Comparing the **Performance** of **different Market Structures** for **Regional Heat Networks**

A Simulation Study into the Impact of Fuel Prices, Consumption Growth and Investment Decisions

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THESIS

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List of terminology

Market mechanism	Market operations where supply and demand determine the price and quantity of heat offered in a free market.
End-to-end	A market characterised by contracts between producers and purchasers
Single-buyer	A market characterised by an entity with sole-right in heat trade
Wholesale	A market characterised by a market pool where producers and purchasers can bid for heat to be produced or consumed
Producer surplus	The amount of money a production unit or producer can make when production cost is subtracted from the turnover
Dispatch	Summoning producing units to produce heat
Merit order	The organisation of the dispatch based on pricing, which is different for each market
Marginal cost	The production costs that only include the fuel and CO_2 cost for producing one gigajoule of heat for the specific production unit
Marginal production asset	This is a term for the wholesale market mechanism, where all producing units bid at marginal cost. The producing unit where the supply and demand curve intersect is called the marginal producing asset.
Niet Meer Dan Anders (NMDA) principle	Translates to English as “No more than otherwise” principle is a price cap on heat. The current policy is to cap it indexed with the gas prices.
Energetisch opwekkings rendement (EOR)	This translates to English as Energetic Generation Efficiency. Uses sustainability scores of heat assets to calculate the systems EOR. This score is point specific.

Executive summary

This research allows quantitative comparison of market mechanisms for heat systems where previously only qualitative comparisons were used for the implementation of heat markets in heating systems. It compares three different archetypes of market mechanisms based on three market performance indicators.

Market mechanism	**Market performance indicators**
1) End-to-end	1) CO_2-emissions
2) Wholesale	2) Consumer price
3) Single-buyer	3) Producers surplus

The government intends to regulate the heating system before the Leiding door het Midden is built. If Eneco were to construct this pipeline, it would create a natural monopoly that the government considers undesirable. To this end, the government has commissioned a study to determine which market forces are best for the system.

The end-to-end and single-buyer markets are characterised by contracts, while marginal production cost distinguishes the wholesale market. Besides, the markets differ based on dispatch and settlement. The end-to-end market uses a fixed order of dispatch of contracts. The single-buyer arranges the merit order through contract prices from low to high. The wholesale optimises based on marginal costs of all individual heat-producing units in the heating system.

The results show that no best market mechanism can be identified. Compared to the other two markets, however, the single-buyer is underperforming in all areas. This means that the importance of the market performance indicators must be assessed to choose between the end-to-end and wholesale market mechanisms. Furthermore, it shows that the markets are affected by uncertainty in different ways. The end-to-end is dependent on consumption growth, the wholesale is highly reliant on price scenarios, and the single-buyer is dependent on both uncertainties.

With the idea of the impact of uncertainties in mind, the investment decisions (Vondelingenplaat and Leiding door het Midden) have the same effects on the market as the uncertainties. The connection of the Vondelingenplaat will unlock a large amount of heat in the heating system. This will enable future growth in consumption to be equalled. For this reason, this investment decision has the most significant impact on the end-to-end market. The Leiding door het Midden connects two separate markets, making it possible to supply heat to the other market mechanisms for cheaper producing units. This means that it affects the dispatch of marginal prices. It, therefore, appears that this investment has the biggest impact on the wholesale market. The investment decisions have little influence on the single-buyer market. For the Leiding door het Midden, this is due to the dispatch on contracts, which already assumes the heating system to be interconnected. Moreover, in the case of Vondelingenplaat, it is because of the price of this contract that it does not have a significant impact on the merit order.

However, the research should be perceived in light of the context of the method used in this research. The current market in the system is the end-to-end market. This means that the input used comes from this system. The wholesale and single-buyer markets use the same data to simulate the market. This means, for example, that contracts negotiated in the end-to-end market are used in the single-buyer market, while negotiations in this market would have led to different contracts. Besides, this means the research compares a practical market with two theoretical markets. Finally, the archetypes used are rare in reality. In reality, all kinds of additional regulation are applicable, and hybrid forms are possible.

One of the recommendations of this study is, therefore, to develop specifically desired markets for the heating system and to re-examine these for impact on the heating system. Also, it appears that there is no preference for the end-to-end or wholesale market. Therefore, it is best to carry out further research before changing the market mechanism.

Preface

At the start of my student days, I started a bachelor in psychology. Now, it is time to complete this educational and enjoyable time with two bachelors (Psychology & Technology, Policy and Management). This master's thesis represents the last step of my time as a student and my graduation requirements to obtain the degree of Master of Science in the field of Complex Systems Engineering and Management at Delft University of Technology. This research was completed in 6 months at the Department of Energy and Industry and Policy Analysis at the Faculty of Technology, Policy and Management and the Department of Investment Analysis at N.V. Eneco Group.

The research provides quantitative insights into what market mechanism is most efficient for the regional heat system in the province of Zuid-Holland. Because of my interest in energy markets and renewable energy, I enjoyed working on this project every day. Besides, the experiences of a large Dutch energy company such as Eneco have taught me a great deal about how the energy transition is continuously evolving in the Netherlands.

This research is intended for policymakers in the field of heating systems, energy companies trading in heat and researchers in the area of energy markets. It provides insight into the influences of three market mechanisms (end-to-end, wholesale & single-buyer) on the heating system. Also, the impact of investment decisions to strengthen/moderate these influences.

Although I experienced the graduation process as pleasant, there have been some minor bumps on the road to the end goal. I would never have been able to solve these bumps on my own. I would, therefore, like to thank all the people who have helped me in completing this research project.

First of all, I would like to thank my graduation committee for their time, effort and support. Pieter Bots, as the first supervisor, was always ready to help when there was any problem, and most of the time, we solved the problem within an hour. Besides, I have always felt that the advice he gives is very person-oriented and that he has a good understanding of where your competencies and pitfalls lie to make timely adjustments to your course of action. I am very grateful for this personal bond and moments of help when they were needed most. Rob Stikkelman was my second supervisor and has helped me a lot in bringing structure to the meta-level. I appreciate the conversations that started with 20 minutes about how life is before discussing the graduation project. This allowed me to loosen up on my fixed pattern of thought for a while and create new ideas for the project. Zofia Lukszo, as chair, for her sincerity and directness. After each meeting, I knew what direction to take, and I have never felt like I was adrift in my project.

Secondly, I would like to thank everyone at Eneco for their input and enthusiasm. Arriving at Eneco feels like coming home. I would particularly like to thank Jan and Thomas for setting up all the conversations with employees within Eneco and the useful meetings in between to get the project, system and ideas on track. I want to thank Frank for his time, effort, personal approach and help.

Finally, I want to express my profound gratitude to my family and friends for their unfailing support during my student years. You have always been there to support my choices and to challenge me both socially and intellectually. This wonderful period would have been very different without you. Thank you so much.

Wilan Hartwig
September 2019, Rotterdam

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1. Introduction

The Dutch government has decided to discontinue natural gas extraction by 2030 (Rijksoverheid, 2019). One of the reasons is the “energy transition” which is currently high on the political agenda in the Netherlands (Wiebes, 2019). This energy transition focuses mainly on reducing fossil fuels in the energy mix, in particular, natural gas. Another reason for the discontinuation of gas extraction are the earthquakes caused by the gas extraction in Groningen. These have led to forceful public resistance against the continuation of gas exploitation in the Netherlands and has accelerated the discontinuation of gas extraction.

However, Dutch society is highly dependent on gas, particularly for the supply of heat. This dependency has arisen as a result of the discovery and exploitation of the Groningen gas field. Since 1959, 2000 billion cubic metres (bcm) of gas was extracted from the gas field, and there is still 800 bcm of gas left (NOS, 2017). Because of these large quantities, an extensive gas infrastructure was built in the Netherlands, providing the industry and residential buildings with gas for heating and cooking purposes. Nowadays, fifty-five per cent of the final Dutch energy demand is supplied by gas, totalling 40 bcm (CBS, 2019; Rooijers, 2014). Together, the gas consumption of the built environment and industry amounts to 33-41 billion cubic metres. Of this, 25-31 bcm is used to produce heat (CBS, 2015). This means that discontinuing gas production will cause a substantial shortfall in the heat supply of Dutch residential buildings.

One of the solutions to substitute gas as a fuel in heat generation are district heating networks. In several cities, these district heating systems have existed for a considerable time. For example, the province of South Holland has local district heating networks in many cities (including Rotterdam, The Hague and Delft). In the port of Rotterdam, waste incineration plants generate heat. Two transportation pipelines connect the waste incineration plants to the city at Schiedam and Katendrecht. From here on, the district heating network extends further to connect offices and homes as well as greenhouse horticulture businesses. This replaces heat produced by the gas-fired boilers in residential buildings and horticultural industry with "less polluting" residual heat from the port. Also, there are combined heat and power plants (CHP), gas and oil boilers in Rotterdam to provide hot water on a more flexible basis to the city. The Hague also has an extensive district heating network with two CHP’s and some gas boilers.

Eneco constructed and owns the entire district heating network of The Hague and most of the infrastructure in Rotterdam. Anticipating the gas exploitation stop and the future demand for heat in these cities, Eneco is planning to build a transportation pipeline (“Leiding door het Midden”) from the port of Rotterdam to The Hague connecting both district heating networks. This will create a regional district heating system which will enable to feed The Hague's future demand for heat with residual heat from the port as well (Warmtealliantie, 2018). With Eneco owning the greater part of this regional network by far, a natural monopoly is created in the field of heat transportation.

The Ministry of Economic Affairs and Climate considers natural monopolies to be undesirable and aims to implement some form of price or market regulation (Green Deal, 2018). The ministry has therefore commissioned research into various forms of price regulation in the heating sector. Qualitative research was carried out into the impact of the technical characteristics and different price regulations of the heat market on the competitive market objectives. These objectives include reliability, affordability, sustainability, future-proof, accessibility and feasibility (Green Deal, 2018; Wissner, 2014). These studies concluded that all forms of price regulation do not have an adequate impact on the heat market (Heida & de Haas, 2019). Since price regulations appear to have an inadequate effect, the next logical step is to implement market restructuring and regulation. However, it is not clear how and in what way this is to be implemented.

This thesis, commissioned by Eneco as the primary stakeholder and owner of the district heating network, aims to evaluate three market mechanisms chosen by the government (end-to-end market, wholesale market & single-buyer market). This involves the simulation of these institutional arrangements as a market mechanism to find future dependency influencing these mechanisms. Chapter two defines the specific problems of market structures and regulation and formulates a research question. Chapter three elaborates on the method through which this research question is answered. Chapter 4 presents a system analysis of the heat market and the three market mechanisms mentioned above. Chapter 5 shows how this conceptualisation is translated into a computational model. The simulation of the model resulted in the generation of data which were analysed to distil results from them in chapter 6. Then, in chapter 7, the results are discussed in light of the research. Chapter 8 concludes the results and discussion. Based on these conclusions, Chapter 9 poses recommendations for scholars, policymakers and Eneco in chapter 9.

2. Problem definition

The introduction showed the characterisation of district heating systems as a natural monopoly which causes a need for market regulation in the future regional district heating system in the province of South Holland. This research has chosen three market mechanisms to investigate, but a method to compare them is undisclosed. The problem definition first discusses the issues surrounding a natural monopoly in more detail. Next, the chapter examines possible solutions to control the harmful effects of a natural monopoly. Finally, a literature study examines the possibilities for comparison and if there is a best-suited market mechanism. Appendix A elaborates the working method of this literature review.

2.1 District heating systems as a natural monopoly

Systems that are composed of large physical network structures, often have a market characterised by a natural monopoly. This is due to the subadditivity of production costs, where these production costs are lower for one company to own a physical network than for multiple companies (Baumol, 1986). This concept of subadditivity also goes for district heating systems (Wissner, 2014). Besides, the monopoly causes problems regarding the number of connections. In this respect, a differentiation should be made based on connection density. From a "cost" point of view, large physical networks have the lowest costs when consumption points are connected in close vicinity to each other. Consumption points for only a few consumers that are situated far from the main pipeline have relatively higher costs to be connected since a limited number of consumers need a pipeline expansion. As a result, no national coverage of district heating is possible without regulation (Hellmer, 2013; Magnusson, 2012). This means that no competition in the district heating infrastructure is possible without regulation (Söderholm & Wårell, 2011).

