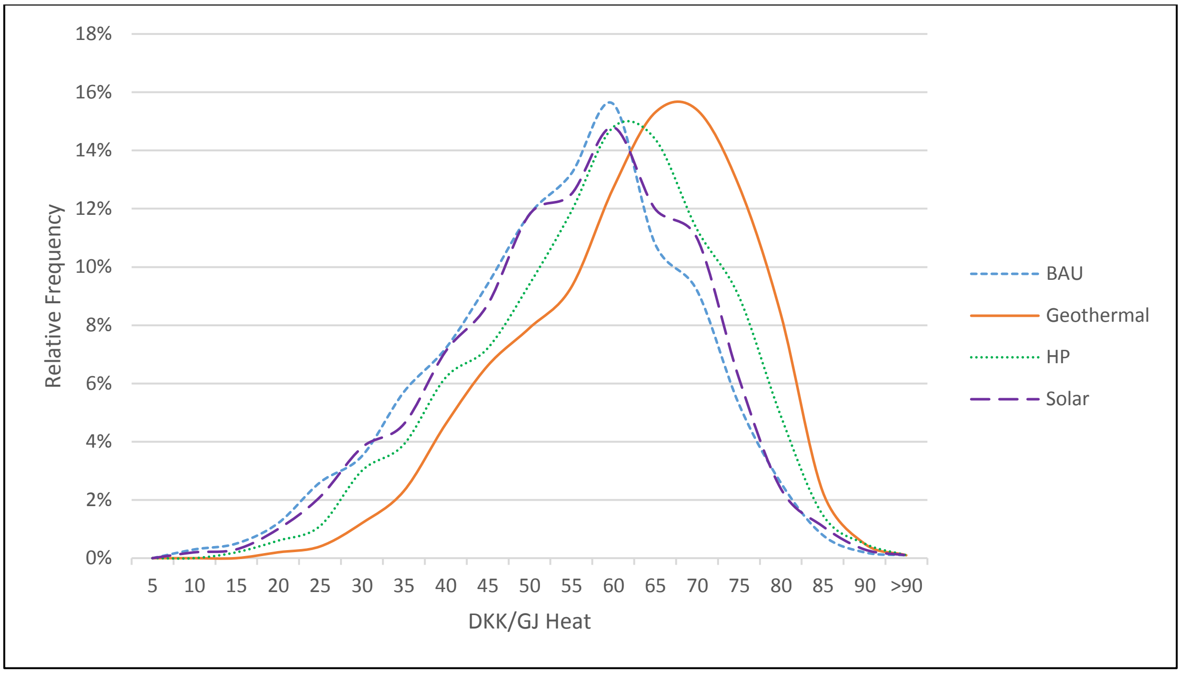


Figure 5.4: Relative frequency plot - Net Heat Production Costs

The coherence from the histogram plot is reflected in the cumulative frequency plot (Figure 5.5). The fact that the relative frequencies in this case are lower compared to the CO_2 emissions is displayed by more horizontal curves for the cumulative frequencies. The ranking among the four distributions is more obvious compared to the relative frequency plot. The HP scenario appears to be the second costly, followed by the Solar and BAU scenario. However, the difference between the last two is only marginal. Looking at it in more detail, 80% of the results of the BAU and Solar profile show a NHPC lower than 65 DKK/GJ heat. The HP scenario is slightly above that, reaching an 80% frequency at around 68 DKK/GJ heat. Eventually, the Geothermal scenario aggregates 80% of its results at a NHPC below 73 DKK/GJ heat.

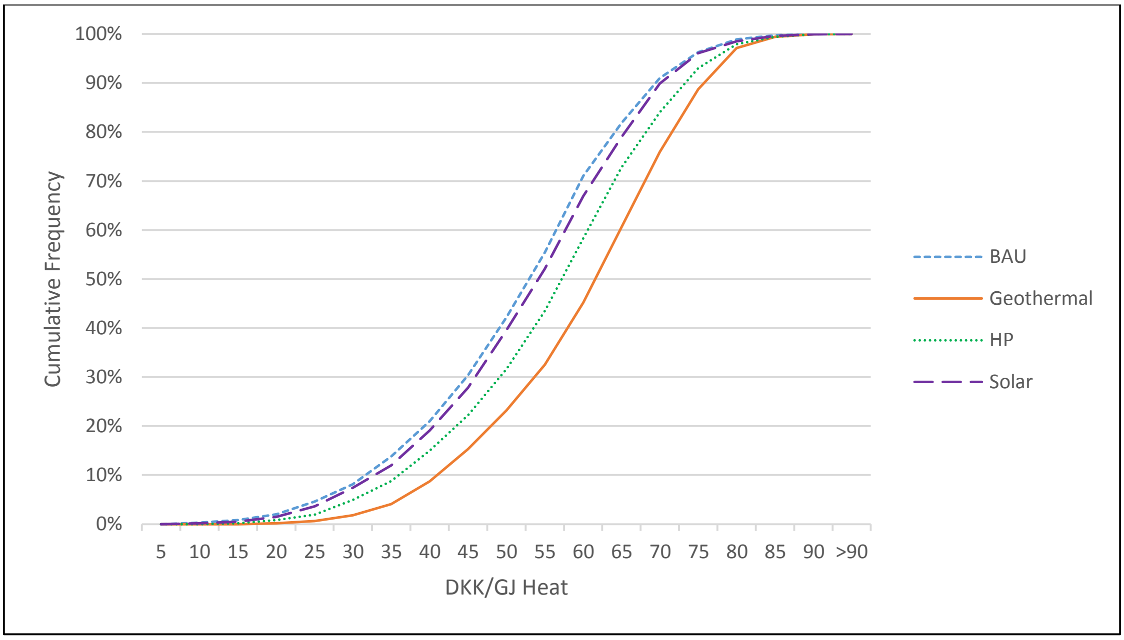


Figure 5.5: Cumulative frequency plot - Net Heat Production Costs

Looking at the primary data, it is found that within 1,000 parameter constellations there are only four cases in which the Geothermal scenario's NHPC are lower compared to BAU. The difference is maximum 3 DKK/GJ Heat. These cases show no similarity regarding the respective heat demand. The observed values are both higher and lower than the distribution's mean. Spot and coal prices for these examples are both located in the lower half of the distribution. All CO_2 quota prices are in the distribution's upper quarter and Portland is not operating in all cases. All investment costs are lower than the expected average. It might not be entirely straightforward that both spot and coal prices are in the lower half for these four scenarios. One could assume that low spot prices and high coal prices are more favorable for the Geothermal scenario. Such a constellation is only possible within the range of the Frank copula which was applied to simulate the correlation between coal and spot price (cf. chapter 4.1). Thus, an extreme case where coal prices are high and spot prices relatively low does only very rarely occur. Additionally, other factors might then be not favorable for the Geothermal scenario. Considering the fact that only four out of 1,000 samples show NHPC which are more economical in the Geothermal case, it could be presumed that it requires a very specific parameter constellation to make this case economically feasible. Such a case would then include relatively low spot, coal and investment costs, while CO_2 quota costs are high and Portland stops operation.

5.1.4 Fossil fuel consumption per heat output

Similar to calculating the CO_2 emissions, the fuel share for power production from NJV was determined by applying the v-formula as described in chapter 2.2.1. Further, the HP's power consumption was incorporated using a fossil share of 40%. This reflects an annual estimate for Denmark's actual physical consumption in 2014 (energinet.dk 2015c).

The two plots showing fossil fuel consumption per heat output are nearly identical with the ones that show the CO_2 emission factors. Therefore, it seemed reasonable to spare its graphical presentation at this point in order to avoid showing a duplicate which has been seen before. The only difference between them is that the HP profile has moved left along the x-axis compared to the Solar profile. This means that in the fossil fuel consumption plot these two profiles are now identical for the first peak and the HP's second peak is shifted clearly leftwards showing a lower fossil fuel consumption. In contrast to that, the HP and Solar CO_2 emission profiles are identical in the second peak. In other words, the HP case exhibits a reduced fossil fuel consumption compared to Solar, but these savings are not reflected in CO_2 emission reductions. An explanation could be that the HP often replaces gas-fueled heat production, which has comparably low CO_2 emissions anyway. Instead of gas it is then fueled by power which has a considerable coal share, thus off-setting CO_2 emissions which are saved due to reduced natural gas consumption.

5.1.5 Annual heat production share

Even though all newly incorporated production units have a comparable heat output capacity, their annual contribution is vastly different. While the Geothermal plant shows an average heat production share of app. 30%, HP and Solar are both below 5% (Figure 5.6). This might also relate to the relative coherent result structure of both HP and Solar for the CO_2 emission factor and the NHPC. The HP scenario has a relatively high standard deviation compared to the other two cases. Both, the Geothermal and Solar scenario have a standard deviation corresponding to 10% and 12% of the average value. For the HP scenario this value reaches nearly 50%. This shows that the HP scenario is more affected by changing input parameters than the other two, implying higher risks and opportunities. The HP can reach a maximum production share of 25%, but it can also go down to below 2% if the parameter constellation is not favorable. The other two scenarios have a shorter range between the extremes. Solar can go down to 3% and up to 4.5%, while for Geothermal the heat production share ranges between 26-43%.

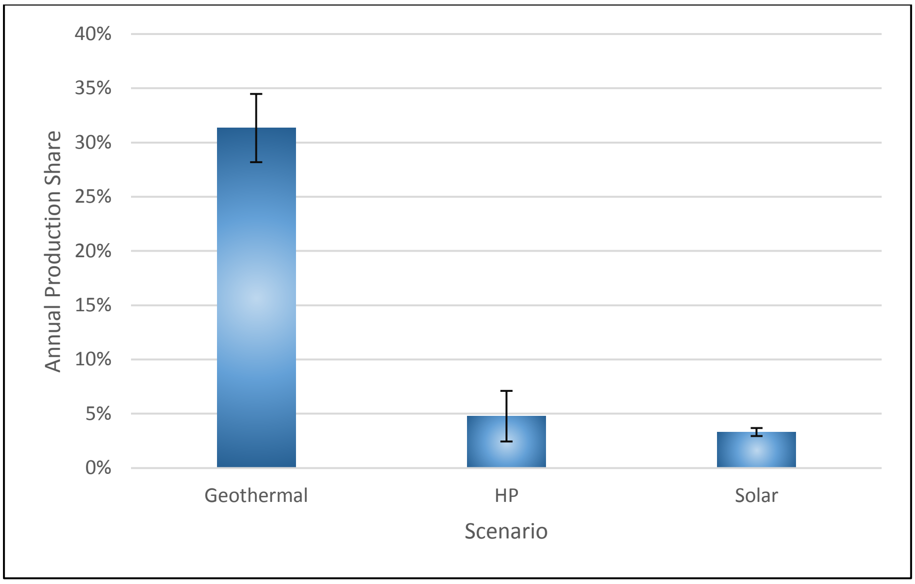


Figure 5.6: Average annual heat production share of the new unit incl. standard deviation

5.2 Correlation Analysis

- *The majority of correlations is weak.*
- *Quota costs of up to 170 DKK/t CO_2 are only weakly, negatively correlated with NJV's power production.*
- *The results show no connection between quota costs and CO_2 emissions.*
- *In case of Aalborg Portland being absent its heat supply would be replaced by fossil fuels mainly. Only in the Geothermal case this is less probable.*
- *In the Geothermal scenario the correlation between DAH prices and heat production share is flipped exponential, meaning that the geothermal plant's output is relatively stable until app. 200 DKK/MWh. The opposite holds true for the HP scenario where it is flipped logarithmic. It decreases greatly at lower DAH prices and reaches a relative stable output after 200 DKK/MWh.*
- *It is found that the correlation between NJV's profit and NHPC is by far the strongest of all. This correlation itself does not come as a surprise, but its strength is worth noticing.*
- *The Geothermal plant can have both positive and negative influence on NJV's economic performance, depending on whether DH sales are appointed to NJV or not.*

The high number of samples and respective results allow a graphical representation in form of scatter plots, which can display possible correlations between two variables. Figure 5.7 shows a selection of variable combinations. For space-saving reasons only scatter plots from the Geothermal scenario are shown in the following. This does not compromise the overall analysis because the plot patterns between the different scenarios were found to be very similar. Also the correlation coefficient (r) was nearly identical in most cases. If this does not hold true, then it will be mentioned for the respective scatter plot. The scatter plots from the other scenarios are shown in Annex 1-3.