The consequences of the existing monopoly are that no competition between different providers of heat is possible. This causes the maximum possible social welfare not to be achieved (Samuelson & Nordhaus, 2010). As a result of market power, the added social value falls sharply. Therefore, natural monopolies on social utilities need to be regulated. This regulation is applied in various ways:

1. a market can be designed
2. ex-ante/ex-post price regulations can be applied.

The latter results in a high increase in administrative costs due to the necessary supervision into the actions of the monopolist (Wissner, 2014). Besides, likely both ex-ante and ex-post price regulation leads to a waterbed effect, where the costs are passed on to the consumer, who was already under pressure due to the market power of the monopolist (Schiff, 2008). Therefore, it is preferred to implement in the province of South Holland, a suitable market mechanism for the heat market including a competitive price with multiple heat providers (Warmtewet, 2013; Wissner, 2014).

2.2 Market regulation for district heating systems

Market regulation for the district heating systems is not as easy as copy and pasting the procedure of the liberalisation of the electricity and gas markets. The difference in the physical heating system as opposed to the electricity and gas system causes the need for different market regulations. Heida & de Haas (2019) has pointed out three reasons why it is challenging to introduce a market in the heating sector:

1) The technical characteristics of the heating system make it very difficult to decompose and implement third-party access.
2) The costs of production and sustainability of heat vary greatly per business case.

3) The district heating networks need to be subsidised to expand.

Also, current research has shown that the scope of district heating networks is often local and that, therefore, it is necessary to determine for each network which market mechanism suits best (Oei, 2016; Söderholm & Wårell, 2011). Comparable market objectives are needed to determine which market mechanism suits a local district heating network best. The market objectives for market regulation formulated by the government are reliability, affordability, sustainability, future-proof, accessibility and feasibility (Green Deal, 2018; Wissner, 2014).

2.3 Comparison of market mechanisms in district heating systems

With the description of market goals and market regulation, a literature study further examines different ways of comparing market mechanisms in district heating systems. First, this section presents studies on the qualitative comparison of market mechanisms. Next, it discusses quantitative studies of comparison concerning existing heating systems. Finally, it examines studies concerning the quantification of market objectives.

2.3.1 Qualitative studies on market mechanisms

While many studies on the comparison of market forces are qualitative, all these studies call for further research on quantitative comparison/confirmation. Oei (2016), for example, compared the markets of Sweden and Denmark and looked at the applicability to the Dutch system. The results of the study do not provide best practices for the Dutch system and ask for a quantitative study of possible heat markets for the Dutch district heating systems. Van Woerden (2015) concludes that the best market mechanism for the district heating network of The Hague is the "single-buyer" model in combination with a pool model of capacity payments. This study also calls for further research into the quantification of this market mechanism in the regional district heating system.

2.3.2 Quantitative studies on existing market mechanisms

Quantitative research has also been carried out on specific market mechanisms in district heating systems. The most advanced district heating networks are in the Baltic States, Eastern Europe and Russia. All these district heating networks have been subject to regulation that promotes market functioning. The overwhelming majority of these networks were operated using the "single-buyer" market mechanism (Aronsson & Hellmer, 2009; Andrey Penkovskii, Stennikov, Mednikova, & Postnikov, 2018; Söderholm & Wårell, 2011). It may, therefore, serve as a possible choice for the district heating network in the province of South Holland. However, it turned out that the single-buyer model has led to corruption, poor payment behaviour and liabilities for the government in the electricity sector (Lovei, 2000). It is questionable whether this single-buyer market is ultimately the right mechanism for the heat market in South Holland. Besides, extensive research on only one market mechanism does not enable comparison between market mechanisms.

Another quantitative single-buyer market mechanism study is from Latvia, which researches benchmarks. These benchmarks are used to determine competitive prices for the producers. However, the disadvantage of this system is that, as with price regulation, there are high costs associated with regulatory entities (Sarma & Bazbauers, 2016). Again, it only compares benchmarks for single-buyer market mechanisms.

2.3.3 More specific research on quantification methods for market mechanisms

Then there are quantitative studies that can be grouped into three different topics:

1. Benchmarking
2. Impact on market objectives
3. Impact of individual market mechanisms.

In the first group, research focuses on possible tariff comparisons between different heat networks. In order to be able to compare rates, parameters and algorithms have been developed (Sarma & Bazbauers, 2016, 2017). It compares the different heat systems on tariff structures, investment incentives, overinvestment risks and cost-efficiency. The scope of Sarma & Bazbauers (2016), however, only focuses on Latvia. As a result, the research looks at the generalisation possibilities of their theory in a follow-up study. From Sarma & Bazbauers (2017) it appears that this generalisation is possible by adapting the former developed theory. However, the study only compares the existing systems. Besides, it is not possible to compare different market mechanisms when reorganising an existing heat market.

The second group relates to the district heating system and the effects on the market objectives. This group calculates social welfare as a whole (He et al., 2019) or optimises economic costs and environmental costs separately (Eladl & ElDesouky, 2019). However, these studies research a fully competitive market in which there are no restrictions in the system. This is partly because the focus is on the electricity market in which heat is produced as a by-product. In the system of the province of South Holland, the emphasis is on heat production and only a few CHP's produce electricity.

The third group specifically researches existing heat networks and the functioning of the market mechanism. According to Penkovskii, Stennikov, Khamisov, Mednikova, & Postnikov (2017), little or no research has been done into the analysis and modelling of market mechanisms in the heat market. Nevertheless, the literature study highlights several studies which have been published. Both Kim & Edgar (2014) and Siewierski, Pajak, & Delag (2018) researched the wholesale market in a heating system. However, their focus was on additional revenues for the electricity market. Both studies show that the revenues for CHPs depend on electricity when selling heat and therefore in a heating market electricity production cannot be neglected. The literature review found no publications of heating systems where the main commodity for the wholesale market is heat.

As already mentioned, the single-buyer mechanism is researched intensively in heating systems. Penkovskii et al. (2018), Penkovskii, Stennikov, & Khamisov (2015) & Penkovskii et al. (2017) have researched the single-buyer mechanism in the heat market by mean of follow-up studies. His latest study concludes that optimisation of the system with a single-buyer mechanism is possible and that the model can be used for restructuring and development of the heat market. However, the single-buyer market is subject to criticism, as stated previously. Besides, currently, the province of South Holland has an end-to-end market mechanism in place. For the single-buyer market and end-to-end market mechanism to be compared information about the quantification of this market mechanisms is needed. However, the literature review shows no publications with quantification of an end-to-end market. Finally, a study by Guichard (2018) research with a focuses on a nodal pool model that creates a market in which locations are also important. However, such a market system is not yet widely used in any energy market and can be viewed as an advanced market mechanism.

2.4 Research question

The literature review has shown that quantification of market mechanisms is necessary in order to choose the mechanism that would most satisfy the objectives set by the Government and the province of South Holland. Therefore, the research question is:

How do market mechanisms influence the overall performance of the regional district heating market in the province of South Holland under uncertainty?

As discussed previously, the three market mechanisms which this study takes into account are:

1. Wholesale market
2. Single-buyer market
3. End-to-end market

Furthermore, the overall performance is tested based on the market objectives: reliability, affordability, sustainability, future-proof, accessibility and feasibility. Chapter 3 further elaborates on these market performance indicators (M.P.I's).
In order to answer the main research questions, this thesis first aims to answer the following sub-questions:

1. What are the economic functionalities of the market mechanisms in the heat and other energy utility markets?
2. What market performance indicators are most suited to compare the market mechanisms?
3. How can the market mechanisms be applied to a regional district heating system?
4. What is the effect of the three different market mechanisms on the market performance indicators of the regional district heating network in South Holland under various scenarios?

The first two questions aim at mapping and clarifying the heating system and the three market mechanisms. The third question aims to develop a tool to compare this market mechanism. The last question relates to the analysis and conclusions of this comparison of market mechanisms.

3. Method

This chapter describes how the research question is addressed. First, it introduces the general approach after which it discusses the different steps in the research. The research question requires conceptualisation and quantification of market mechanisms and market performance indicators in order to be able to compare these different markets. A quantitative comparison is possible by modelling and simulating the market mechanism. Therefore, this research uses a modelling and simulation approach to answer the research question.

The planning office for the local environment has published a framework of standards to guarantee the quality of model development (PBL, 2009). All studies of the planning office use this framework of standards, including the modelling and simulation of the climate agreement in 2019 (Hekkenberg, 2018). In the climate agreement, many different energy sectors are modelled and economically assessed, including the heat market. Besides, this research uses the modelling cycle developed by Augusiak, Van den Brink, & Grimm (2014). This modelling cycle (figure 1) is much used in literature amongst others in Schulze, Müller, Groeneveld, & Grimm (2017) with studies in the field of socio-ecological simulation.

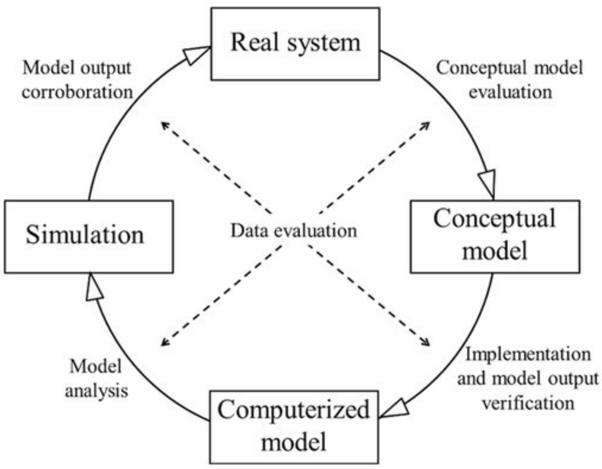

Figure 1. Modelling cycle for simulation studies (Augusiak et al., 2014)

The different steps of the modelling cycle are elaborated below with the focus on research. This research first describes the heating system and the market mechanism through system analysis in chapter 4. Essential aspects of the heating system and the market mechanisms are:

1) The physical system (e.g. production, transport, storage and use)
2) The actors who operate in this heating system
3) The different roles and responsibilities in a district heating system
4) The distribution of these tasks and responsibilities for the different market mechanisms
5) The market objectives set to assess market mechanisms
6) Uncertainties affecting the system

The system analysis leads to a conceptual model that can be used in the next step to create a computerised model.

Chapter 5 discusses how the conceptual model is translated into a computerised model. To do this, it first discusses a modelling and simulation program that is suitable for the system. It then describes how the implementation is possible. Next, chapter 6.1 discusses the model behaviour in order to check whether the conceptual model is correctly translated into the computerised model. It also examines whether the modelled outcomes and model behaviour correspond to what is expected.

After the model functions correctly, it simulates many scenarios. In this case, a scenario typifies different configurations of scenario variables, where these scenario variables have different levels (chapter 4.6). When simulating, the market model receives as input the specific values of that scenario and simulates the outcomes of the different market performance indicators. The scenario analysis includes the three market mechanisms since this research compares them — table 1 shows in the scenario's column, the abbreviation of the scenario variable and its level. E2E, SB & WH represent the end-to-end, single-buyer and wholesale market respectively and A, B, C & D are dummy scenario variables. This enables the comparison of the different markets and scenarios. This comparison is made based on the spread of these scores between scenarios. If the spread is more significant for a particular market mechanism, this means that there is less risk for that M.P.I's. When averages deviate, this means that a particular market mechanism or set of scenarios performs better/worse than the others. Chapter 6 shows and discusses these results.

Table 1. Conceptual results table

Scenario's	M.P.I. 1	M.P.I. 2	M.P.I. …	M.P.I. 6
E2EA-B-C-D-				
SBA-B-C-Do				
WHA-B-C-D+				
E2EA-B-CoD-				
SBA-B-CoDo				
WHA-B-CoD+				
E2EA-B-C+D-				
SBA-B-C+Do				
…..				

The discussion (chapter 7) discusses the results and presents them in light of the method used and the simulation programme. Then the conclusion (chapter 8) merges the results, discussion and the answers to the various sub-questions in order to answer the main research question. It indicates the conditions attached to these conclusions as well. The recommendations are formulated based on the conclusions and contribute to a clarification of the problem definition.

Recommendations (chapter 9) are made in two ways: the first concerns the limitations of the study and the method and indicate what follow-up research needs to be carried out in order to sharpen the conclusions or to further deepen the problem. Besides, it formulates possibilities for policymakers. The second, are recommendations for Eneco on what use the model is for them.

4. System analysis: Towards an open heat market

This chapter aims to conceptualise the heating system of the province of South Holland and the three market mechanisms (end-to-end, single-buyer & wholesale). This chapter elaborates on:

1) The physical heating system (e.g. production, transport, storage and use)
2) The actors operating in this heating system
3) The different roles and responsibilities in a district heating system
4) The distribution of these tasks and responsibilities for the different market mechanisms
5) The market objectives set to assess market mechanisms
6) Uncertainties affecting the system

As an overview, the map below (figure 2) shows the constructed and planned for construction assets of the entire regional heating system of the province of South Holland.

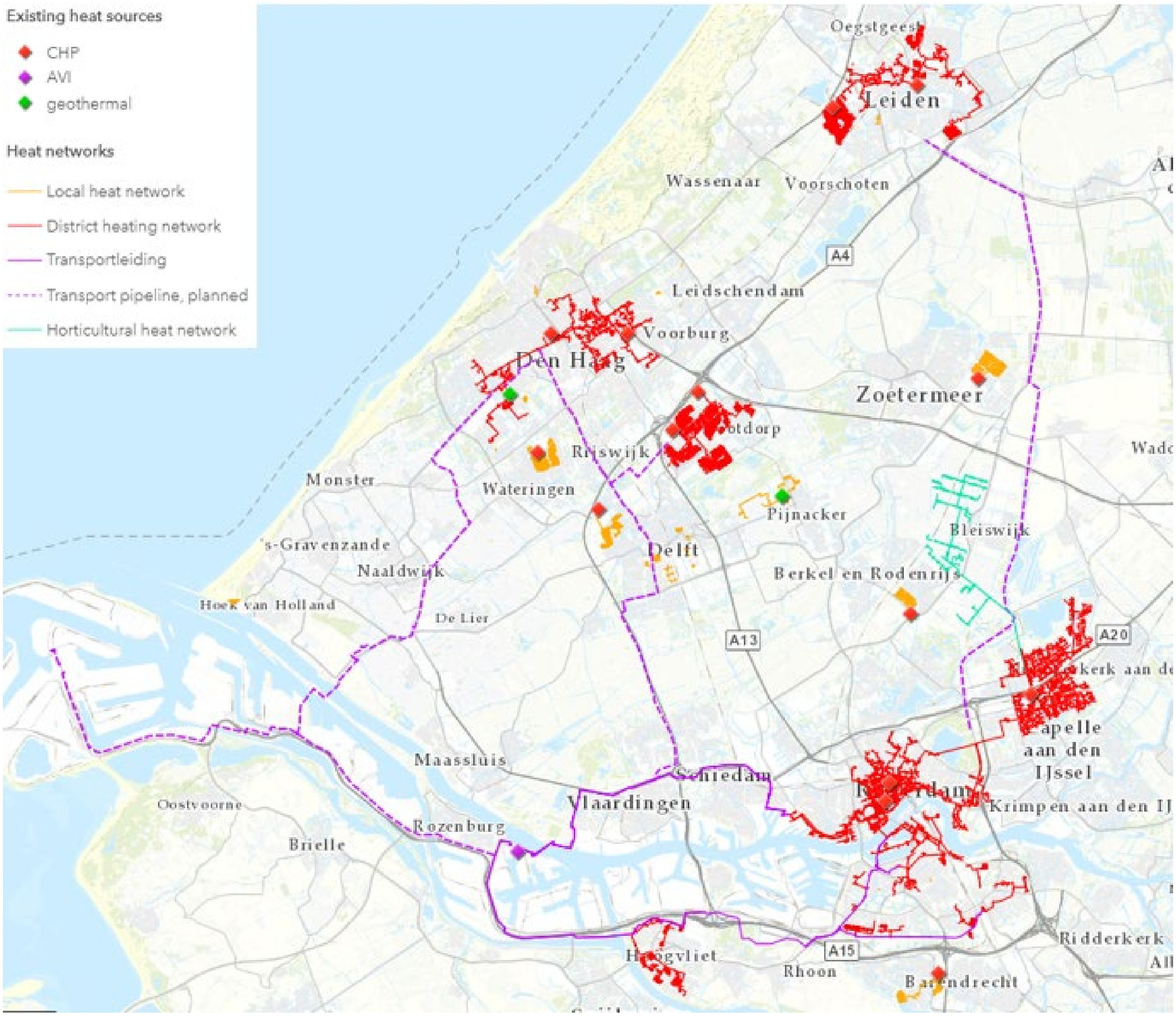

Figure 2. The heating system in the province of South Holland.

4.1 The physical regional heating system

The conceptualisation first requires a description of the physical system. The system is divided into four subsystems (production, transportation, storage & consumption) and geographical integration of these subsystems. The subsections discuss the assets in the subsystems and the properties of these assets.

4.1.1 Production of heat

For the generation of heat, several producing assets can be considered (Groot, Leguijt, Benner, & Croezen, 2008; Schilling, 2018). There are Combined Heat and Power (CHP) Assets, which generally use gas to produce both electricity and heat. Also, heat is generated utilising waste incineration plants in the port, and industries can exploit residual heat instead of dumping hot water. Furthermore, there are currently gas and oil boilers that function as back-up installations in case of maintenance of one of the CHP assets or malfunction of assets. Finally, several pilot projects make use of geothermal energy. Heat-producing assets have several important properties that indicate what kind of heat they can offer to the system. For example, they have an installed capacity, which signifies the maximum amount of heat they can feed into the system; some assets are also able to produce electricity. Then each asset consumes its type of fuel and produces heat, CO_2-emissions and or electricity. The usage of fuel and production of CO_2 generate production costs. Electricity, on the other hand, generates mainly an income. Every production unit consumes its type of fuel. Where for that unit a certain amount of the fuel generates a certain amount of heat, electricity and CO_2. This is called the efficiency of the heat-producing asset. Finally, some assets cannot easily be turned on or off. That is why they need start-up cost and time to come into use or discontinue operations. The properties with their units are described below in table 2.

Table 2. Characteristics of heat-producing assets with units

Characteristic	**Unit**
Installed capacity	Megawatt thermal [MW_{th}], Megawatt electricity [MW_e]
Fuel cost	Euro per-fuel unit [€/ fuel unit]
Efficiency	Megawatt produced/ Megawatt consumption [MW_p/MW_c] %
CO_2-emission	Tonnes CO_2 per Megawatt [Ton/MW]
Ramp-up/downtime	Gigajoules per minute [GJ/min]
Ramp-up/down cost	Euro [€]

4.1.2 Transportation of heat

The generated heat must be transported to the industrial clusters and neighbourhoods to provide them with heat. During transportation, hot water is put under pressure. There are two different transport systems needed. The first is transportation pipelines which transport water at 120 ^oC. The transport pipelines feed the heat into a heat transfer station. At this station, the heat is exchanged with the distribution network. In order to transfer heat to the distribution network, a heat potential of about 30 ^oC is required. This means that in addition to the 120 ^oC supply, there is also a second, colder discharge pipeline network needed for every closed heat transportation system. The discharge pipeline carries 90 ^oC of heat (Chiu, Castro Flores, Martin, & Lacarrière, 2016; RVO, 2018). At present, two pipelines of this kind connect the waste incineration plant in the port of Rotterdam to the city of Rotterdam, called "Leiding over Noord" and "Nieuwe Warmte Weg". "Leiding door het midden" will be connected to "Leiding over Noord" and then connected to the distribution network in The Hague.

The distribution network has a supply temperature of 90 ^oC to the houses and offices. The discharge of this heat has a temperature of 70 ^oC. In the province of South Holland, many larger cities have such a distribution network (including The Hague, Rotterdam, Dordrecht, Leiden, Delft & Ypenburg). The distribution network supplies the heat for consumption in homes and offices. The heat is converted from a heat exchanger to enter the building at 70 ^oC. The heat is used and returns at a temperature between 40-50 ^oC (RVO, 2018). Figure 3 shows the heat transportation system from production to consumption with according temperatures.

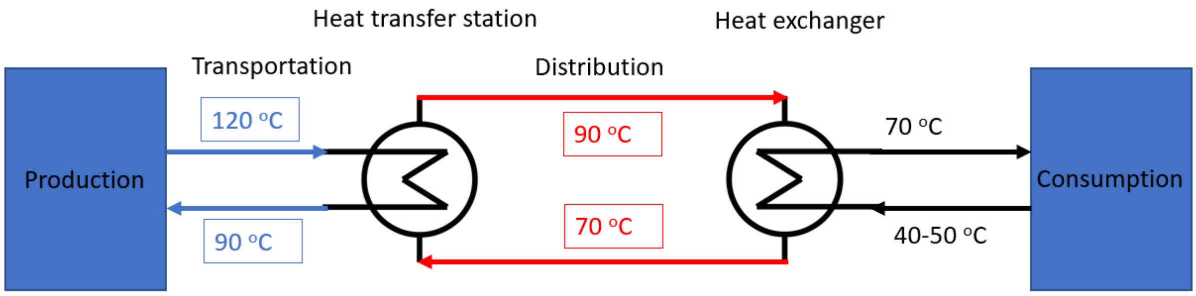

Figure 3. Transportation system with temperatures

In addition to the different temperatures, the transportation system also has other properties that are important for the heating system to function. The pipes have a specific capacity of the amount of heat that can flow through them. Furthermore, pumps create a flow in the pipelines, which account for most of the transportation cost. There is also a loss of heat on the pipelines. The properties of their units are described below in table 3.

Table 3. Characteristics of heat transporting assets with units

Characteristic	**Unit**
Capacity	Megawatt thermal [MW_{th}]
Flow	Gigajoules per second [GJ/s]
Heat loss	Gigajoules/meter [GJ/m]
Temperature difference	Difference in temperature [ΔT]
Transportation cost	Euro/gigajoules [€/GJ]

4.1.3 Storage of heat

Perfectly matching supply and demand is not possible, due to, for example, an unexpected downpour. Therefore the system makes use of buffers to balance supply and demand. There are two types of buffers. The first is used for short-term balancing (from one day to one week). Second, high-temperature storage is possible in empty salt caverns. This would make long-term storage possible, e.g. excess heat can be stored in the summer for use in the winter (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Schepers & Valkengoed, 2009). The Hague is currently in the process of carrying out one pilot project for such a high-temperature storage facility, but it is not expected to be operational until 2035, and the impact is highly uncertain.
The short-term buffers currently installed in the province of South Holland all have their capacity to store heat. Besides, the buffers can store heat at a certain speed or give it to the heating system. During storage, the buffers also lose heat. Table 4 shows the storage properties.

Table 4. Characteristics of heat-storing assets with units

Characteristic	**Unit**
Capacity	Megawatt thermal [MW_{th}]
(Dis)charge rate	Megawatt [MW]
Heat loss	Gigajoule per hour [GJ/hour]
Storage cost	Euro/gigajoules [€/GJ]

4.1.4 Consumption of heat

First, residential buildings and offices consume heat. Second, the industry uses heat for manufacturing and growing purposes. Transportation pipeline generally feeds the industries because the industry requires higher temperatures of heat (e.g. in the form of steam). An example is the plan to connect the Heineken brewery to the transport pipeline "Leiding over Oost". In the province of SouthHolland, such big industries are not yet connected but are planned for connection. An industry which requires the same heat as residential buildings are the horticulture sector, which often also has its WKOs to generate heat (WarmteKoude Zuid-Holland, 2018). They are already connected in the east of the province and will be connected in the 'Westland'. The characteristics of consumption of heat are the demand pattern. Which can be viewed as a tub over a year with high demand in the winter and low demand in the summer.