A correlation coefficient describes the strength of a relationship between two variables. It can take values between -1 and +1. The closer it gets to +/- 1, the stronger the correlation (positive or negative). The value 0 indicates that there is no correlation at all. A decisive factor for r is the sample size, which in this case is 1,000 – a large amount of samples. The smaller the sample, the more likely it is to produce correlations due to pure chance. Though, such correlations are often not significant. On the other hand, the larger the sample, the more difficult it is to generate correlation due to randomness, but it is relatively easy to obtain significance (Janda 2001). The present correlations were not tested for significance because in this case there is no real population from which one would have taken a sample in order to draw conclusions about the population. Therefore it seems less interesting to determine how likely it is that statistics from a sample will also be observed for the whole population. Getting back to the correlation coefficient, the question arises how to interpret the numerical expression. There is no universally-valid interpretation scheme, but it is possible to find guidelines in literature. In the following, the correlation strength is described by the following terms which refer to a given interval for r.

$r \approx 0$	No correlation
$\lvert r \rvert \leq 0.5$	Weak correlation
$0.5 < \lvert r \rvert < 0.8$	Medium correlation
$\lvert r \rvert \geq 0.8$	Strong correlation

Table 4: Interpretation scheme for correlation coefficients; adapted from Jann (2005)

DK1 DAH prices have a strong, positive correlation with the annual power production from NJV, which is not entirely surprising (Figure 5.7). In this case the relationship is best approximated by an exponential model, even though one could also assume a linear relation. CO_2 quota prices show a weak, negative correlation with NJV's power production. From a visual perspective, this correlation is only hardly observable. It is possible to recognize a certain downward trend at the upper end of the plot and also the density of the plot's upper half seems to decrease moving from left to right. Still, a quota price until app. 100 DKK/t CO_2 does not seem to have any substantial impact on NJV's power supply operation. Even though it is not displayed in Figure 5.7, it should be noted here that the relation between quota prices and coal consumption is nearly identical with the one between quota prices and power production from NJV.

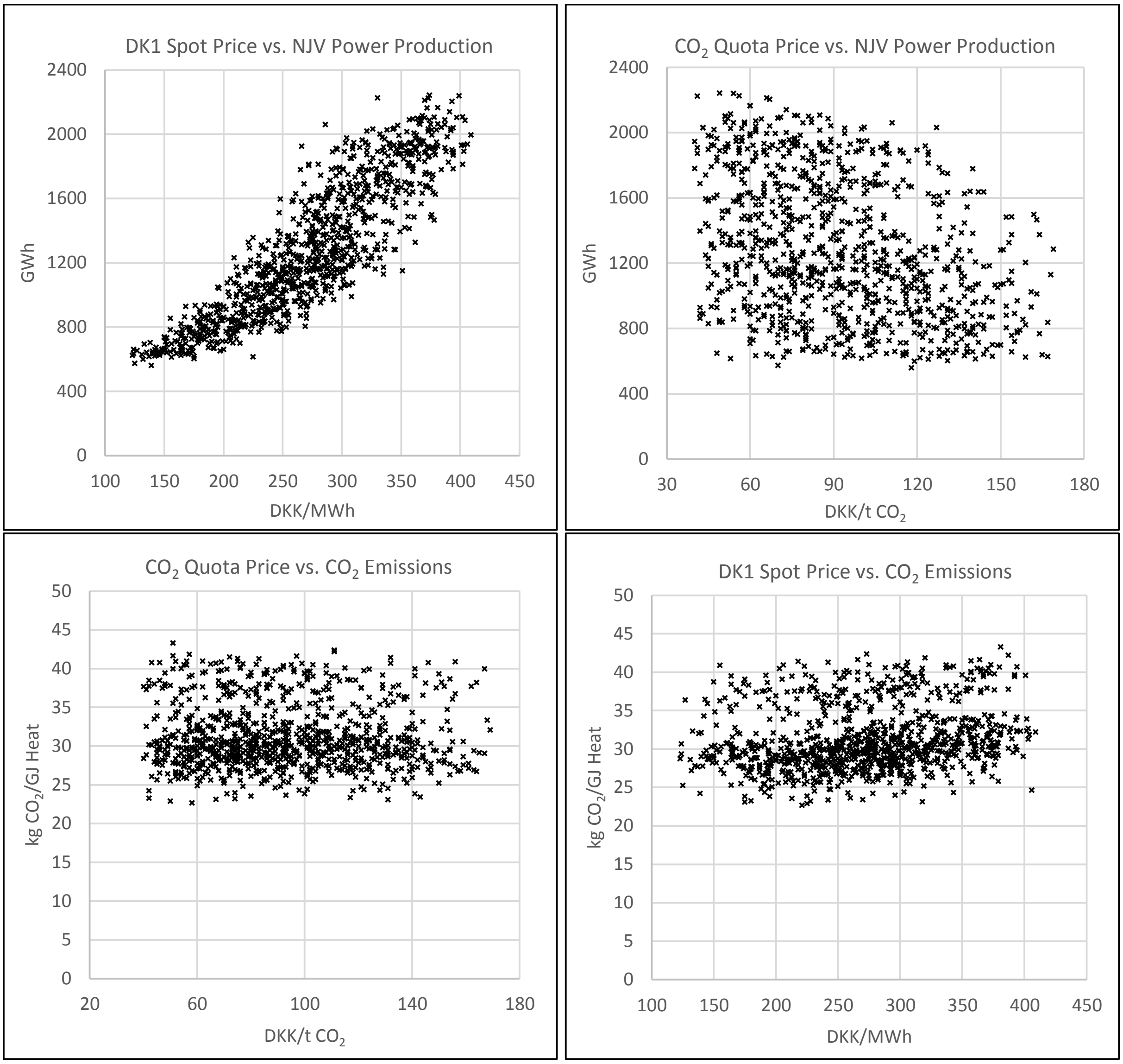
It is remarkable that there is no correlation between quota prices and CO_2 emissions. Thus, one could say that increasing quota prices won't decrease the CO_2 emissions per GJ heat. Though, it should be considered that CO_2 emissions from NJV power production were excluded for this factor (cf. chapter 5.1.1). Despite weak correlations between quota prices and power production/coal consumption there is no such trend for CO_2 emissions from heat output. One could deduct that NJV's heat output does not react to quota price variations, because it is the system's final unit to fulfill the demand. There is no other unit in a comparable NHPC range which could replace such marginal heat production. On the other hand, NJV is also the only unit which is subject to quota costs and this could also account for the missing correlation. Comparing the quota price – CO_2 emission plot between the Geothermal and the Solar scenario one finds that the latter one is more separated between two horizontal stripes. It seems like there are two areas of possible CO_2 emission values (cf. Annex 3). In the Geothermal plot one might also detect a stripe with a higher event density at around 30 kg CO_2/GJ Heat, but the overlaying stripe is not clearly segregated but rather scattered. This two-part distribution of events is most probably reflecting the fact that Aalborg Portland was assigned a 20% probability of shutting down its operation. Hence, in the Solar scenario Aalborg Portland's production would be replaced by fossil fueled heat production. In the Geothermal scenario this consequence is not that clearly visible. The impact of Aalborg Portland becomes also clear when looking at the spot price vs. heat production share plot for the Solar scenario (cf. Annex 3). While there is no correlation between these two parameters, the missing presence of Aalborg Portland has a positive influence on the solar unit's annual production share. This could be related to the low demand in the summer period, where Aalborg Portland and Reno-Nord are often sufficient to cover demand and the solar thermal unit's heat would be rejected unless there is sufficient thermal storage capacity. It could be worth investigating in how far industrial excess heat influences the operation of solar thermal units or in how far it requires additional seasonal storage volume.

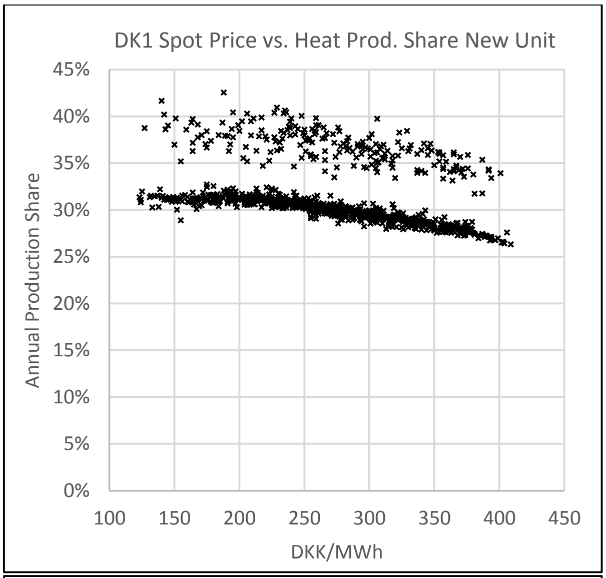
DK1 spot prices exhibit a weak, positive correlation with CO_2 emissions. One can also detect the separation between events where Portland is available and those where it is not. Though, this pattern is much more obvious in the scatter plot showing DK1 spot prices against heat production share (Geothermal scenario). It is best described by a flipped upside-down exponential function. The correlation is weak, which could be explained by the influence of Aalborg Portland. For low spot prices the production share ranges between 30% - 42%. With increasing prices the production share declines at an accelerated rate. This behavior is not surprising either, since the unit's NHPC are obviously DAH price depending. Consequently, geothermal production becomes less economic the higher the DK1 spot price. It is worth noticing that this behavior turns out to be reversed exponentially, meaning that the production share is relatively stable at the beginning of the spot price range. It is then straightforward that for the Solar scenario the production share shows no correlation towards spot prices. Regarding the HP Scenario it is noteworthy that its plot is best described by a flipped upside-down logarithmic function (cf. Annex 2). It also shows a weak correlation only, but it is in fact very close to the higher end of a weak correlation range. Opposite to the Geothermal unit, the HP's production share decreases most at a lower spot price range, i.e. until app. 200 DKK/MWh. After that it stabilizes at a low plateau while spot prices continue increasing.

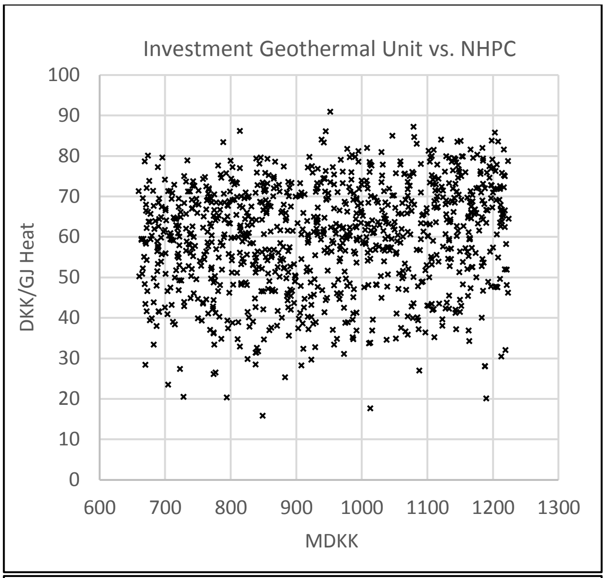
The investment for the Geothermal unit against NHPC shows a weak, positive correlation. It is even weaker in case of HP and there is no correlation for the Solar scenario. Similarly, CO_2 quota costs have a weak, positive correlation, though not as weak as it is the case for the investment costs. The coal price shows a medium, negative correlation against the NHPC. This can only be explained by the applied correlation between coal and spot prices (cf. chapter 4.1). Higher coal prices correlate with higher spot prices and as a consequence the operation of NJV is more profitable which effects the NHPC positively. DK1 spot prices show a strong correlation with the NHPC, both for a linear and a flipped upside-down exponential function.

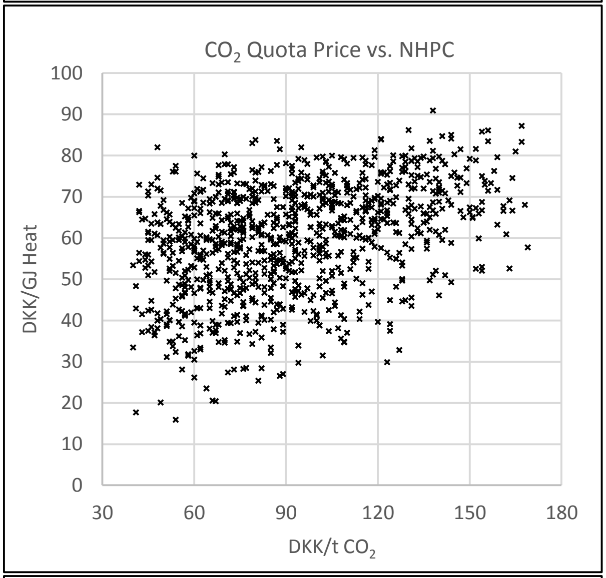
Eventually, the strongest correlation is found for NJV's profit against NHPC. With increasing profit, the NHPC decrease and vice versa. Obviously, this pattern is not astonishing given the present model set-up. Though, the strength of correlation and consequently the dependency of Aalborg's heat price from the operational profit of NJV is quite remarkable. One can also observe that most of the events aggregate on the negative side of the x-axis. To be more specific: under the given model set-up and probability distributions, the operation of NJV is only profitable in less than 17% of the parameter constellations, given that sales profits from DH production are not included. Obviously, this statement changes drastically when one includes DH sales into the profit calculation of NJV. The last scatter plot in Figure 5.7 shows the correlation between NJV's annual profit incl. DH sales and the NHPC. In order to account for DH sales, purchase prices from 2015 were applied. In this case, NJV becomes profitable in app. 83% of the observed events. The correlation is of similar strength compared to the plot without DH sales. This shows two things: 1) it is of outmost relevance which perspective one takes when doing this analysis and 2) DH sales have a huge impact on the economic performance of NJV. In the present example it is probably more realistic to take the latter perspective, i.e. to include DH sales into the profit calculation. Nonetheless, a 17% frequency of loss-making business is remarkable.