Table 5. Characteristics of heat consumption with units

Characteristic	Unit
Demand	Gigajoule per hour [GJ/h]

4.1.5 Geographical location

The heating system only functions properly when the subsystems integrate correctly. The network topology (figure 4) combines information from the heat transition atlas (figure 2) and the subsystems to show a simplification of the various heat-producing assets, transport systems, short-term buffers and demand clusters.

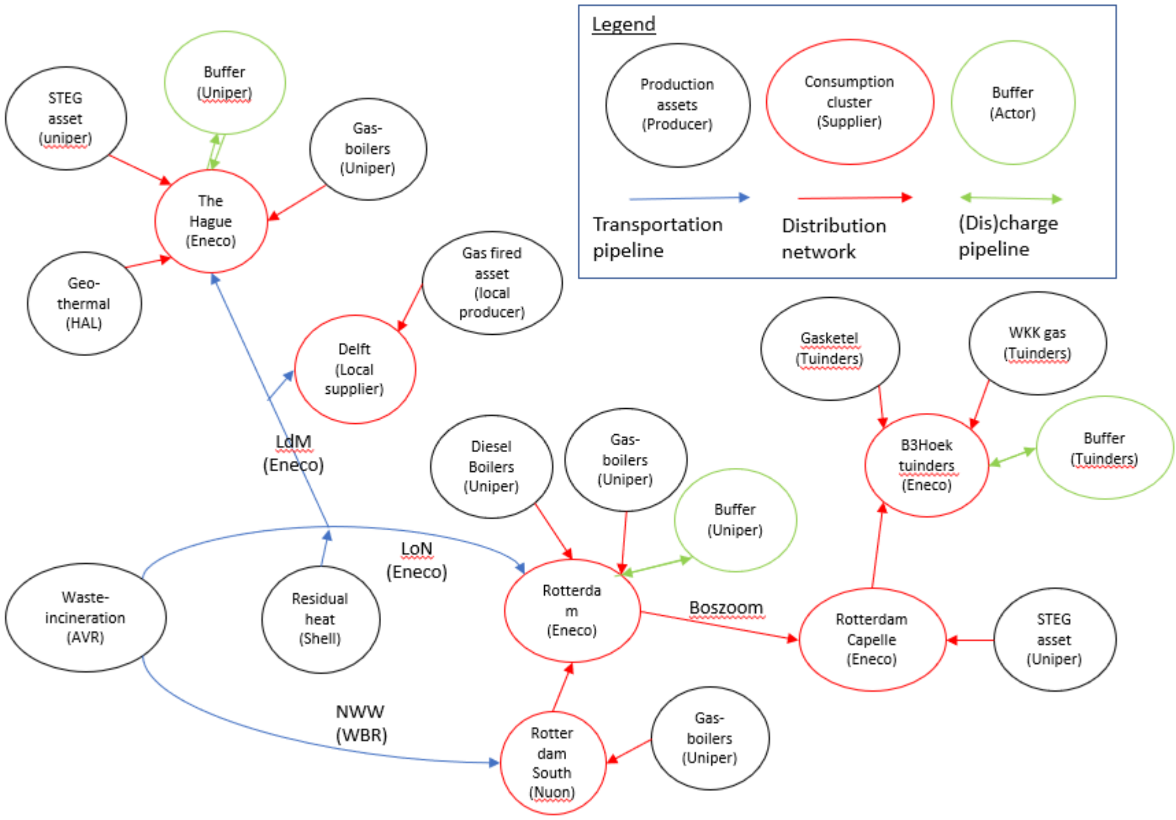

Figure 4. Network topology

4.2 Actors in district heating systems and markets

This paragraph discusses the different actors involved in district heating systems and markets. The subsections first explain what the actor does, then which parties are in the province of South Holland and end with their interests.

4.2.1 Producers

Producers exploit different types of heat sources (gas, geothermal energy, residual heat and more). In the regional district heating system of the province of South Holland, Uniper, Warmtebedrijf Rotterdam (WBR), Afvalverwerking Rijnmond (AVR), Tuinders & Haagse Aardwarmte Leyweg B.V. (HAL) are producers of heat. Also, the horticulturalists in the Bergschenhoek, Bleijswijk and Berkel en Rodenrijs (B3Hoek) produce heat for the system (mainly for their use). In the future several producers are expected to connect to the heating system, such as Shell, which is going to supply residual heat and the Westland will be connected. Which will be able to supply heat, often through locally fired combined heat and power plants and a biomass plant.
These producers have an interest in the following characteristics of the heating system:

- Acceptable tariffs for connection and use of the heat transmission system. Where the margin between income and costs are in balance.
- Growth of heat connections and other outlets.
- Equivalent treatment of producers. For example, equal treatment for tariffs and similar conditions for the connection and use of the heating system.
- Equal sharing of risks, e.g. through guarantees on payment and off-take and protection against imbalance caused by other producers.

4.2.2 Purchaser

Customers take heat from the transmission grid and producers. Most customers are heat distributors. Eneco, WBR and Vattenfall are currently the heat distributors in the heating system in the province of South Holland and are therefore customers of the district heating transport system. Another large heat purchaser in the system are the Horticulturists. The essential characteristics of the purchaser are the same as those of the producer. The only difference is the difference in desired certainties in production instead of consumption.

4.2.3 Transporter/Network operator

The transporter is the actor who creates and operates the heat transport. This research assumes an independent transporter. For the network operator, the following characteristics are essential:

- The rates for connection and use of the transport system are cost-covering.
- The obligations are proportionate and manageable.
- All parties share the risks in the system.
- Opportunities for profitable operation, including enough influence on the development of the heating system, opportunities to cover full run risks and the provision of a level playing field for users.

4.2.4 Program manager/Portfolio manager

The program manager ensures coordination of balance between supply and demand for heat. The program manager can take different forms per market mechanism. For the program manager, it is crucial that:

- He has options to flexibly control production and consumption in case of imbalance in the market.
- It gives nsight into production and consumption by the various producers and customers.
- Has the authority to declare any expenses to the other parties.

4.2.5 Market operator

The market operator only applies to the wholesale market. It is an actor who takes care of the processing of the bids in the market, aligns these bids as a programme manager and distributes the final costs and revenues.

- The market operator needs to be able to influence heat producers/customers in the event of imbalance in the network.
- Insight into the price offered and the amount of expected production/consumption from a producer and customers.

4.2.6 Municipalities

Municipalities are directly involved in the realisation and use of the heat transport system. They are responsible for the planning and realisation of the heat transition. From this perspective, the following characteristics are essential:

- Possibility of controlling local development and realisation in order to connect transport capacity to district-oriented heat plans.
- The grip on competition between local and regional heat sources (e.g. future geothermal wells).
- Affordability and a fair distribution of the costs of heat for end-users in the municipality.
- Insight and influence on the origin and sustainability of the heat transported to the municipality.

4.2.7 End users

End users consume heat according to their own needs. However, they are not directly involved in the transportation of the heat. Nevertheless, the end-user is one of the most critical players in the heating system, since it will pay for most of the cost of the heat and relies on heat to fulfil its basic needs. The following characteristics are essential to them:

- Reliable supply of heat when the end-user deems it necessary.
- The ability to differentiate between suppliers and to make choices on the sustainability, origin and price of heat.
- Fair distribution of costs over the entire heat chain and insight into this distribution.
- Ability to anticipate tariff changes and contribute to cost reduction.

4.2.8 General public interest

In addition to all the specific parties involved, heat transport also plays a role in the general public interest. The heat transport system is part of the entire energy transition and regional heat transition and supply. The interests involved consist of:

- The general public interests of energy supply: Affordability, sustainability and security of supply.
- Effective and efficient use of the regional heat transition.
- Since the development, implementation and operation of the heating system over the entire heat chain are complex. The organisation of the market must facilitate enough coordination in this regard.

4.3 The different roles and responsibilities in a district heating system

This subsection describes the different roles and responsibilities that a well-functioning district heating system should have. It groups these roles and responsibilities into three different parts:

1) Availability
2) Usage, contract & pricing
3) Information exchange and payment

4.3.1 Availability

Availability includes all the tasks required to organise an available heat transport system. This subsection further subdivides the tasks into development, realisation, maintenance, economic exploitation, and determining the temperature regime. These aspects are one by one discussed below.

The development contains everything that needs to be done in order to be able to proceed to realisation. This includes choices such as:

- Which areas need to be connected
- Which routes the pipes must follow
- What capacity each pipeline needs
- Which pipe is constructed when
- Which system conditions (temperature and pressure) apply
- Which specifications apply to operate systems

The construction of heat networks is capital intensive, and the choices made in the development process have a significant impact on the final costs for the end-users. However, this also has consequences for the other parties involved in the chain. For example, connecting residual heat in the port of Rotterdam can provide cheap heat for the end-user. However, this is detrimental to producers because this creates more competition in the network. Dimensioning is also essential, as is the case with "Leiding door het Midden". Because the pipeline would be built based on growth, the question is whether this growth is ever going to take place.

Realisation includes the tendering, financing and coordination of, and supervision of, the execution of construction work. However, this has little impact on the market organisation, nor on maintenance, which includes maintenance and management.

Economic operation signifies the management and control of the profit and losses endured during operation of the heat transmission system. This includes the following

- The collection of all fees paid by users or other parties involved
- Payment of all fees
- Managing and bearing profit and loss

This is hugely relevant to the market organisation because of risks. For example, in the case of over-dimensioning. Whoever wants to over-dimension the pipeline must share in the price and risks. Which has been a point of struggle in the past not to construct “Leiding door het Midden”.

Finally, there is the temperature regime, which has a significant impact on the business case of users of the transport system. It creates opportunities for making the system more sustainable. However, the temperature regime can be adjusted during operation and is therefore neglected in this research.

4.3.2 Usage, contract & pricing

The use of the heating system includes all the tasks required to use an available heat transport system. This starts with connecting a source or user to the system. When both are connected, the heating system is ready for daily operation. This daily operation consists mainly of the transport of heat according to a programme. This program ensures that one day in advance, both supply and demand are matched. When an imbalance occurs in the system, the network operator compensates for this by shutting down locally producing facilities or increasing the consumption of large consumers. For this to work, agreements are made with programme managers and with parties in the system who can easily regulate heat production/consumption. This is also known as the capacity market. However, this supplemental application for the market mechanism is not included in this study because archetypes are used to compare markets.

Because producers and purchasers make substantial investments and commitments relating to the production and purchase of heat, contracts are required to seal off risks. The contract and pricing can be divided into an agreement with three different parties: Producer, Customer and Transporter. The price of heat is different depending on the market mechanism, due to the negotiation and conclusion of other contracts:

- A purchaser invests in a distribution network and undertakes heat supply to end-users. That is why the purchaser wants the assurance of a sufficient supply of heat with the required sustainability. The margin between costs (purchasing and transport) and revenues (sales to end-users) must be sufficiently balanced to manage and use a profitable distribution network. In order to guarantee this security of supply, the purchaser usually enters into commodity contracts with producers for a period of several years to several decades. These contracts include capacity, price and quality of the heat. Besides, the purchaser also wants the reassurance of the heat supply. The customer, therefore, concludes a connection and transport agreement to ensure the provision of heat.
- A producer invests in a heat source and therefore wants to be sure of enough sales and turnover from heat. The producer wants a margin between costs (production and transport) and income from the sale of heat that is profitable for the source to produce heat. At present, a producer receives this security by concluding a contract with a customer about the capacity, quality and availability of the heat, among other things. A producer is also able to contract reserve capacity, which guarantees availability is more important than the actual heat produced. Besides, the producer must also commit to the transporter employing a connection and transport agreement.
- The transporter(s) determine the connection and transport agreements. They invest in a transport system and operate the transportation of heat from the source to the customer. The transporter wants to ensure enough income and controllability of costs, which together result in a profitable transport system. A transporter receives this assurance by entering into a transport agreement in which capacity, price, availability and quality are included in the agreement for years to decades. The connection costs are often costs that bring about the opening up of the source or the customer.

Because these different parties demand different requirements from the contracts, the conclusion is that covering production and transport costs mainly determines the price of heat. Besides, part of the price of heat is used to cover risks such as security of supply. How this combination of covering costs and risks is achieved differs per market mechanism, and therefore the market mechanism also has a different price for the commodity heat.

A requirement posed by the government is the safeguarding of the general public interest. The aim is to maximise the economic and social surplus. This requires a form of coordination in which this form can take place both extrinsically (by a designated coordinator) and intrinsically (through market forces). Besides, efficient use also means the effectiveness of investments in the transport system. Not only does this allow everyone to enter the heat market (as a producer or consumer), but it also protects against unnecessary expansions of the heat network, the costs of which are ultimately passed on to the end-users. However, it is precisely this expansion that needs to be stimulated where necessary in order to provide as many users as possible with (sustainable) heat. While, as discussed earlier, a monopoly position is undesirable in the heating system where one party has the option of negotiating all contracts.

4.3.3 Information exchange & payment

Information exchange between actors in the district heating system is vital since they are needed in all the different tasks in the heating system and used to align programmes, contracts and costs. It is therefore desirable for the heat network to provide clear, correct and reliable information. However, unlimited transparency involves risks, which causes commercial actors to be reluctant to share information. That is why it is crucial in the market to pay attention to the provision of information. The parties need to determine which information is essential for sharing and which information is available for sharing purposes to a limited extent.

Ultimately, it is possible to charge for the costs of the consumed heat. The tariff structure of heat is considered, considering the commercial reality of the heat transport infrastructure together with the public interests (sustainability, affordability and security of supply). Policymakers setting tariffs should consider the following:

- Security of supply
- Investment security (cost-covering + reasonable return + term of security)
- Stimulating innovation (stimulating efficiency, making it more sustainable, reducing costs)
- Affordability (efficiency incentive, tariff regulation)
- Non-discriminatory (no favouring of competitors or customers)

The affordability of heat is currently a debated issue. In order to protect the consumer, the price of heat is capped by the Heat Act. This is under the 'no more than otherwise' principle. In this case, the heating price is linked to the gas price, so that the end-user cannot pay more for heat than end-users of gas. However, the Netherlands wants to shut down gas exploitation in order to reduce CO_2-emission. Consequently, the price of gas and heat is expected to rise as a result of the rising CO_2-emission taxes. It may turn-out that this is unfair to the heat user. The heat market, therefore, should be uncoupled from the gas market in time.

4.4 The distribution of the tasks and responsibilities for the different markets

The three market mechanisms are discussed based on the different roles and responsibilities discussed above. The difference between the markets arises from fulfilling these different roles and how these roles interact with each other. The main difference is how the markets match supply and demand. The market mechanisms discussed here are archetypes. This means that other variations and combinations of these archetypes are also possible.

4.4.1 End-to-end market mechanism

Producers and customers entering into contracts with each other for the supply and purchase of heat characterise the end-to-end market. Besides, they contract temporary transport capacity for operation with a third party that acts as an independent operator of the transport network. The customers decide which source they want to use, and the producers and customer agree upon the route which the heat will follow. At the end of the contract period, there is a possibility of concluding new long-term contracts, or the network operator can decide to auction the transport capacity periodically.

In this market mechanism, the network operator is a technical service provider that does not occupy a market position and is responsible for the expansion and maintenance of the transportation system. On behalf of the portfolio manager, this party ensures the transportation of heat. Besides, the portfolio manager also has programme responsibility for each connection in the portfolio. The task is to coordinate the programmes in such a way that the portfolio is in balance. Entry into the transport network of new heat or new off-take takes place when this is advantageous for the producer and the customer and when transport capacity is available on the desired route. When new sources or customers enter the grid, the grid manager grants them access, provided they have reached agreement on the supply of heat and transport capacity is available.

A lack of transparency characterises this market in terms of information. The information about incurred costs between producers and customers is not public, and payments in respect of commodity heat are also in commercial hands and not public. This can lead to perverse incentives. However, the network operator can grant non-discriminatory access to the transport network, so that this is not an obstacle to the new entrants.

4.4.2 Wholesale market mechanism

A single independent pool operator that manages a market pool characterises this market mechanism. This role can also be carried out by the independent system operator, but this is not necessary as the pool operator does not have a market position. Producers and customers have access to this market pool where an integrated heat product is traded (a combination of production and transport). Whether or not the heat is traded depends on the price that is requested or offered. The balance between supply and demand is established based on price, transport costs and sustainability unless congestion is present in the system. In theory, the specific heat is priced because the producer offers at marginal costs because he always has a turnover above these costs. When these quantity and price curves intersect, a price and quantity of traded heat are created. The supply and demand are coordinated on an hourly and daily basis, and this gives the customers and producers a choice. This means that in this market mechanism, economy and ecology are optimised simultaneously.

The independent network operator also determines the expansion and modification of the transport network. If requested by producers or customers, they modify or expand the network in order to make it accessible. However, the network can also be expanded in policy terms to make more sustainable heat available in other areas, such as the residual heat in the port of Rotterdam. However, unlike the other two mechanisms, the grid manager can influence the matching of supply and demand by solving congestion problems.

This market mechanism includes a great deal of transparency. The hourly prices for heat and the prices for sustainability are known or can be calculated using information from the market pool. The pooling platform arranges the payments in the system. Here, the costs of transport can be added to the costs, if necessary, or agreed separately. Transparency is partially lost if long-term contracts are concluded as security.

4.4.3 Single-buyer market mechanism

A monopolist who buys heat transports it through the network from the sources and sells heat it to the purchasers characterises this mechanism. The single-buyer can consist of a collective of producers, a collective of customers, a mixed collective or an independent manager. Since the first three might cause conflicts of interest and this study assumes independent network operation, the single buyer will represent an independent operator at the same time. This single-buyer has the exclusive right to trade heat in the transportation system. Moreover, with this, the single-buyer also occupies a market position, including the price and volume risks, which makes independent grid management impossible for the single-buyer. This means that the single-buyer can either contract transport capacity and pass it on in his prices, or leave the transport capacity to the customers. The buyer and producer must follow the programme set up by a single-buyer. After all, the single-buyer must match supply and demand.

The single-buyer as monopolist determines what new heat supply and demand comes onto the market and in theory, only does this if it is favourable to him. However, the single-buyer can be bound to regulation in order to be stimulated to connect cheaper or more sustainable sources. The incentive to meet the demand as efficiently as possible exists, of course, because it is in his interest to offer the purchased heat to the customers.

Because the single-buyer has the exclusive right to trade in heat, the single-buyer is the only one who has all the financial, technical and physical information relating to the transport network. As a result, the single-buyer is the party that must provide all users with information, thereby treating these users in a non-discriminatory manner. The exchange of information once again makes it clear why the single-buyer is best served by an independent party.

4.5 The market objectives set to assess market mechanisms

In the introduction and problem definition, the government mentioned six market objectives that measure the preferability of the market. This section further elaborates these market objectives. Because qualitative research has already been carried out, this research does not include the qualitative criteria.

4.5.1 Reliability

First, there is the objective of reliability, which means that the market mechanism must enable guarantees for the supply of heat to the end-user. This requires that the market mechanism create possibilities:

- To offer customers of the transmission system security of supply through overcapacity or interruptible demand contracts with specific (wholesale) consumers.
- Need to optimise/use peak and backup installations

This study provides a surplus of heat by adding residual heat from the port to the regional heat supply.

4.5.2 Affordability

The market organisation must ensure that affordability for the end-user is guaranteed. This means:

- Facilitating system optimisation
- It leads to an efficient and proportional organisation of the market for all parties involved
- Enables efficient contracting by all contracting parties, both for transport and commodities

For this study, this means that the total system costs are examined and compared with each other. Besides, the marginal costs are compared to look at commodity prices. In this way, it shows if the end-user pays in proportion to the costs of heat generation and transport. Furthermore, system optimisation is something that follows from this research, which means that it can be used as a reference when the market has been implemented. The calculation for this consumer price differs per mark mechanism; therefore, Chapter 5 (Computational model) elaborates how this is calculated.

4.5.3 Sustainability

This is an essential theme for the heat transport system, partly because it is intended to replace gas consumption and thus to make the heat supply more sustainable. It is, therefore, important that the market mechanism facilitates the following:

- It offers opportunities to stimulate parties to become more sustainable.
- Offers parties the opportunity to govern efficiently and effectively based on sustainability incentives
- Provides enough transparency to be able to monitor and assess sustainability.

This study includes the first two requirements. Regulation enforces the latter and therefore falls outside the scope of this study. The difference in CO_2-emissions measures the first two statements.
Another prescribed measurement of sustainability by the government is equivalent generation efficiency (EOR). This measurement is determined based on scoring on sustainability per type of heat supply and the path the heat takes to consumption. This makes it a very path-dependent and complex measurement tool, which this research does not take into account.

4.5.4 Future-proof

The heat transport network needs to be scaled up in order to facilitate the transition and evolution of the heat supply to take place through district heating systems. That is why the market mechanism must also provide for this:

- The possibility for parties to invest in the transport system and to have enough return on investment.
- The possibility for sources and customers to have enough perspective on the return on the investments and commitments they have entered.
- The market mechanism can evolve in terms of the number of connected parties, diversity of actors, utilisation of the transport infrastructure and integration of other energy markets.

This study can measure the future-proofing of the system by looking at the costs of the investment, in this case, 'Leiding door het Midden', and the returns that are generated. This concern the time of the return of revenues. The costs of the investment compared to the marginal price/total system costs shows how expensive transport over this pipeline should be over a specified period. Using the gas price as a reference framework (NMDA principle), it is possible to determine whether the market mechanism allows for this type of investment at all.

4.5.5 Accessibility & feasibility

This study does not consider these two market objective because they are legislative and must be solved through regulation. All market mechanisms require a certain amount of regulation for these market objectives. Accessibility refers to the connection to the heat network in order to take or supply heat from it. This, therefore, relates to the permissibility of this.
Feasibility refers to the legal feasibility of market mechanisms, i.e. they can be implemented following the applicable law. Besides, parties must be sufficiently obliged to make their reports and quality declarations transparent.

4.6 Uncertainties affecting the system

District heating networks should be able to be used for 50 years or longer. Market mechanisms can be adjusted relatively quickly in the interim. However, the foundations of this market mechanism, described in this study as archetypes, must be practicable for a much more extended period. There are two kinds of uncertainties in the future. The first are uncertainties that cannot be influenced, which are called scenario variables. The second type of uncertainty relates to individual design choices through which a degree of influence is exercised in the system; these are called design variables. The specific types of variables for the district heating system are discussed in more detail below. After formulating these variables, an experimental design was set up to define the various future scenarios.

4.6.1 Scenario and design variables

In the district heating system and the market mechanism, two important scenario variables emerge. First, there is the pricing of fuels and CO_2, as discussed earlier, the Netherlands wants to get rid of gas as heating fuel and is, therefore, going to increase the tax on gas. As a result, increasing the gas price. Besides, as a result of the energy transition and the construction of solar and wind farms, there has been a decrease in the price of electricity, which can even lead to negative prices. Finally, the CO_2-price is regulated through policy from the EU and perhaps also from the Netherlands. The trends of these prices in the future are therefore uncertain. Eneco has outlined five scenarios for this:

- *Low* is a world view where everything goes wrong in terms of sustainability and can partly be seen as an extreme test.
- *Reference* is a world view in which current policies are continued.

- *Tides* is a world view in which a major next crisis arises in which Europe falls behind. After which Europe will recover through aid from Asia and America.
- *Paces* is a world view in which everything goes wrong because of an EU crisis as a result of which countries no longer cooperate, which causes an empty flow of knowledge to other countries and the demise of Europe.
- *Circles* is a world view in which everything in terms of sustainability is on track and integration of sustainable technologies ensure ever-increasing improvements.