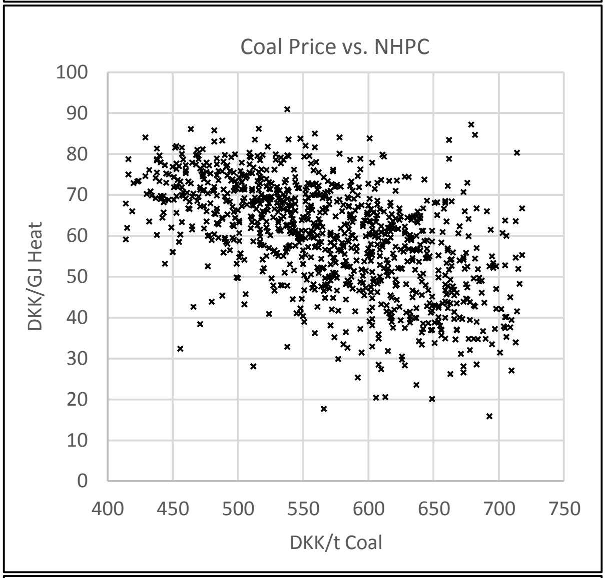
What is even more interesting is to compare this pattern against the equivalent from the BAU case (cf. Annex 1). The correlation is similarly strong and has obviously the same direction, though the frequencies for either profitable or loss-making businesses are different. Looking at it when DH sales are not included, the frequency of loss-making events for NJV in the BAU option is 98% compared to 83% in the Geothermal case. Again, this shows the economic dependency of NJV towards reimbursements from DH production. When DH sales are included, loss-making cases are reduced to 12% for the BAU case compared to 17% in the Geothermal case. These results are not directly straightforward. While a geothermal unit reduces the risk of losses when one looks at the economic performance of NJV without DH reimbursements it does the opposite when sales are included. An explanation for the loss reduction could be that in the event of a year with low spot prices, the geothermal unit will take over production hours where NJV would have only produced in order to satisfy heat demand. Hence, the system's exposure towards spot price fluctuations is reduced. Considering the case where DH revenues are included, the geothermal unit has a negative impact on NJV's loss frequency. This could be due to the fact that the geothermal plant replaces a considerable share of NJV heat production and as a consequence the revenue stream from DH sales. When DH revenues are not included this has no effect on the economic performance and thus showing the geothermal unit's value from a different perspective.

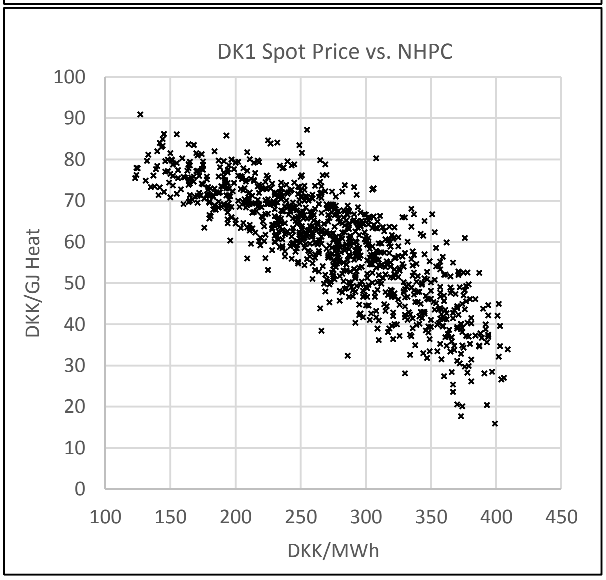



DK1 Spot Price vs. Heat Prod. Share New Unit
Annual Production Share
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
100 150 200 250 300 350 400 450
DKK/MWh


Investment Geothermal Unit vs. NHPC
DKK/GJ Heat
100
90
80
70
60
50
40
30
20
10
0
600 700 800 900 1000 1100 1200 1300
MDKK


CO_2 Quota Price vs. NHPC
DKK/GJ Heat
100
90
80
70
60
50
40
30
20
10
0
30 60 90 120 150 180
DKK/t CO_2


Coal Price vs. NHPC
DKK/GJ Heat
100
90
80
70
60
50
40
30
20
10
0
400 450 500 550 600 650 700 750
DKK/t Coal


DK1 Spot Price vs. NHPC
DKK/GJ Heat
100
90
80
70
60
50
40
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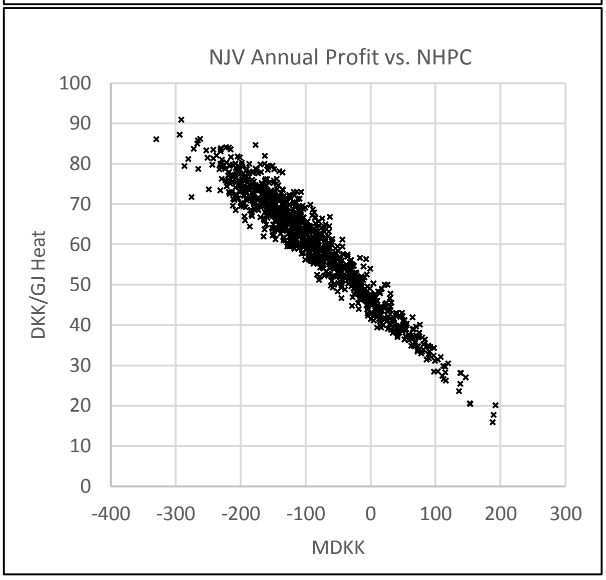
20
10
0
100 150 200 250 300 350 400 450
DKK/MWh


NJV Annual Profit vs. NHPC
DKK/GJ Heat
100
90
80
70
60
50
40
30
20
10
0
-400 -300 -200 -100 0 100 200 300
MDKK

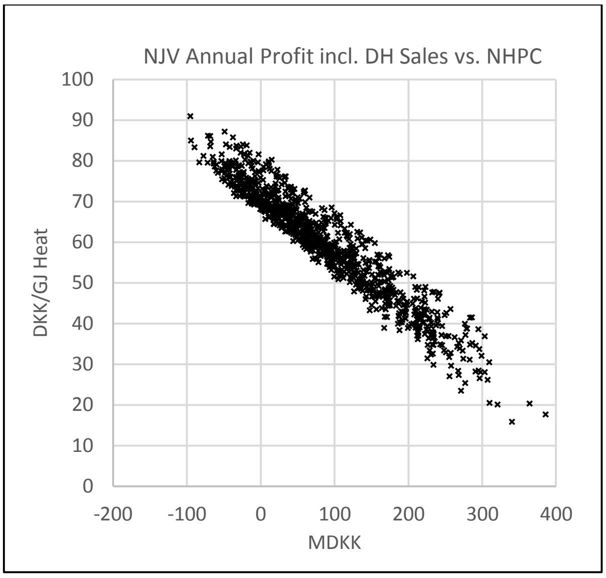


Figure 5.7: Selection of scatter plots from the Geothermal scenario

5.3 Comparison with a 3-scenario analysis

- *The regular 3-scenario analysis confirms previous findings that the CO_2 emission factor is hardly influenced by fluctuating input variables.*
- *The Geothermal case shows CO_2 emissions reductions, but those come at higher NHPC. Only in the renewable scenario the Geothermal scenario is more economic, but differences are relatively small.*
- *Heat production shares are similar to what was found previously. HP's production share varies between 2 - 20%.*
- *The scenario analysis does not produce fundamentally different results compared to relative and cumulative frequency plots.*

In order to assess possible advantages of the methodological synthesis between energyPRO and MCS, output data from a 3-scenario analysis are analyzed. Therefore, three scenarios are designed which could represent possible future developments in the energy sector: a conservative, renewable and fossil scenario. The first one implies a stable heat demand and spot prices on the 2013 level. Coal, natural gas and quota prices are kept on current levels. The investment costs for new production units is set according to expected average costs. Aalborg Portland is operating, which is also the case in the two other scenarios. In the renewable scenario heat demand is slightly reduced compared to 2013 data, assuming moderate increases in heat efficiency and building insulation. DK1 spot prices are based on current future prices traded at NASDAQ, which are considerably lower than current prices. Coal, natural gas and quota prices are increased so that they reflect values on the right-hand side of the respective distributions. The investment costs are at the lower end of the possible range, taking into account that renewable investments could benefit from public support in such a scenario. The fossil scenario's heat demand is on a 2013 level. DK1 spot prices take the value of the highest forecast. Coal and natural gas prices are slightly reduced compared to the conservative case and it is assumed that any emission trading scheme was abandoned, thus quota costs are set to 0. The investment costs for new production units are at the higher end, reflecting that such investments are neither supported nor does the technology learning curve advance as expected. Figure 5.8 shows CO_2 emission results, NHPC and the annual production share for a one-year analysis. Fossil fuel consumption is excluded for space-saving reasons as it is nearly identical to CO_2 emission results.

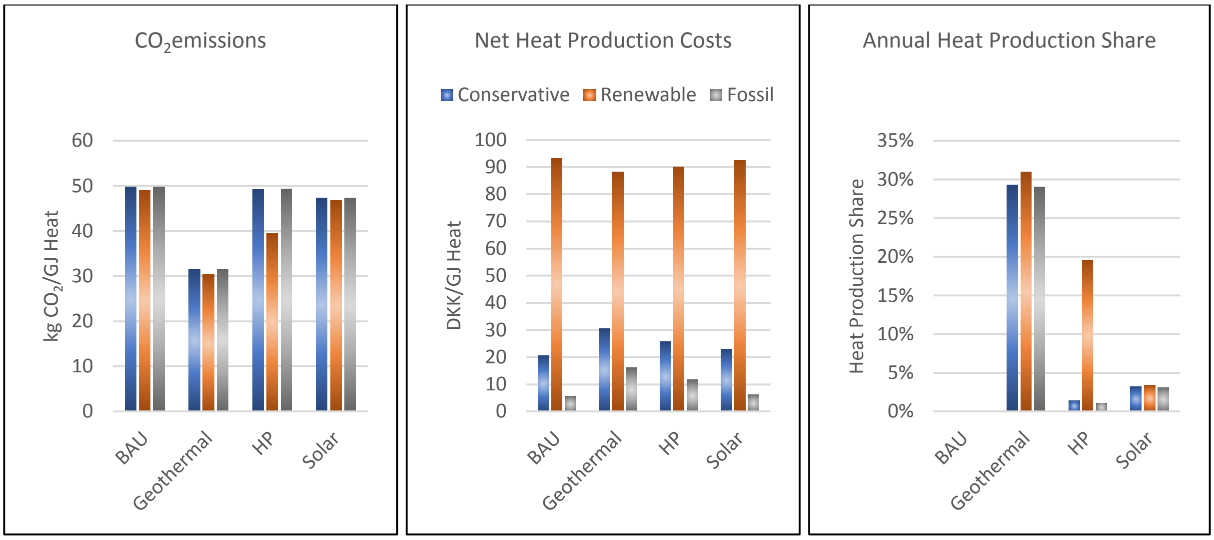


Figure 5.8: Compilation of results from a regular 3-scenario analysis

The presented CO_2 emission results show a similar picture compared to the relative and cumulative frequency distributions. Emissions in the Geothermal case are lowest, no matter which scenario is considered. Highest emissions are found for BAU with only minor differences towards HP and Solar. It is remarkable that for most cases the difference between the scenarios is negligible. This could be related to the relative high peak frequency that is found for CO_2 emissions compared to the other parameters. Distribution profiles are less scattered here and more centred on the peak. It also indicates a rather robust system, which is hardly affected by variations input parameters. The only deviation is found for the HP case. Here, CO_2 emissions are clearly lower in the renewable scenario.

Results for NHPC are also in line with what could be seen from the frequency distributions before. Differences between the three scenarios are substantial. The range of observable NHPC reflects the two extreme tails of the frequency distributions. The Geothermal case shows the highest costs for the fossil and conservative scenario. BAU is the cheapest option, followed by Solar and HP. Opposite to that, in the renewable scenario, the Geothermal option is least costly, but the differences between the scenarios are relatively smaller.