Secondly, there is uncertainty in the growth of heat connections in the province of Zuid-Holland. If there is a policy that makes it easier to connect houses to district heating, this will result in stimulation of heat consumption. However, technological innovation in electric boilers may result in low growth. Therefore, Eneco varies the growth scenario in three levels. Decisions on which a certain degree of influence can be exercised include the investment decisions in the Leiding door het Midden and the Vondelingenplaat. To a lesser extent, Eneco can influence the market mechanism through lobbying. However, the final decision remains with the government.

4.6.2 Experimental design

This subsection discusses the experimental design for this research that was used for the simulations. This research uses a period from 2018 to 2040. This decision is for two reasons: first, the use of infrastructure is 50 years or more and therefore requires a relatively long period in order to make sensible statements about this system. On the other hand, the predictions of prices after more than 22 years are already becoming somewhat imprecise, and there is little added value in looking further into the future. This research uses 2018 as a starting point because prices and consumption in the various district heating networks of the province of Zuid-Holland are known for this year. This enables the simulation of these models and to compare them.

Due to a large amount of data and expected modelling time in the simulation of all years between 2018 and 2040, this research takes three different years. The first moment is 2023 because at this moment the construction of the Leiding door het Midden and the Vondelingenplaat are planned. Moreover, the second and third moment are 2030 and 2040 because these are increasingly significant time steps in the future, which also allows long-term expectations to be tested.

Table 6. Experimental design

	Configurations				
Design variables					
Chosen years	2018	2023	2030	2040	
Market Mechanisms	E2E	SB	WH		
"Leiding door het Midden"	Constructed	**Not** constructed			
"Vondelingenplaat"	Connected	**Not** connected			
Scenario variables					
Consumption growth	Low	Medium	High		
Fuel prices	Low	Reference	Tides	Paces	Circles

As fuel prices and heat consumption are given for 2018, only three scenarios can be compared that differ due to the different market mechanisms. Besides, base case comparison examines the influence of the Leiding door het Midden on this system. This results in a total of 6 scenarios for the base case. The scenario analysis examines three years, three market mechanisms, two times two investment decisions of whether to construct the Leiding door het Midden and Vondelingenplaat, three possibilities of consumption growth and five possibilities for fuel prices. This results in a total of 546 scenarios.

5. Computational model

This chapter translates the conceptualisation of the system analysis into the computational model. First, the chapter looks at the type of problem the dispatch of the district heating system is facing. Secondly, Linny-r and his functionalities are discussed to solve the problem. Finally, the implementation of the market mechanism discusses the dispatch and settlement.

5.1 Dispatch of district heating system as a unit commitment problem

The purpose of this study is to test the market performance of three different market mechanisms on the formulated market objectives. However, the market mechanisms have two similarities that are used as a basis for comparison:

1) the physical system of production, transport and consumption is the same for all three.
2) A requirement for all three market mechanisms is that the deployment of producing units and transmission lines must always meet the heat demand.

These similarities and requirement of the basis of the market mechanisms as a unit commitment problem (UCP) (Tahanan, van Ackooij, Frangioni, & Lacalandra, 2015). Using mixed-integer linear programming (MILP), it is possible to solve the unit commitment problem for this heat network (Anand, Narang, & Dhillon, 2019; Koller & Hofmann, 2018; Thorin, Brand, & Weber, 2005). A graphical specification language which solves UCP's with MILP is the program Linny-R (Steep Orbit, 2019).

5.2 Linny-R and its functionalities

This section describes Linny-R and the functionalities of Linny-R. First, it discusses the meaning of the graphical language. It also discusses the way UCPs are solved. Finally, it discusses the general inputs for modelling a heating system.

5.2.1 Graphical language of Linny-R

Linny-R is a graphical modelling program. This means that Linny-R models a system through connecting ovals, arrows and squares. The design of this modelling program provides a better representation of the system to be modelled compared to other modelling programs such as MATLAB and Python. Figure 5 shows the three most essential elements of Linny-R:

1. Products
    a. As input in the form of fuel
    b. As output in the form of heat
2. Links
    a. As a connector between product and process
    b. As a connector between process and product
3. Process

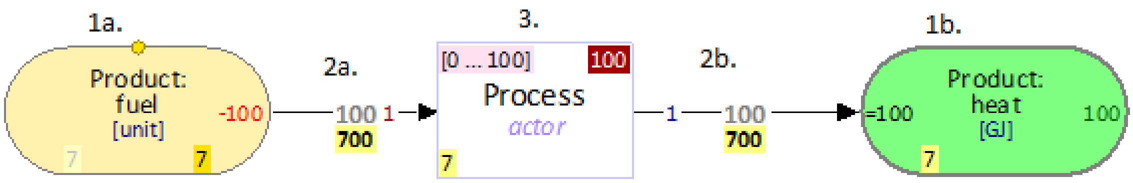

Figure 5. Graphical language of Linny-R

Figure 6 shows the products in a much-simplified heating system. In the heating system, products represent: fuels, CO_2, produced heat, stored heat or contracted heat. The middle of the oval shows the name of the product, with the unit below *[between brackets]*. In the fuel product (1a) is shown in red -100, which is the stock of this product. In the lower-left and right corner, there are two sevens, the first being the cost price of the product and the second being the price of the product per unit. These may differ from each other when a different process produces another product. The product: heat (1b) shows a =100 number. This shows the target that is set for the product. In the heating system, this is used to indicate a fixed amount of heat consumption. The green colour indicates that the target is met.

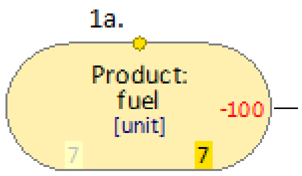

Figure 6. Products in Linny-R (left as input, right as output)

Figure 7 shows the links between the products and processes. A link can only connect a process to a product or vice versa. The links contain three types of data. First, the 1 in blue and red, indicates the rate per level of the process. The number 100 in grey indicates the flow of the respective time step. Moreover, in yellow (700), the costs associated with the commodity flowing over the link are shown.

Figure 7. Links in Linny-R (left from product to process, right from process to product)

In the heating system, a process (figure 8) mainly represents a producing unit or transportation pipeline. Besides, it can be used for the storage of heat or as a contract. The process can represent a contract because a contract is assumed to be a set of agreements, including the quantity of heat at a specific price. This means that when heat from a contract is called upon, the quantity of heat must be injected into the system at the given contract price. The middle of the process shows the name of the process, the purple text in italics below shows the owner of the process. In the upper left corner of the screen, with the notation [0...100], the bounds of the process are shown. Each step represents an extra level, where this level is equal to an extra produced unit. For the heating system, these are used to model installed capacity, among other things. The current production level shows in red in the upper right corner. Finally, in yellow, the cost of one unit produced by the process is displayed.

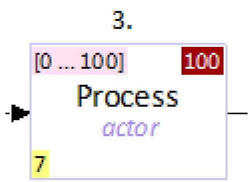

Figure 8. Process in Linny-R

5.2.2 Solving a UCP in Linny-R

Linny-r can solve a UCP by matching supply and demand. For this, the program uses decision variables, constraints and objective function. Figure 9 shows a simplified representation of a heat chain, based on which the method of solving the UCP is explained.

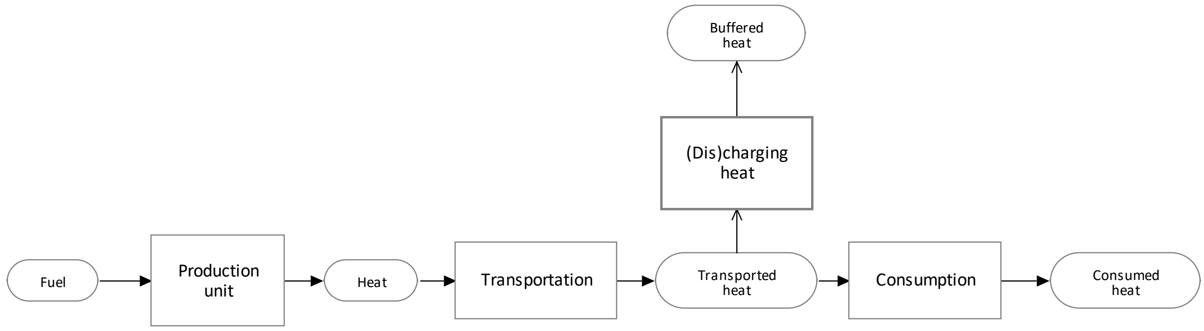

Figure 9. Production, transportation and consumption in Linny-R

The decision variables in the heat network consist of the capacity used per producing asset and the capacity transported per pipeline with the maximum installed capacity as a limiting factor. The heat flows, apart from the buffers, have all been modelled downstream. This means that the producing assets (+ buffer loading and unloading) must be equal to the heat demand. In this case, the "cheapest" assets are used first, which generally gives the order of dispatch. However, in the event of congestion in the transport network, a more "expensive" assets may be dispatched because the cheaper asset cannot transport enough heat to the right place. The price is formulated based on production costs where not only the fuel price is essential, but also the start-up costs of the producing asset in question. Constraints limit the baseload and maximum load that a producing unit can produce. Besides, it limits the possible amount of heat in transport lines.
The objective function solves the UCP based on these decision variables and constraints. It maximises the revenues of the system (minimises costs), by adjusting the decision variables and by matching the heat demand with the production as cheaply as possible in this way.

5.2.3 Setting up the regional district heating system in Linny-R

This study uses general configurations, settings and inputs when setting up a district heating system in Linny-R. First, this paragraph describes the infrastructure. Secondly, it describes the general inputs and finally, the solver settings.

For the three market mechanisms, the heat infrastructure, heat generation and consumption, do not differ. The only difference that occurs is the production and transport of heat from the AVR. Through contracts, WBR buys heat from AVR and sells it on to Eneco near Rotterdam South. Eneco has a summer and winter contract with AVR. This is different for the wholesale market. It assumes that this contract does not exist and that AVR, therefore, has a total installed capacity of 260 MW. Appendix B shows the complete heating system for the three different market models.

Several input variables are needed to implement a heat infrastructure and market in Linny-R. These are described below in table 7 & 8. The first gives an overview of the universal input needed. The second gives an overview of market mechanism-specific input that is needed.

Table 7. Universal input variables for the heat infrastructure

Universal input variable	**Unit**
1. Production	
Installed capacity	MW
Ramp up/down cost	€
Fuel consumption	Gas: m^3/MWh Biomass: ton/MWh Waste: ton/MWh Diesel: ton/MWh
Electricity production	MWh_e
CO_2-emission	Ton/MWh
Efficiency	% Fuel used per produced gigajoule
2. Transportation	
Installed capacity	MW
Transportation cost (only LdM)	€/GJ
Heat loss	GJ/m
3. Consumption	
Hourly demand	GJ
4 Pricing	
Fuel prices (Gas, CO_2, Electricity, Diesel, etc.)	€/GJ

Table 8. Market-specific input variables for Linny-R

Market-specific input variable	**Unit**
1. Wholesale specific input	
Network topology with production units	See figure 4
2. Single-buyer specific input	
Contract prices	€/GJ
Fictional prices to order	€
3. End-to-end specific input	
Contract prices	€/GJ
Fictional prices to order	€

The solver settings set a runtime of one year where the timesteps are in hours. This means that the timeframe is from 1 to 8760 hours. The optimisation is done in steps of 24 hours at the same time with a look ahead of 48 steps. I have chosen for the optimisation of 24 hours because it enables optimisation of one full day, which corresponds to the operations for the electricity and gas markets. I chose three days for the look-ahead function since prices are assumed to be known in a timeframe of three days. Besides, weather and prices forecast reasonably predict the trend for three days. Furthermore, start-up costs are considered for CHP's because their start-up cost is high. Finally, to restrict the runtime for each scenario, a limit of 60 seconds was set for the solver target search. After 60 seconds, the solver chooses a sub-optimal found value. I chose this because with these 60 seconds the market models already run for 6.5 hours.