The results showing annual heat production shares is not surprising either. The Geothermal case has by far the highest shares. Differences between the scenarios are only marginal. The HP's heat production share shows great variations. While for the conservative and fossil scenario, shares are between 1-2%, it reaches nearly 20% in the renewable scenario. This can also explain the low CO_2 emissions in this scenario. In the previous analysis HP showed also a relatively high standard deviation which is reflected at this point. Solar shows only little deviations between the different scenarios, indicating a very stable production share, hardly depending on input variables. Eventually, the presented results show the core of what is presented in the frequency plot analysis. CO_2 emissions are substantially lower in the Geothermal case, but NHPC are highest. The BAU option shows opposite results. Only in the renewable scenario the Geothermal option is more economical. The scatter plots could show though, that such a renewable scenario is highly unlikely (only 4 out of 1,000). This is not directly obvious from the regular analysis and one might overestimate the economic feasibility of a Geothermal investment based on the scenario analysis. The HP case seems to be highly dependent on the input parameters as it shows the greatest deviations for the production shares.

5.4 Comparison with a sensitivity analysis

- *Sensitivity analysis reproduces main findings from the correlation analysis.*
- *DK1 spot prices show highest impact on NHPC for all scenarios. Coal and quota prices follow after that. Annual capital costs from the investment have a comparably small impact, the biggest is found in the Geothermal scenario.*
- *Relation between spot prices and CO_2 emissions similar to what is indicated by correlation analysis.*
- *Production shares for both Geothermal and HP show an identical relationship with DK1 spot price types compared to what was found before.*

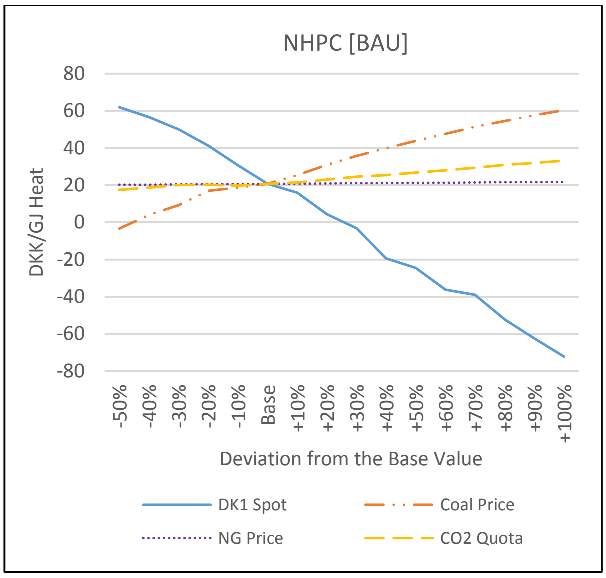
In a next step output data from a sensitivity analysis are presented and compared with results from the previous MCS analysis. Sensitivity analysis is commonly presented in the form of tornado or spider charts (Middleton 2001). The latter one was chosen here since it offers insights into the type of influence that parameters have on output data. This could include linear, exponential or logarithmic relationships. A tornado chart would not be able to show such data. Since those information were also generated from the correlation analysis it seems interesting to examine whether this is repeated in a sensitivity analysis.

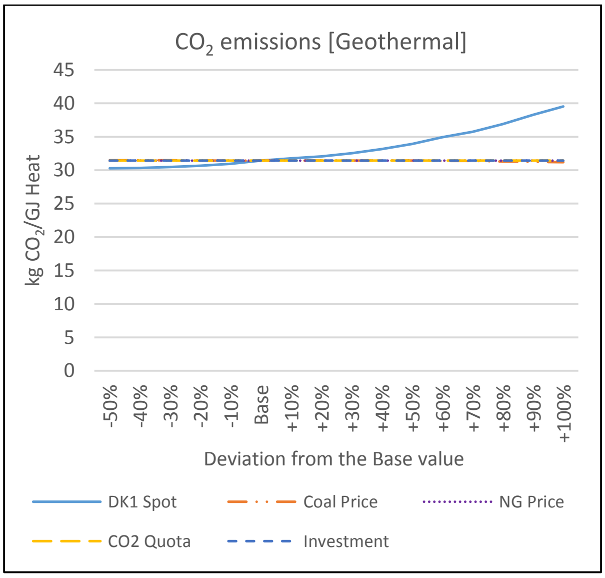
For the sensitivity analysis input values from the conservative scenario were taken as the base case (cf. chapter 5.3). The range of sensitivity goes from -50% until up to +100% of the base value. The heat demand is fixed to 6,778 TJ and Portland is available in all cases. This leaves five input variables for this analysis, i.e. DK1 spot price, coal price, natural gas price, CO_2 quota price and the initial investment costs. Regarding output variables, NHPC, CO_2 emissions per heat production and production share of the new unit were chosen. Fossil fuel consumption is not presented for reasons explained previously. For space reasons only a selection of interesting spider charts is presented in the following. Those which are similar for all scenarios are not repeated, but they can be found in Annex 4.

The spider chart showing changes in the development of NHPC [BAU] indicates that the various input variables have a different influence on the final NHPC (Figure 5.9). The appearance is nearly the same in all four scenarios. DK1 spot prices have the strongest influence, which is graphically expressed with its line being the most vertical. The fact that it even enters negative prices is due to the high spot price increase (+100%) which goes clearly beyond the maximum that is applied for the probability distributions (cf. chapter 4). This flaw was accepted deliberately as for the other input variables alterations of up to 100% are within previously defined ranges. In fact, for CO_2 quota costs it was not even enough, but 100% seemed to be an appropriate range for all input variables and it was also considered that the sensitivity range should be uniform after all. The other lines are more horizontal, meaning that with greater relative changes of the input variable, the output value alters less compared to more vertical lines. After DK1 spot prices, coal prices have the second strongest influence, followed by CO_2 quota prices. Natural gas prices have nearly no influence on the NHPC, which is straightforward, because natural gas fuelled production is limited to reserve plants, which only have a minor production share. From the spider chart the relation between NHPC and DK1 spot prices appears to be linear, while in the correlation analysis it was found that it would be best described by an exponential model. Though, the difference towards a linear model was only marginal and thus the results found here are actually not vastly different from the previous findings. The CO_2 quota profile exhibits a similar pattern as it was observed in the correlation analysis. Both have a moderate, positive and linear influence on the NHPC. A major difference is found for the impact of coal prices on the NHPC. From the sensitivity analysis it can be seen that with increasing coal prices, also the NHPC increase. This seems reasonable, considering that higher coal prices imply higher operational costs for NJV. Since DK1 spot prices remain unchanged it negatively affects the economic performance of NJV which eventually leads to higher NHPC. The correlation analysis indicated that increasing coal prices lead to decreasing NHPC, but it was also noted that this is most probably due to the applied correlation methodology (cf. chapter 5.2)

Therefore, the difference output data here do not necessarily imply that sensitivity and MCS generate different findings.

According to the spider chart for CO_2 emissions [Geothermal] one finds that only DK1 spot prices have an influence on emissions (Figure 5.9). The relation appears to be exponential. Contrary to that, correlation analysis found a weak, linear relationship. Despite different types of relations, both show that the spot price impact is small. From -50% to +100% of the initial DK1 spot price, CO_2 emissions increase by only 33%. The fact that the other input variables show no influence is in line with findings from the correlation analysis. Quota prices showed no effect and coal prices did that only to the extent as they were correlated to DK1 spot prices. Compared to the Geothermal case, the CO_2 emission spider chart for the BAU, HP and Solar scenario shows no influence for any input variable. Only the HP scenario shows that spot prices have a marginal, positive impact on CO_2 emissions, though this effect is so little that it is hardly distinguishable from a horizontal line. This corresponds to data from the MCS, as no correlations between CO_2 emissions and input variables could be found. This behaviour could be explained by the methodology for allocating NJV's fuel shares between heat and power production. Low spot prices reduce NJV's coal consumption and its electricity production. In these cases the ratio between fuel for heat and power is higher, as more fuel is appointed to heat production. With increasing spot prices, fuel consumption and electricity output increases. This reduces the heat-power ratio and consequently it also reduces the CO_2 emissions allocated to heat production. Though, the overall fuel consumption of NJV increases and this offsets the ratio decrease. In other words, a high heat-power ratio is often found with overall low coal consumption and thus CO_2 emissions. Reducing the ratio is accompanied by a higher coal consumption, hence higher CO_2 emissions which offsets the ratio reduction. This could explain the absent relation between spot prices and CO_2 emissions in these three scenarios.





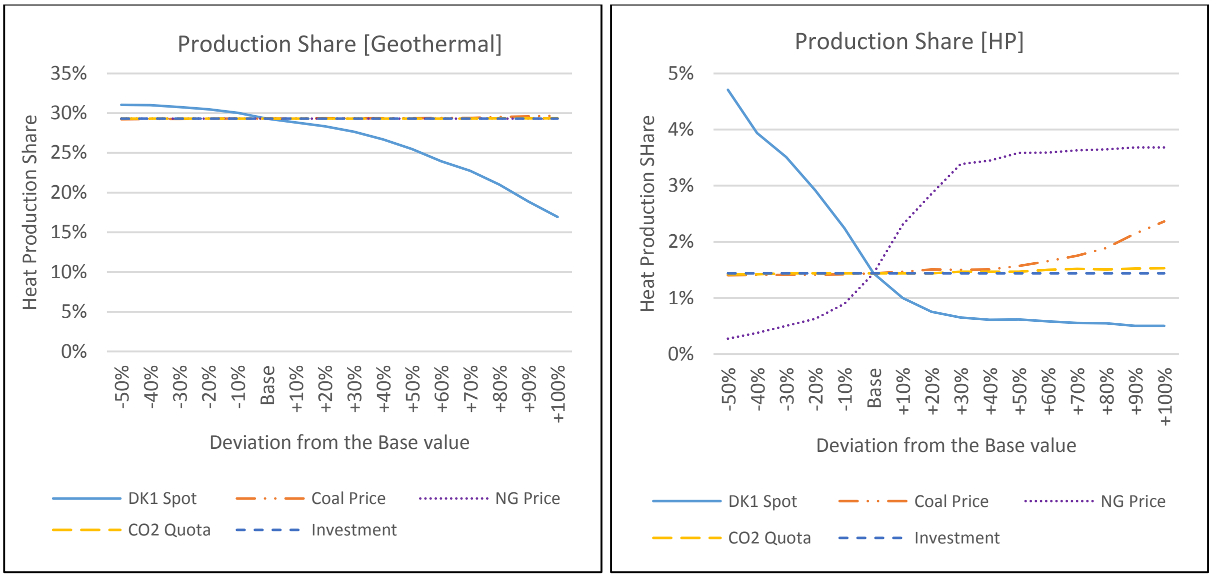


Figure 5.9: Selection of spider charts from a sensitivity analysis for all four scenarios

The Heat Production Share [Geothermal] shows a similar pattern as observed for the CO_2 graph (Figure 5.9). The only input factor which has an influence on it are DK1 spot prices. The shape appears flipped exponential, which is exactly in line with the scatter plot pattern from the correlation analysis. For the Solar case, there is no input variable which shows an effect on its heat production share. Looking at the last graph, the HP's production share exhibits a different pattern to what was seen before. DK1 spot prices have a flipped logarithmic influence on the annual share. The same pattern is also found in the correlation analysis. Spot prices beyond +20% of the base value have nearly no effect anymore. Before that, the spider chart shows a strong impact for that. Also the natural gas price shows a considerable effect. With increasing gas prices, the HP's production share increases and vice versa. Starting off in an exponential shape it shows a strong effect on the annual production share between -10% and +30% of the base value. It could indicate that within this range the HP and natural gas plants are in close proximity in terms of heat generation costs. It should also be noted that coal prices start to have an influence after passing app. +50% of the base value. This could relate to hours, where the HP replaces heat production from NJV, as due to increasing coal prices its heat generation costs surpass the ones from NJV.

6 Discussion

The discussion is divided into three sub-sections. At first, the general research approach is reviewed. Aspects of comparability and validity are considered throughout this section. After this the implications that aroused from the synthesis of MCS and energyPRO are discussed. The applied modifications and approaches are questioned in regards to the final results. The last part of the discussion goes back to the initial research question and examines in how far it could be answered. Did the suggested tool synthesis create additional value? If so, how is this expressed in the results?

6.1 Research approach and scenario design

A valuable analysis should consist of different scenarios which are comparable to each other. This can imply similar financial parameters or technical requirements. In the present thesis, the initial scenario approach was characterized by a strong focus on a homogeneous heat output capacity for the new production plants. This was originally due to considerations which included an electric boiler. A main requirement for such a unit would be that it could cover NJV's electric output in minimum condensation or back-pressure mode. It was expected that this could prolong the turbine's lifetime and it would save start-up costs as a consequence of a reduced number of shut-downs. Thus, all subsequent scenarios were designed so that they had a comparable heat output capacity. Halfway through this research project it turned out that the establishment of an electric boiler is now more than probable. Therefore it did not make sense to consider it as one alternative in the current project. Though, the scenario design remained and it was not revised before continuing. It should have been clear to the author that despite similar capacities, the annual production can be vastly different. This holds also true for the investment costs, which are not as equal as they should have been. Overall, these two flaws in the scenario design limit the comparability of the proposed scenarios to a great extent. By introducing emission reductions per capital costs it was tried to encounter this methodological weakness. It turned out that emission reductions are not as much influenced by investment costs as expected. For the remaining parameters the limited comparability needs to be taken into account when discussing the results.

In order to increase the comparability in future studies it would be advisable to agree on some key investment figures beforehand. This could mean that a maximum investment capital is defined and then it would be possible to draw conclusions on which investment generates the greatest benefits in terms of CO_2 emission reductions, renewable energy share, etc. Besides, one might also define a technical goal for the system, e.g. that the investment should generate a certain renewable energy share or that it should cause fossil fuel consumption to decrease by a defined percentage. Then it would be possible to have a clear statement regarding which investment delivers this goal most economically. Unfortunately, such a precise investment set-up was neglected at the project beginning. It could be ascribed to the fact that the present research started simultaneously with the actual *Forsyningskatalog* project and that such an investment framework was not described back then. It could also be that such discussions, especially about maximum investment capital were not within the range of the author's competence levels. The methodological framework for scenarios as presented in chapter 2.4 should have been considered thoroughly at an earlier stage of the project. It might have helped to realize the flaws in the existing scenario design. After all, the final accountability is to be found within the author's unawareness towards these issues. Retrospectively, the lack of a clearly defined framework for the discussed investment decision had a great, negative effect on the quality of the results.

Another issue to be discussed is the rough modelling of the HP and the Geothermal unit. It basically comprises two COPs which are fixed throughout the year. In contrast to that one could have modelled a variable COP, which is determined by the theoretical Lorentz efficiency and system efficiency, as it was done by Østergaard and Andersen (2016). The Lorentz efficiency is then depending on the HP's inlet and outlet temperature which in turn depends on other parameters, such as supply and return temperature at the DH plant. These again vary according to the pipe heat loss coefficient, the flow rate of DH water and the required inlet temperature at the consumer side. In their energy system such an extensive modelling approach was reasonable because it included a new concept which foresees booster HPs at the consumer side. For central HP DH systems they found annual COP variations between 4.7 in the winter and 5.2 in the summer period. Their COP is higher compared to the one used in the present thesis which is due to lower forward DH temperatures in their model. One could have also assumed that the HPs input temperature would allow for a higher COP because of the availability of industrial excess heat or the like. Since it could not be taken for granted that such a source existed and that it would supply sufficient amounts, this option was eventually discarded. After all, it seems justifiable that an extensive HP modelling was neglected, given that annual COP variations are moderate and that the focus of the thesis was not about HP optimization. For reasons of integrity and transparency the theoretical modelling potentials shall be noted here nonetheless.

In general the present scenario approach considers the implementation of one technology only. This is a limited reflection of the real investment possibilities. Of course one could also diversify the DH production portfolio even further and combine several technologies, e.g. HP and solar thermal. Apart from that one could also include technologies which were neglected in the scenario design as small-scale pilot projects. Even though they were sorted out for modelling and other reasons it does not mean that one should entirely neglect them as an investment possibility. In such a case, it would only serve different purposes.

The results show that NHPC are by far most dependent on the economic performance of NJV. Hence, its role and accurateness in the model is of decisive importance. This could be perceived problematic because its operational possibilities, both from a technical and a market perspective are least assured. Technical data, such as start-up time and costs as well as O&M costs were only estimated based on general, public available data. Maybe even more significant, additional revenue streams from the balancing or intraday market were not taken into account. Further, fluctuations in the annual average spot price were included in the model, but the annual profile itself remained unaltered. It would have been interesting to integrate an increasing or decreasing volatility of the spot market into the model. A more general problem in regards to NJV is its optimization framework system. In the present project, production was optimized against Aalborg's DH system and the DK1 DAH market. In reality, NJV is operated by Neas Energy A/S starting from the 1st of June 2016 (energy-supply.dk 2016). This means that NJV will be operated within Neas production portfolio, which includes wind, PV, hydro, decentral CHP, central CHP, and electric boilers. Therefore, its optimization might be greatly different from what the current model suggests, meaning that the model's validity needs to be questioned. Besides, energyPRO calculates the heat production costs for NJV on an hourly basis and based on that it decides how to arrange the production portfolio. In reality, AAK might pay a fixed price per GJ heat delivered from NJV and thus the modelling concept in energyPRO is obsolete. It might have been more accurate to include a fixed price for NJV's DH sales into the model, which would have changed the priority functions etc. One could also question the necessity of energyPRO in this case, given that heat delivery from Portland and Reno-Nord is not adjustable and that the remaining demand is covered by NJV anyway. Then it would have only been necessary to set-up an excel spread sheet comparing the price for DH delivery from NJV against what a new production unit could deliver. Finally, using energyPRO including the whole model set-up might have been an over-complication of the whole situation. Knowledge about the contractual terms between AAK and Neas Energy A/S could have made it much easier to find appropriate answers. Everything comes down to the question in how far AAK is (by contractual agreement) exposed to the economic risk of operating NJV? At this point no details about the reimbursement and payment scheme between Neas Energy A/S and AAK are known. This makes it impossible to give a conclusive assessment of the models validity. In fact, any further study of Aalborg's DH system is useless as long as such details are not included in the model design.

The results have also shown that the operation of NJV is not profitable in app. 17% of the cases, which could indicate that the present model misses some revenue potentials. On the other hand this could be one of the reasons why Vattenfall divested NJV recently, even though the official version refers to the political attitude shift of the Swedish government. The amount of unprofitable events could also be traced back to the applied copula correlation, which might not have been strong enough (cf. chapter 4.1). This point leads to another aspect of the validity discussion, but this time in regards to the realization of MCS.

6.2 Using MCS for techno-economic energy system analysis

In order to conduct a MCS in combination with energy system analysis with energyPRO it was necessary to generate input data from distribution profiles. These profiles needed to be defined in terms of scatter width, minimum and maximum value and possible correlations with other input variables. It shall be noted that the author had no previous experience in this field and further no databases with existing profiles could be found. Several articles from peer-reviewed journals served as reference points for some distribution profiles. Still, the concept of these studies never really matched the present case, so the obtained input was never more than a rough estimate of what could be appropriate. In order to obtain more valid distribution profiles one should have consulted several experts in the respective parameter field and ask for their opinion in terms of distribution shape, most likely value, minimum and maximum. In fact, ModelRisk provides a feature where experts can adjust these values and control the responding profile on screen, allowing to let them find the most suitable profile. Time constraints did not allow to incorporate such an extensive approach.

As previously said, there are reasons to doubt the appropriateness of the Frank copula strength between coal, natural gas and DK1 DAH prices. It might have been more appropriate to increase the strength of the correlation in order to generate a less scattered relation between these input variables. Recent studies have drawn contradictory conclusions regarding correlations between electricity and fuel prices. De Menezes et al. (2016) conclude that electricity prices at the French (EPEX) and Nordic (Nordpool) spot market have decoupled from fossil fuel prices. Their study analysed a time horizon from 2005-2013. Instead, prices are associated with price alterations at the neighbouring spot markets. Opposite to that, the British spot market (APX) is still coupled, while it shows a lower correlation with other connected markets. In contrast to these results, Castagneto-Gissey (2014) finds a strong link between coal and electricity prices for all central European countries, analysing a time frame from 2008-2012. It is highlighted that not only coal-intense power markets, such as the British and German show strong correlations, but even the hydro-dominated Nordpool market depends on future coal prices. Besides, he also shows a strong correlation between CO_2 quota costs and future electricity prices and stresses that power generators incorporate quota costs over proportionally into electricity costs. Aatola et al. (2013) come to the conclusion that quota costs have a positive, but uneven effect on spot prices. They investigated data from 2003-2011. More precise, in markets where mainly coal-fired power plants represent marginal plants, this impact is greater than for gas. Eventually, this short literature excursion did not give a coherent opinion on correlations between spot and fuel prices. Thus, the copula strength that was applied in here is found to be appropriate as it is somewhere in between strong and no correlation. For future studies CO_2 quota costs should definitely be included into this correlation scheme. It could also be interesting to examine correlation strengths between such parameters in more detail.

Certain correlations were deliberately not implemented into the model. However, apart from these omissions, it might also possible that some correlations have been left out unintentionally. This possibility cannot be excluded here either. It would have been also promising to include taxes and fees in form of probability distributions. Especially since the PSO tariff is now under revision and likely to be abandoned in the near future (finans.dk 2016). A more accurate approach would have included a prior sensitivity analysis of the present model in order to assess the different input variables according to their impact, as shown by Arnold and Yildiz (2015). Based on such ranking it is possible to limit the number of input variables for MCS to the ones which are most decisive. It is argued that constraining the number of input variables saves computational time, because both the generation of distribution profiles and the iterative calculations are time consuming processes. From a practical view in the current case this argument is only valid to a certain extent since the most time consuming process is not the MCS computation itself, but the simulation time in energyPRO. From a methodological perspective a prior sensitivity analysis would have strengthen the validity of this study because it would have ensured that the most important input variables are subject to the MCS. In the present thesis the sensitivity analysis was conducted after the actual MCS since the focus was laid on the result comparison. Though, in future studies this should be done in reversed order.

6.3 Value creation through synthesizing energyPRO and MCS with ModelRisk

Finally, the question shall be discussed in how far the suggested methodological synthesis between energyPRO and MCS has created value for investment decisions within energy planning. To begin with, ModelRisk as a software for MCS could not be fully exploited. The result viewer function was not available, because the actual MCS was not done in an excel spreadsheet but within energyPRO Interface. It was not possible to insert the results from Interface into the programme so that the visualization tools from ModelRisk could have been used. This existence of such an option should not be excluded in general, since it might be possible that there are ways to go around this problem, but those have not been available during this project phase. Eventually, the use of ModelRisk was reduced to the generation of distribution profiles for input data generation. This included a random number generator, a user-friendly interface to generate distribution profiles based on their main parameters and the option to define correlations for certain input variables. This has been essential throughout the project, though theoretically it would be possible to make such functions in excel as well. Especially if one uses only a limited number of distribution types, this option could be interesting. As a main benefit one would save the yearly licence fee for ModelRisk which can cost up to $2,000. Luckily, for the present project a student licence for less than $70 could be obtained, so costs were justifiable after all.

Another main aspect that needs to be taken into account when assessing additional value through this new method approach refers to time consumption. Pure calculation time for the whole set-up took nearly three days. This leads to a final calculation time of around 5-6 days, simply because programme crashes and interruptions would not allow to use night time efficiently. Also during the day it was necessary to check the computation continuously, thus occupying additional work time. The time exposure makes it also extremely laborious to adjust the model's characteristics after one obtains the first batch of results. Under normal conditions there is no problem in changing the model set-up after the first analysis in order to increase its validity or comparability, since calculation time is not essential. The present case does not allow such thing, which is especially disadvantageous when deadlines have to be considered. The present methodology loses a lot of temporal flexibility compared to using MCS or energyPRO individually. In fact, after the first flaws were discovered in the present model design, it was shortly contemplated to run a new MCS simulation. This would have implied another 5-6 days of delay for the results. Eventually, it was then decided to neglect this option and time reasons were the most decisive factor here. The expenditure of time for the present analysis would only be reasonable if one generated results which are more valuable for investment decisions or energy system analysis. This cannot be confirmed in the present case, looking at the comparisons in the chapters 5.3 and 5.4. The key results found in the analysis of frequency distributions were also available from the regular 3-

scenario analysis. The Geothermal scenario offers considerable CO_2 emission reductions, but this comes at higher costs. Production shares are very different between the scenarios, with Solar having the lowest share, Geothermal the highest and HP in between, showing large fluctuations depending on input variables. What could not be observed from that are findings from the correlation analysis in terms of relations between different variables. Though, the presented sensitivity analysis could reproduce all those relationships. Often it would also indicate the same type of relationship, e.g. a flipped exponential between spot prices and the Geothermal's production share or a flipped logarithmic between spot prices and the HP's production share. Sometimes the findings between both methods would deviate slightly, but it should be noted that the correlation coefficient for some scatter plots was also only marginally different for either exponential or linear models. Further, there are no substantial differences between the two sets of output data, as they would not lead to contradictory conclusions. The correlation between spot prices and NHPC or NJV's economy were found to be the strongest, which is also reflected in the sensitivity analysis. Otherwise, most correlations are weak and this could have been deducted from both methods.