5.3 Comparison and implementation of the three market mechanisms

The previous chapters described the similarities between the three market mechanisms. However, differences between the markets are necessary in order to compare them. Chapter 4 showed that the market mechanism differs in the way it dispatches and settles. This section further describes how the differences translate into the Linny-R graphical modelling language. First, the chosen market goals are described as market performance indicators. Next, it describes the differences per market mechanism. Note, however, that the market mechanisms implemented in the computational model are archetypical and other varieties are possible.

5.3.1 Market performance indicators to compare markets

The previous chapter 4.5 formulated the market objectives *(words in italic)*. This section discusses how they can be transformed into market performance indicators (<u>Underlined words)</u>.

- *Affordability* is quantified by the height of the <u>Consumer price</u>. Using Linny-R, it is possible to calculate consumer prices for heat based on the dispatch and fuel prices. How this Consumer price is calculated differs from one market mechanism to another and are explored in greater depth further on.
- Quantifying the *future-proof* objective is done by calculating the <u>Producer surplus</u>. This gives an idea of the business case of producing heat, and if large enough, it encourages future investments in heat production and transportation. Linny-R can calculate the hourly production costs per producing asset and compare these with the consumer price. When consumer price is deducted from the production costs, the producer surplus is what remains. Also, the producer surplus is calculated differently per market mechanism and is further explained in the next paragraphs.
- Finally, *Sustainability*, Linny-R can calculate the amount of <u>CO_2</u> produced per asset and therefore, also the total amount of CO_2 produced. This is a result of the sum of CO_2 produced per production unit.

5.3.2 The implementation of the end-to-end market mechanism

Contracts between producer and retailer characterise the end-to-end model. This market mechanism currently exists in the province of South Holland. This study does not model the negotiations of contracts themselves but uses the given prices to simulate the market for the dispatch of the contracts. This means that in this system, the dispatch does not take place according to what is most efficient, but according to the preference of contracts. The contracts consist of a heat price (Euro/GJ), fixed merit order (#) and the (maximum) heat to be supplied (MW). The producers who are engaged in the contracts can choose which production unit to dispatch, but they must meet the contracted production when asked. The fact that the merit order is fixed in the contracts means that the dispatch takes place based on the fixed merit order connected to the contracts. Figure 10 shows an example of such a merit order, with each colour showing a different contract party. When prices differ within a contracted actor, this is shown by different pricing blocks (red). The more expensive contracts must first be used before the cheaper contracts are executed. The fixed merit order probably increases the expected costs in the system.

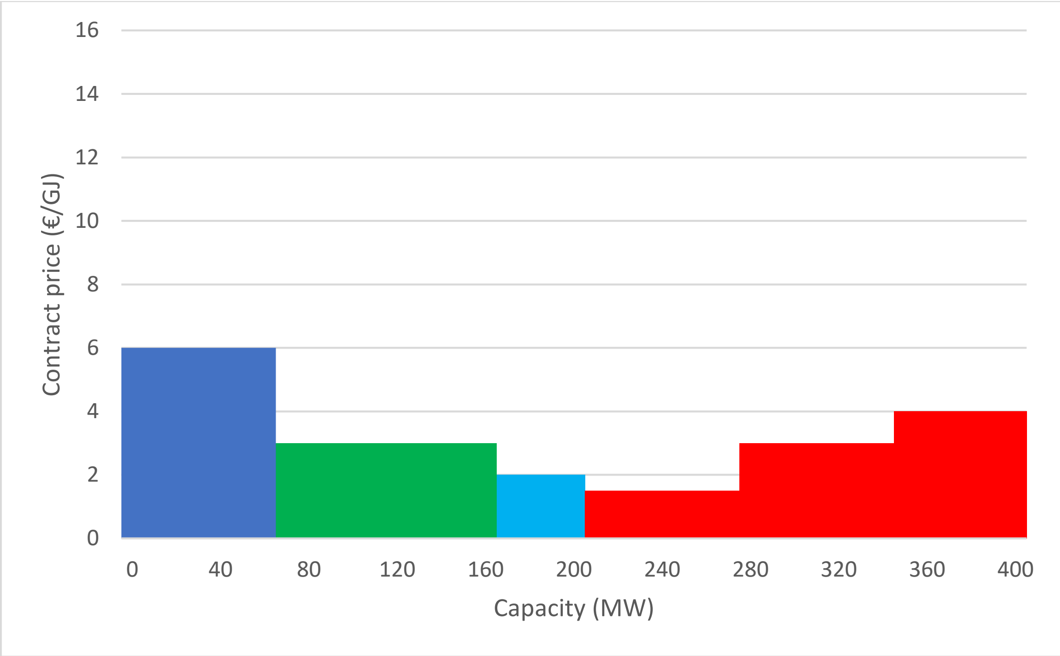

Figure 10. Example of dispatch of end-to-end market

By default, the goal of Linny-R is to minimise costs. This means that when entering the contract prices, the agreed order is not automatically applied by the program. Therefore, the products have fictitious cost arranging the merit order. For producer D, the fictitious price is chosen high enough to allow Linny-R to optimise on the production costs of its producing units. In this way, the most cost-efficient power plant for producer D is the first to be dispatched, which is also a prerequisite for ultimately calculating the producer surplus. Figure 11 represents a simplification of the end-to-end market mechanism in Linny-R.

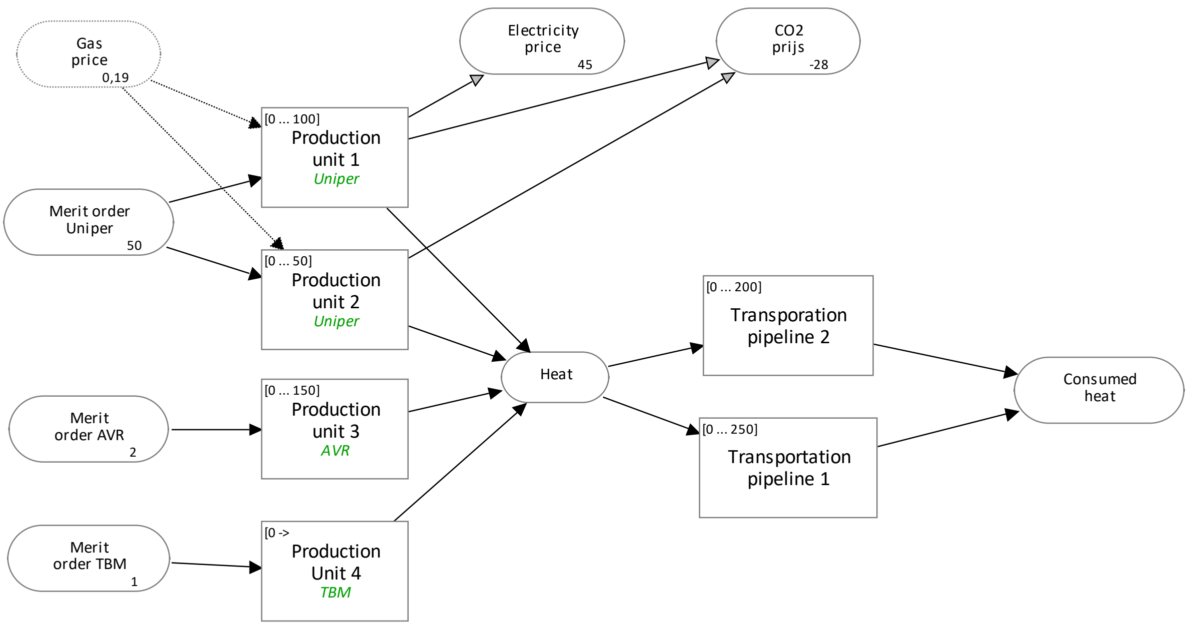

Figure 11. Simplification of the end-to-end market mechanism in Linny-R

For producer D, there are graduated contracts for heat purchased. When a certain amount of heat is consumed, the price of heat increases. These reserves and prices are based on the costs for base, variable and peak loads that producer D can deliver over the year. So, the most expensive quantity of heat corresponds to the expected deployment of the peak load production units. These contract levels are modelled in Linny-R as product reserve with a specific price as contracted. The system uses a reserve with a higher price when the stock is exhausted. This is implemented this way since the prices correspond to the expected use of each production unit type (base, variable & flexible). So, throughout the year, the prices do not matter if it is real-time or at the end if the expected number of hours per contract price is met. In real-time, the settlement proceeds at the end of the year as well, so this models the same behaviour. Figure 12 shows a simplified representation.

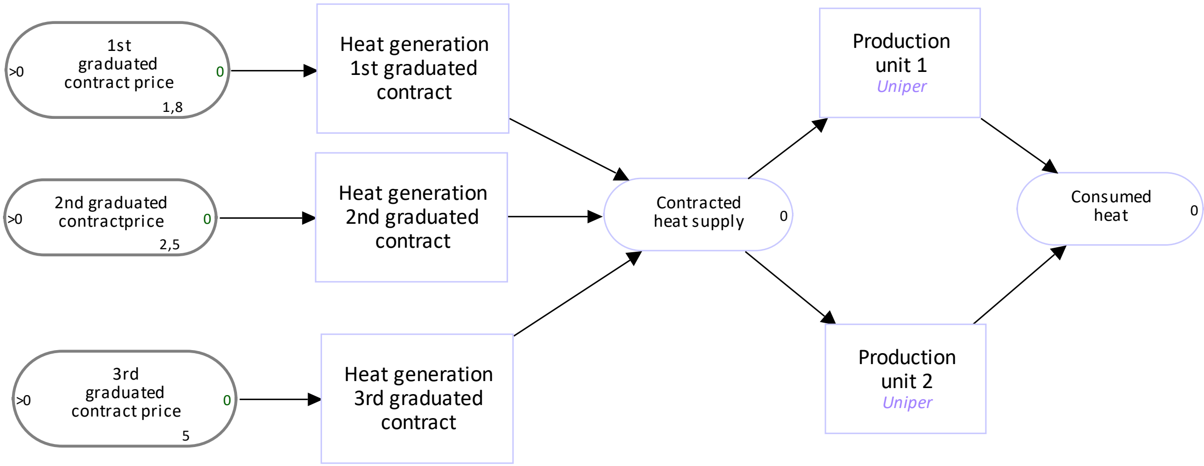

Figure 12. Simplification of the contract segments for producer D.

The calculations of the consumer price and the producer surplus are different for the contract market mechanisms and the wholesale market. Here is described how these market objectives are calculated for the end-to-end market.

The consumer price calculates the average of the contracts entered into per hour (eq. 1). The contracts differ in contracted capacity and therefore, both contract price and produced heat has to be taken into account. As the consumer price is fixed, the average over the year of all these hourly averages is taken. This ultimately covers all the contracted costs of the independent network operator.

Equation 1

$$Consumer\ Price = \frac{\sum_{n=1}^{8760}\left(\sum_{i=1\ \&\ j=1}(CoPr_{ij} * PL_i) * \frac{1}{\sum PL_i}\right)}{n_{total}} \quad \forall PL_i \in \mathbb{N} : PL_i > 0$$

The producer surplus is also calculated on an hourly basis. Every hour a producer earns the contracted price for his produced heat. However, he incurs production costs in the form of fuel costs for each gigajoule of heat produced. Therefore, for the producer surplus, these costs must be deducted from his income from the contract.

Equation 2

$$Producer\ surplus = \sum_{n=1}^{8760}\left(\sum_{i=1}((Cp_w - CoPr_{ij}) * PL_i)\right) \quad \forall PL_i \in \mathbb{N} : PL_i > 0$$

5.3.3 The implementation of the wholesale market mechanism

An independent market operator and market platform where the producing companies can offer their capacity at a specific price characterises this mechanism. Moreover, customers can offer their demand at a specific price. This research assumes that the bidding is done at marginal cost because turnover is generated above these costs. This means that the production cost of one gigajoule per production unit determines the merit order (Figure 13). The different colours represent different production plants. Due to changes in gas, electricity and CO_2 prices, this merit order can shift. The marginal producing unit determines the market-clearing price. It is possible in the heating system to produce against negative prices (black column), since CHP's produce both electricity and heat. When the electricity is profitable, the heat can be sold against negative values to break even. Another note, in comparison with the contract markets, the marginal prices fluctuate more than the contract prices do since the prices are fixed in those markets.