The only remaining advantage of MCS in combination with energyPRO is that it allows to make statements in terms of frequencies and probabilities. Obviously, such data quality cannot be generated from scenario or sensitivity analysis. E.g. it was shown that only in 4 out of 1,000 events an investment into a Geothermal plant would be more economical compared to the BAU strategy. Also, the impact of a Geothermal plant on the economic performance of NJV in terms of frequency of loss-making businesses could only be deducted from the MCS. Still, such additional value comes at a high price considering computation time and extra work load for probability distributions.

7 Conclusions

The present thesis explored the opportunities of a synthesis between two tools from different fields of study. EnergyPRO is a widely applied software for techno-economic energy system analysis, functioning on a deterministic basis. MCS is a probabilistic tool for quantitative risk analysis, commonly used in the Finance and Econometrics sector. The combination of both was supposed to generate a valuable contribution towards an upcoming investment decision of Aalborg Kommune. The municipality assesses the investment possibilities for an additional, sustainable DH production plant. This was the initial motivation behind the present research project and it culminated into the following research question: How could MCS and energyPRO be integrated to give recommendations for an investment decision?

Starting to give answers to this question, both tools were described in detail, while the focus was on the risk analysis section. For the practical part, scenarios were designed which could show potential investment opportunities for Aalborg Kommune. These comprised three different technologies, i.e. HP, Geothermal and Solar thermal. After that, methodological necessities which aroused from the integration process were described. This included the set-up of probability distributions for energyPRO input variables and the definition and modelling of correlations between those. Then, the results were analysed against the research question. From the perspective of AAK, the results are only relevant to a limited extent. Flaws in the model set-up, the scenario design and the methodological approach reduce the result's validity. A lack of practical knowledge regarding details of the contractual agreements also accounts for that. It is found that a thorough theoretical framework for the scenario design could have improved the result's quality considerably. From a research-oriented point of view the results showed that value addition through the tool synthesis is only marginal. The difference between regular scenario analysis and the suggested method is not as fundamental as expected. Considering relative and cumulative frequency distributions, the scenario analysis could produce similar key results and subsequent recommendations would have been nearly the same. The sensitivity analysis generated output data which are very similar compared to those shown in the correlation analysis. Insights into relationships between variables can be achieved from both methods. The remaining advantage of combining MCS with energyPRO is reduced to statements about frequencies of occurrence. Therefore, investment decisions do not necessarily become more solid and it needs to be questioned whether the additional workload is worth the marginal value creation.

For future research that aims at integrating both energy system analysis and MCS it will be essential to reduce the computation time. Such analysis should only be conducted when one has thoroughly reviewed the respective model and the possibility of subsequent model adjustments can be nearly excluded. It seems reasonable to start with scenario and sensitivity analysis and only consider MCS in case that the previous results leave doubts or specifically highlight the impact of different parameter constellations.

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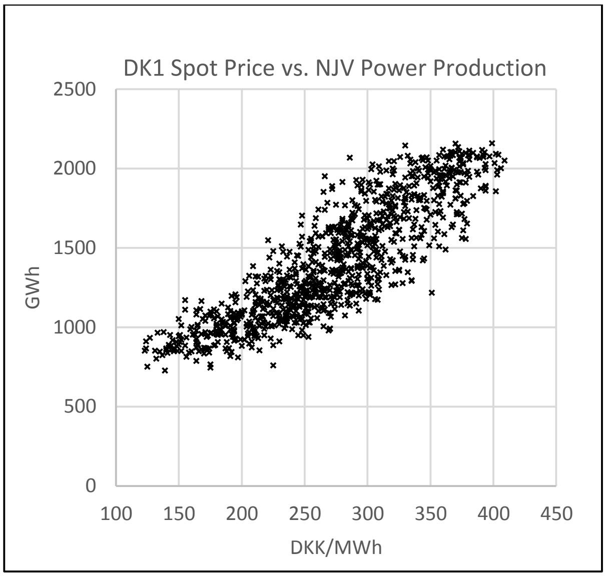
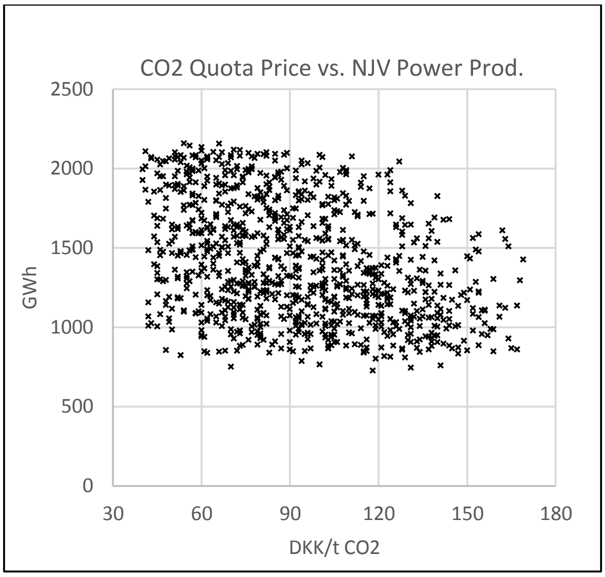
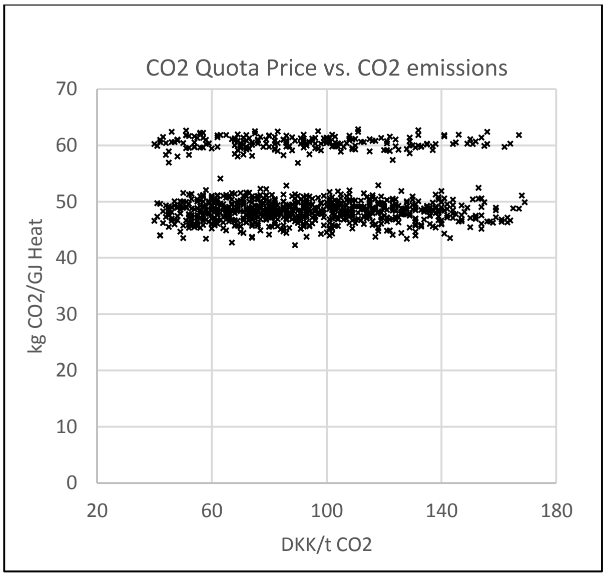
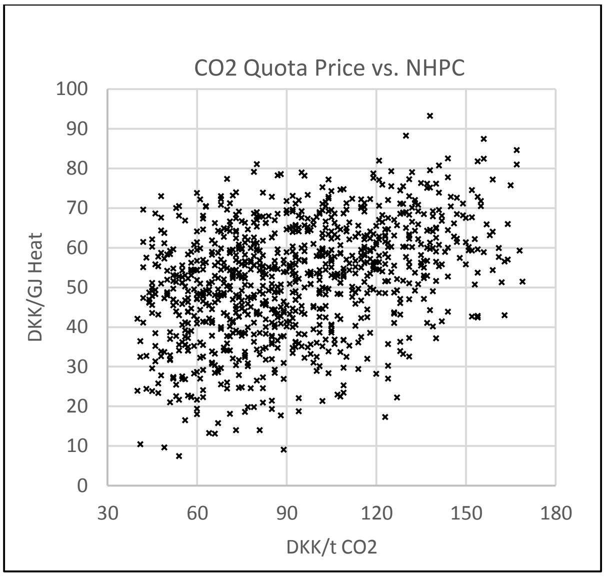
9 Annex

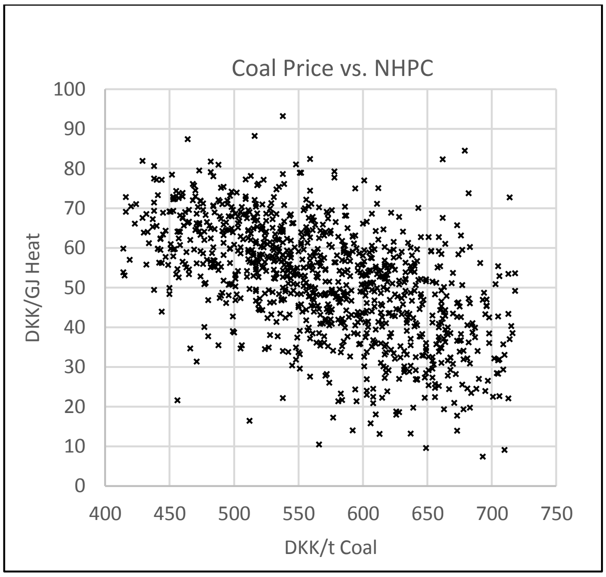
Annex 1: Selection of Scatter Plots from the BAU scenario

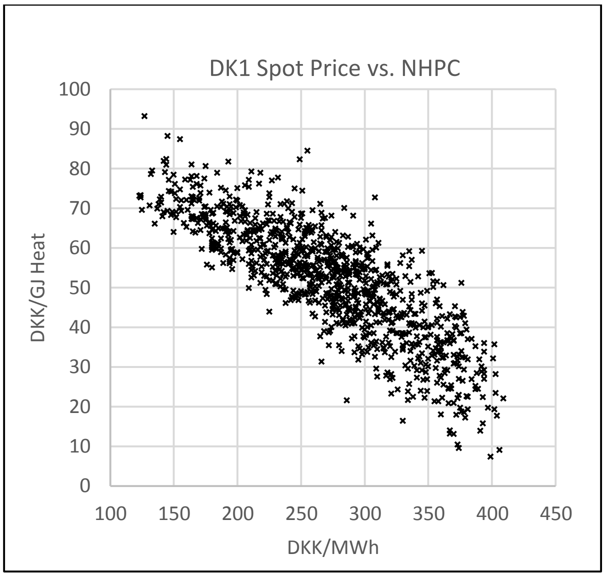


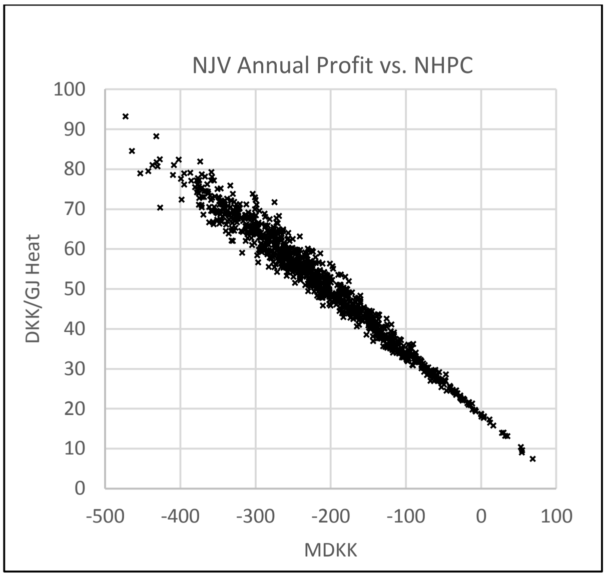


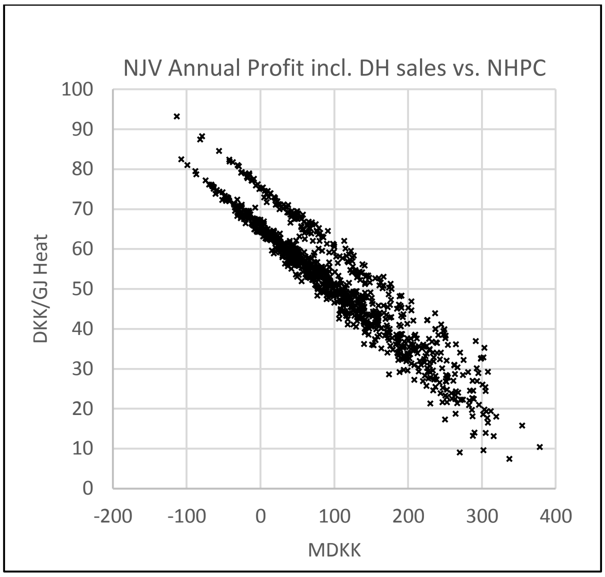


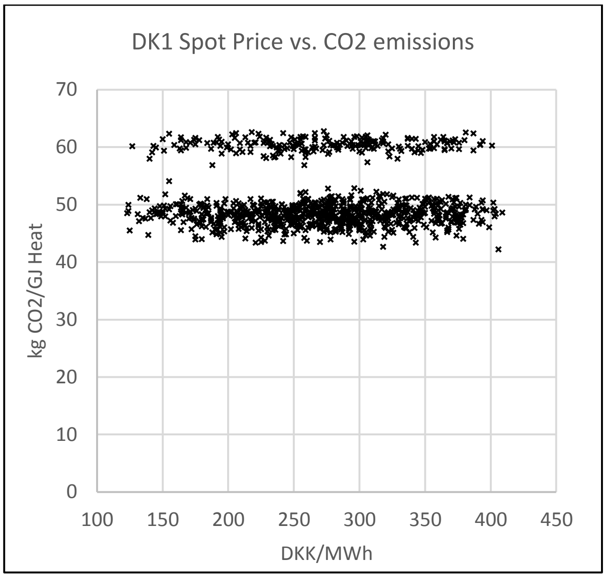




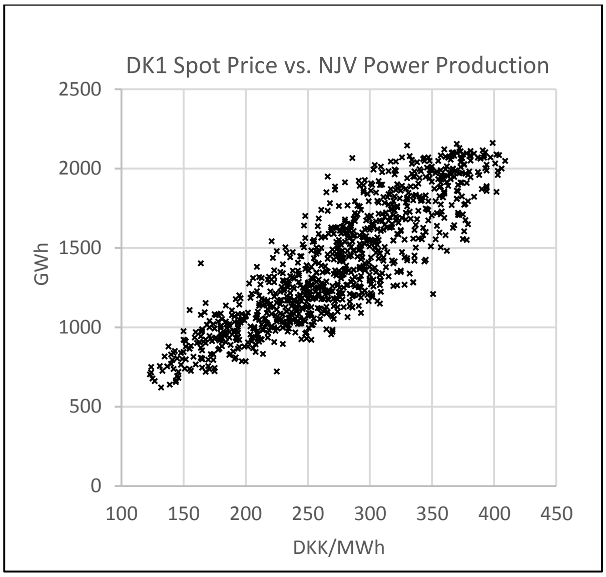


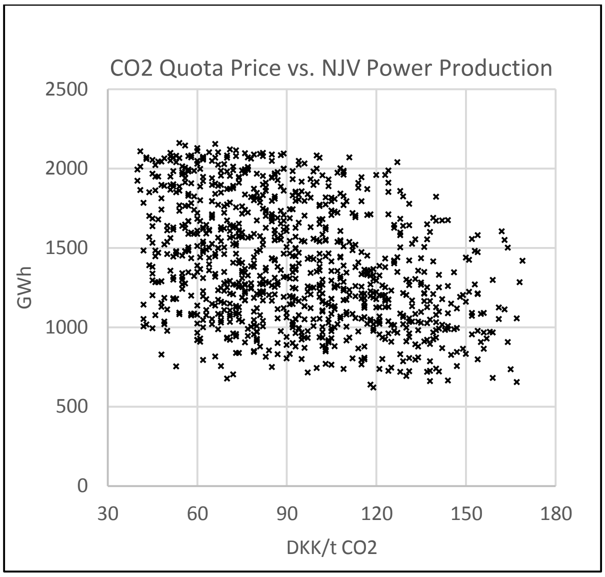

NJV Annual Profit vs. NHPC
DKK/GJ Heat
MDKK
100
90
80
70
60
50
40
30
20
10
0
-500
-400
-300
-200
-100
0
100

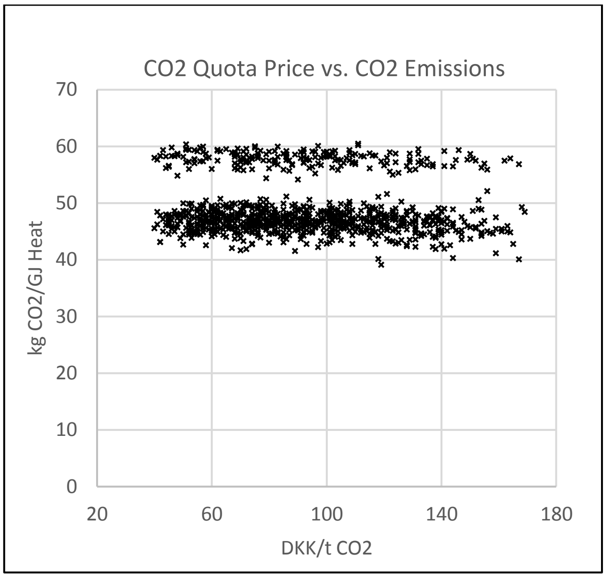

NJV Annual Profit incl. DH sales vs. NHPC
DKK/GJ Heat
MDKK
100
90
80
70
60
50
40
30
20
10
0
-200
-100
0
100
200
300
400

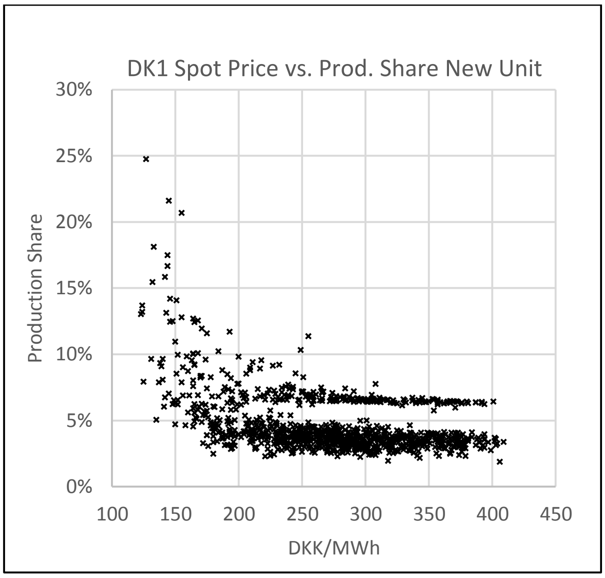

DK1 Spot Price vs. CO2 emissions
kg CO2/GJ Heat
DKK/MWh
70
60
50
40
30
20
10
0
100
150
200
250
300
350
400
450

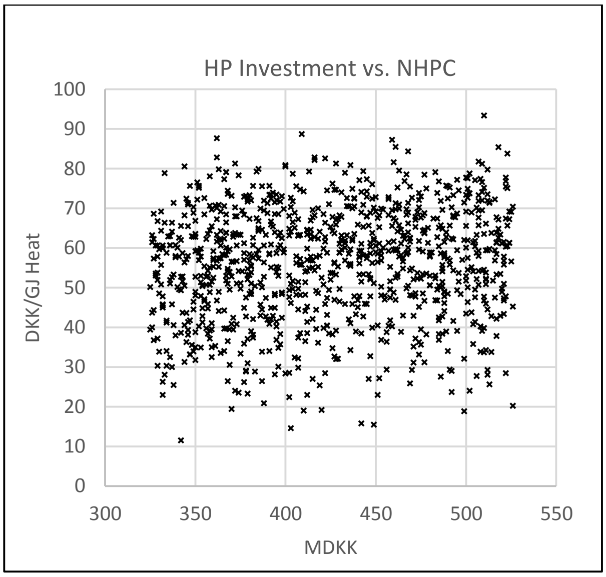
Annex 2: Selection of Scatter Plots from the HP scenario

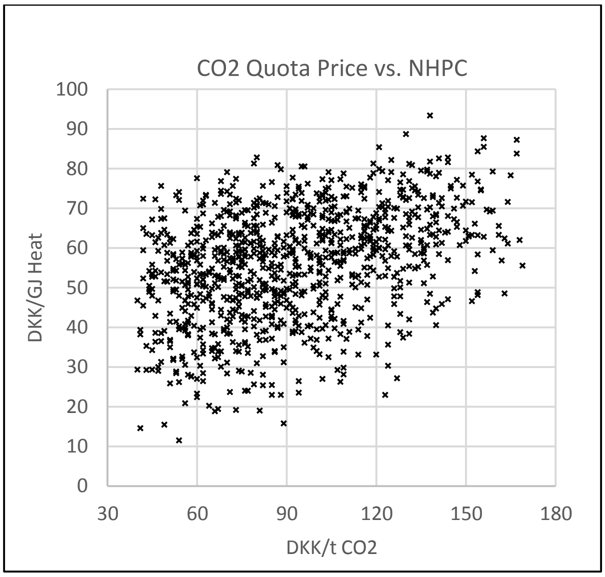


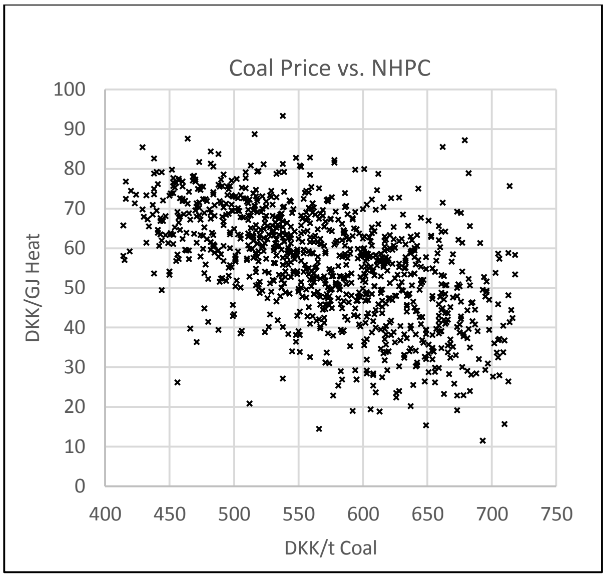


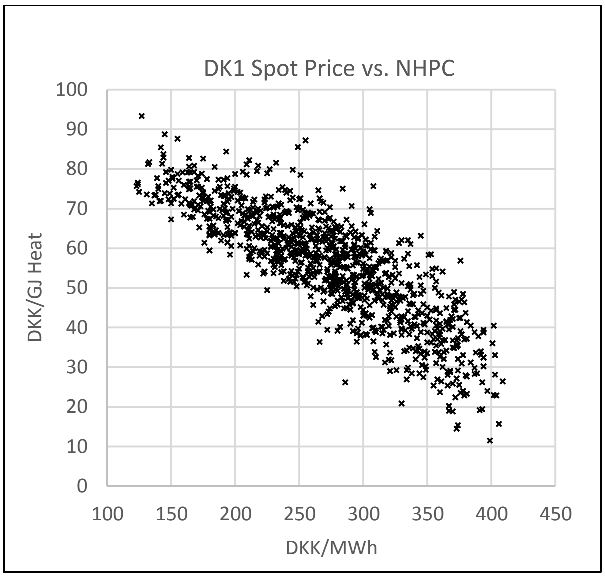


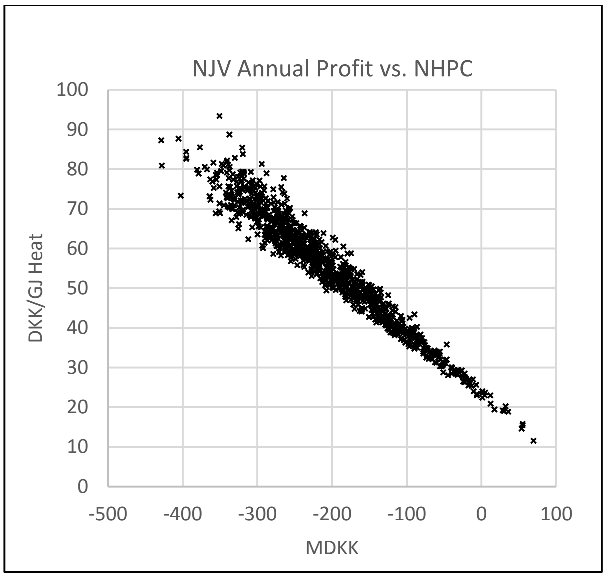


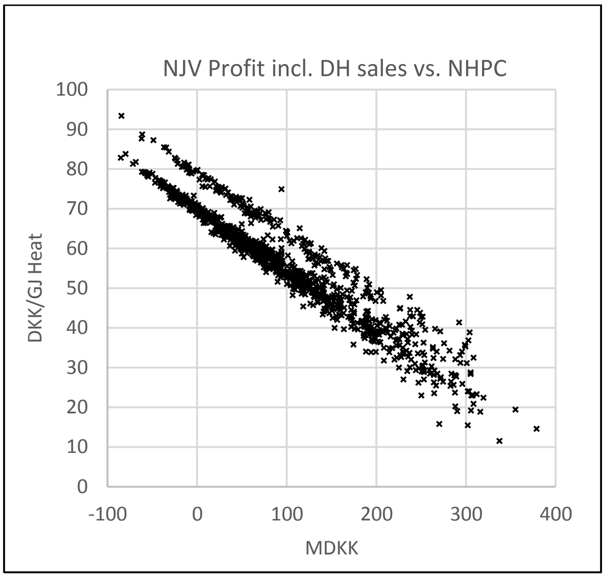




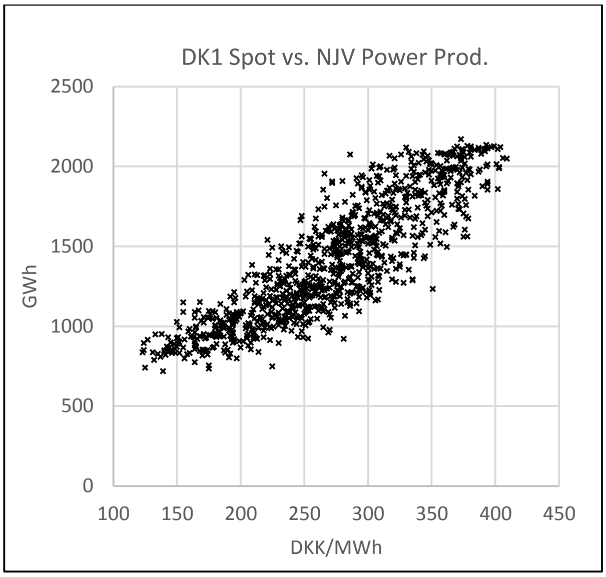

Coal Price vs. NHPC
DKK/GJ Heat
DKK/t Coal
0
10
20
30
40
50
60
70
80
90
100
400
450
500
550
600
650
700
750

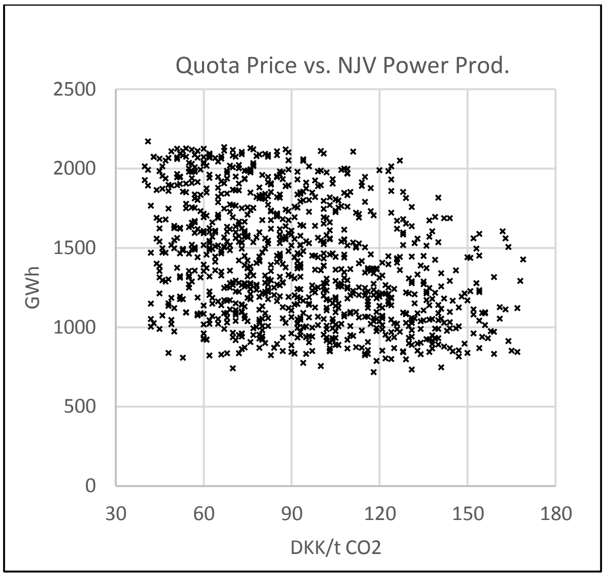

DK1 Spot Price vs. NHPC
DKK/GJ Heat
DKK/MWh
0
10
20
30
40
50
60
70
80
90
100
100
150
200
250
300
350
400
450

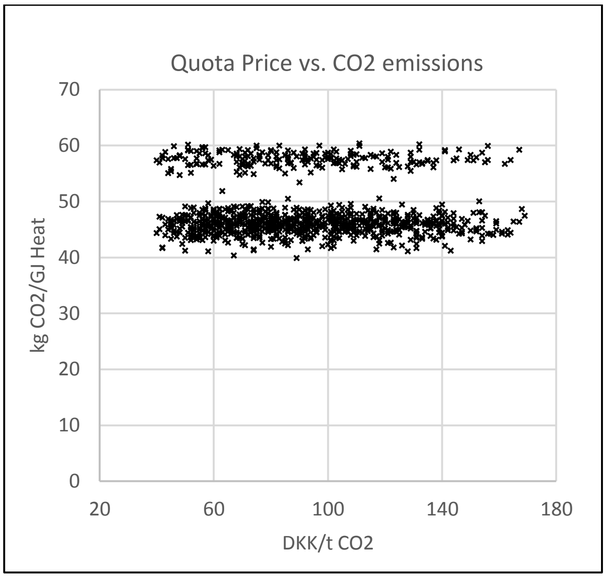

NJV Annual Profit vs. NHPC
DKK/GJ Heat
MDKK
0
10
20
30
40
50
60
70
80
90
100
-500
-400
-300
-200
-100
0
100

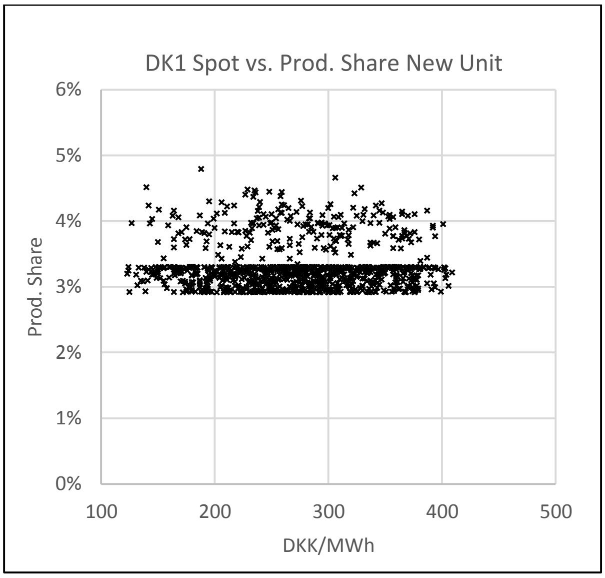

NJV Profit incl. DH sales vs. NHPC
DKK/GJ Heat
MDKK
0
10
20
30
40
50
60
70
80
90
100
-100
0
100
200
300
400

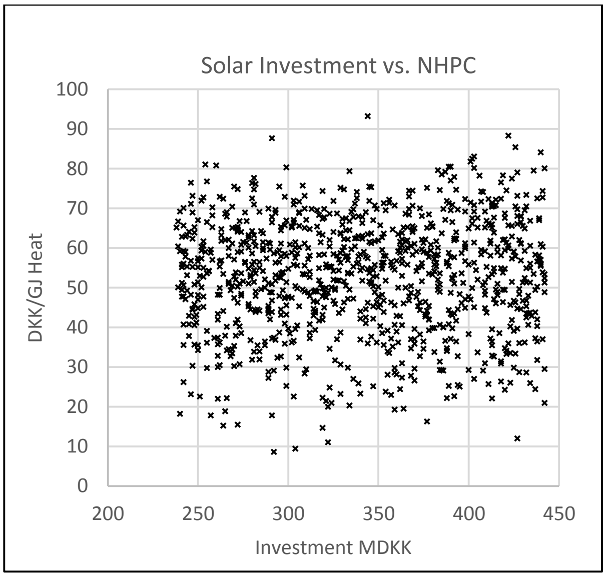
Annex 3: Selection of Scatter Plots from the Solar scenario

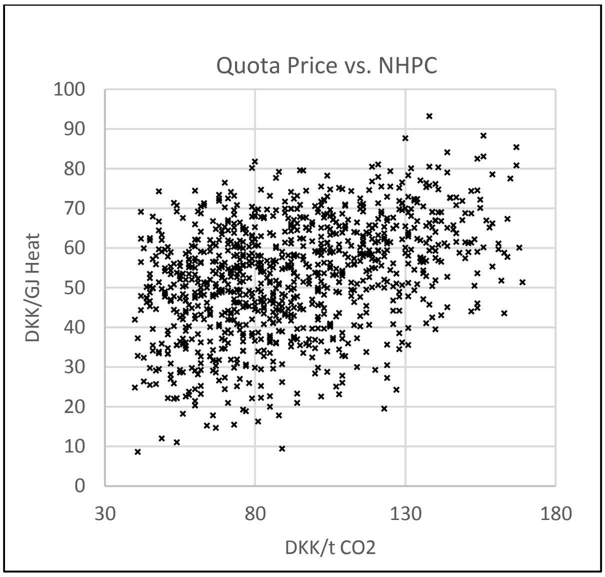


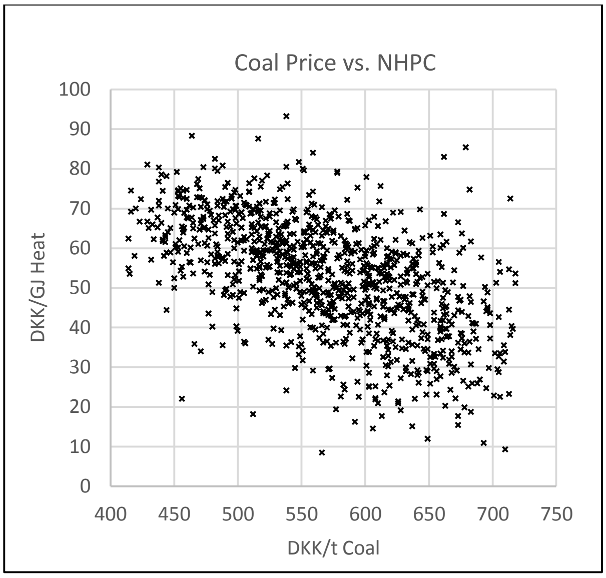


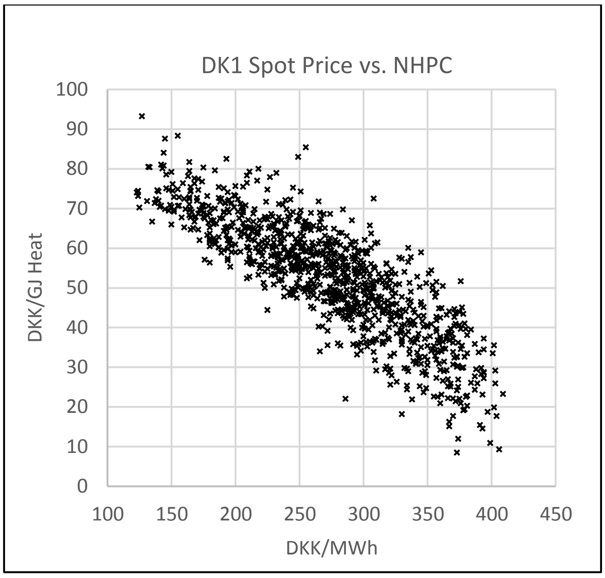


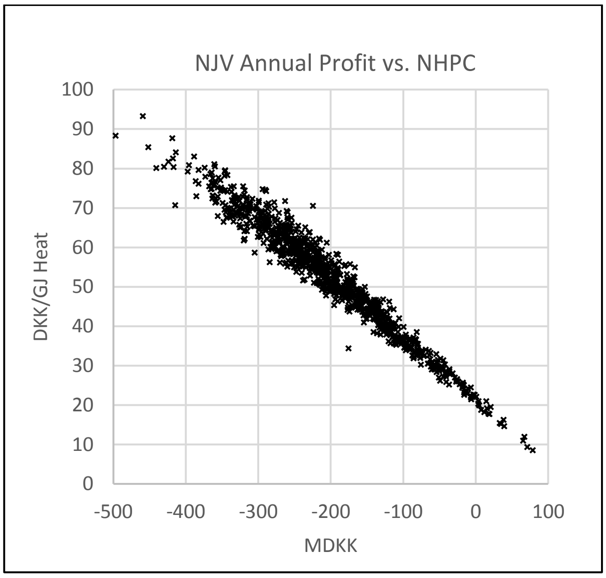


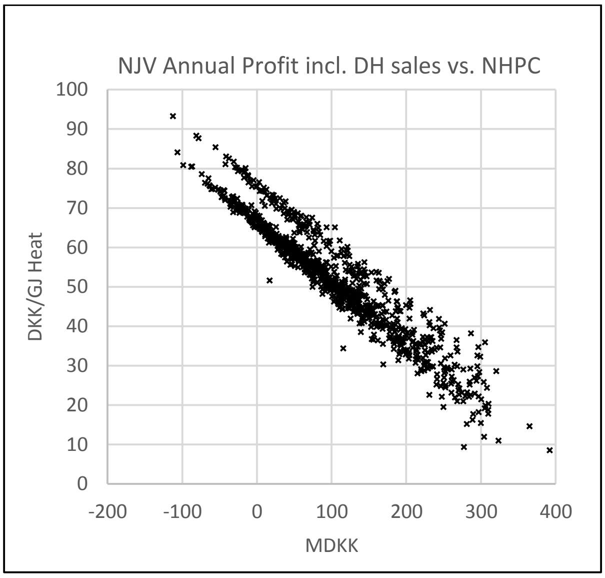





Coal Price vs. NHPC
DKK/GJ Heat
DKK/t Coal
0
10
20
30
40
50
60
70
80
90
100
400
450
500
550
600
650
700
750


DK1 Spot Price vs. NHPC
DKK/GJ Heat
DKK/MWh
0
10
20
30
40
50
60
70
80
90
100
100
150
200
250
300
350
400
450


NJV Annual Profit vs. NHPC
DKK/GJ Heat
MDKK
0
10
20
30
40
50
60
70
80
90
100
-500
-400
-300
-200
-100
0
100


NJV Annual Profit incl. DH sales vs. NHPC
DKK/GJ Heat
MDKK
0
10
20
30
40
50
60
70
80
90
100
-200
-100
0
100
200
300
400

Annex 4: Selection of spider charts from the sensitivity analysis that were not displayed in chapter 5.4