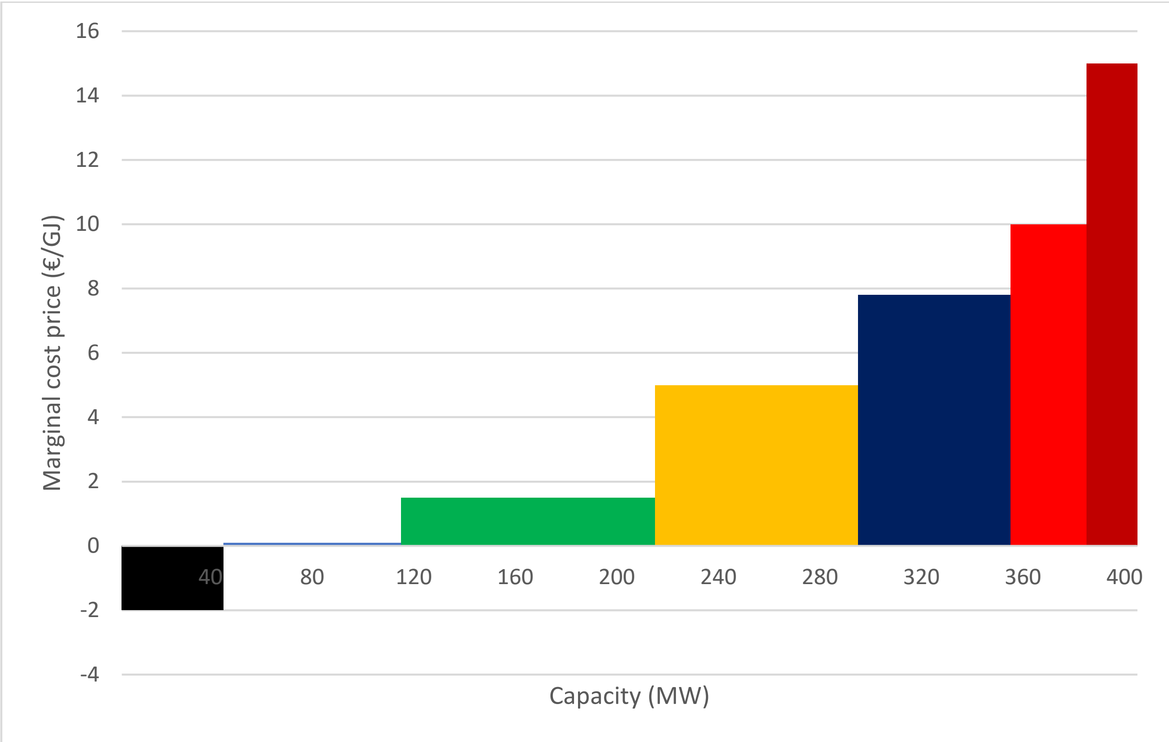

Figure 13. Example of dispatch wholesale market

The optimisation of this market mechanism is what Linny-R does. The program looks at the different cost of productions per production unit and the limitations in the transport network. It then searches for the 'cheapest' merit order and calculates the corresponding costs. Figure 14 represents a simplification of such a system.

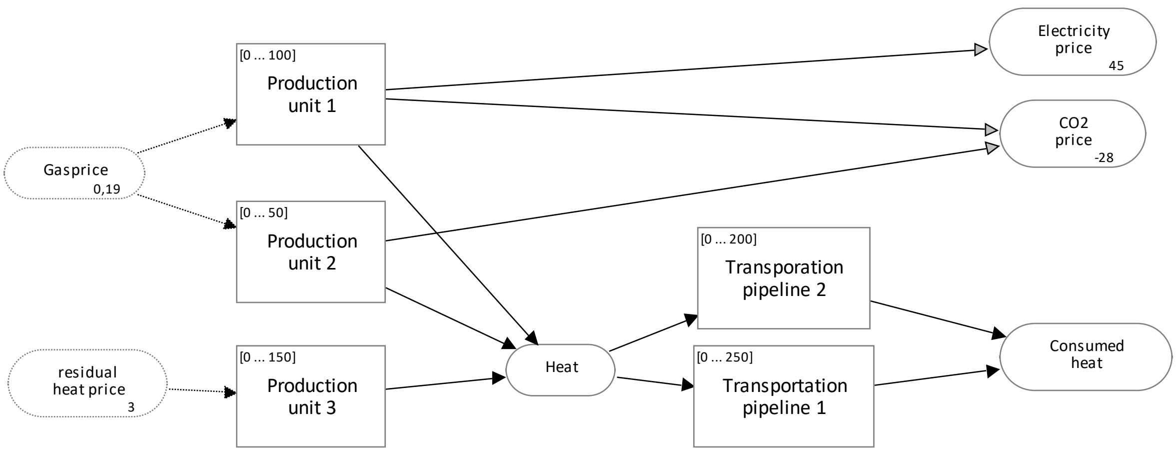

Figure 14. Simplification of the wholesale market mechanism in Linny-R

The bid of the marginal central dictates the market-clearing price. The market pool operator uses this price for the entire market. As a result, all consumed gigajoules sell at the same price. This means that Linny-R calculates the consumer price by finding the maximum production cost price of all producing production units. This is calculated for every hour, since, the market operator is independent, the consumers pay a fixed price over a year. This means that the consumer price can be averaged over the year. Equation 3 shows how consumer price is calculated.

Equation 3 $$Consumer\ Price = \frac{\sum_{n=1}^{8760}(Max\ (CoPr_i))}{n_{total}}\ \ \forall PL_i \in \mathbb{N} : PL_i > 0$$

The producer surplus can be calculated by looking at the hourly marginal central price and the hourly production costs per production unit. By adding this up, the total annual turnover in the heat market can be calculated (equation 4).

Equation 4 $$Producer\ surplus = \sum_{n=1}^{8760}((Cp_c - CoPr_{ij}) * CL_j)\ \ \forall CL_j \in \mathbb{N} : CL_j > 0$$

5.3.4 The implementation of the single-buyer market mechanism

A party with the sole right to trade in heat typifies the single-buyer market mechanism. This party enters into contracts with both producers and Purchasers. The contracts and their associated prices are classified based on their flexibility and peak load. Because the single-buyer has the sole right, he can use cheaper contracts in the load categories rather than more expensive ones. The single-buyer can use prices per hour and over the year because he is independent and has the exclusive right to act. Figure 15 shows a simplification of merit order. The colours show different contracts. Where in the colour tones represent the categories.

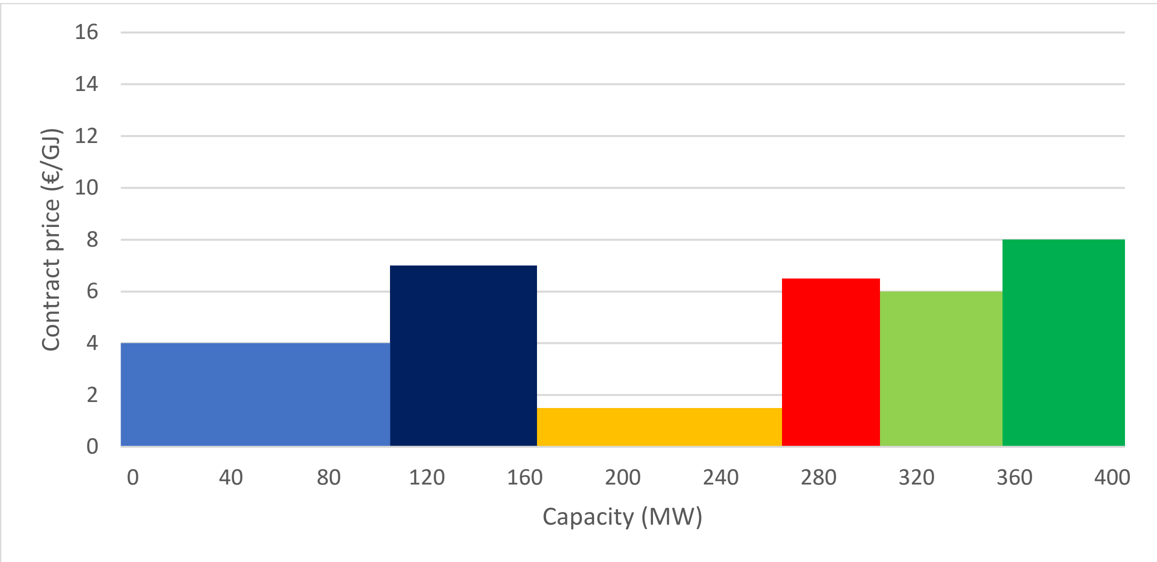

Figure 15. Example dispatch single-buyer market

The problem of optimising contract prices is similar to the end-to-end market. This model multiplies contract prices by 1000. This means that the first to be optimised is the contract prices. Within producer Ds contracts, the production units are optimised using the prices of electricity, gas and CO_2. These are in the order of dozens and therefore do not influence the merit order of the contracts. Figure 16 shows a simplification of the single-buyer market mechanism.

This model includes the levels of producer D his contracts. The three categories are linked to the corresponding production unit. The CHP plants have the cheapest contract, the Gas turbines the second graduated contract and the gas and oil burners the third graduated contract. The last contract level is used when the previous three levels are exhausted. The contract price is multiplied by 10,000 to use this as a last resort when heat demand is high on icy days. Figure 17 shows a simplification of the graduated construction of the single-buyer market mechanism.

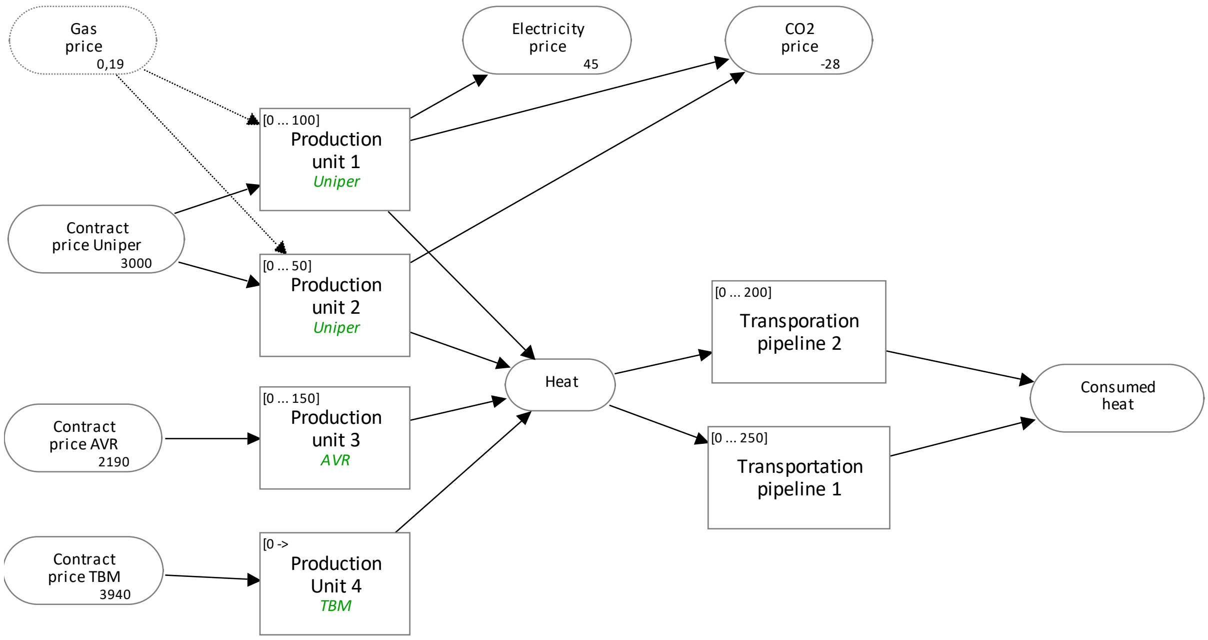

Figure 16. Simplification of the single-buyer market mechanism in Linny-R

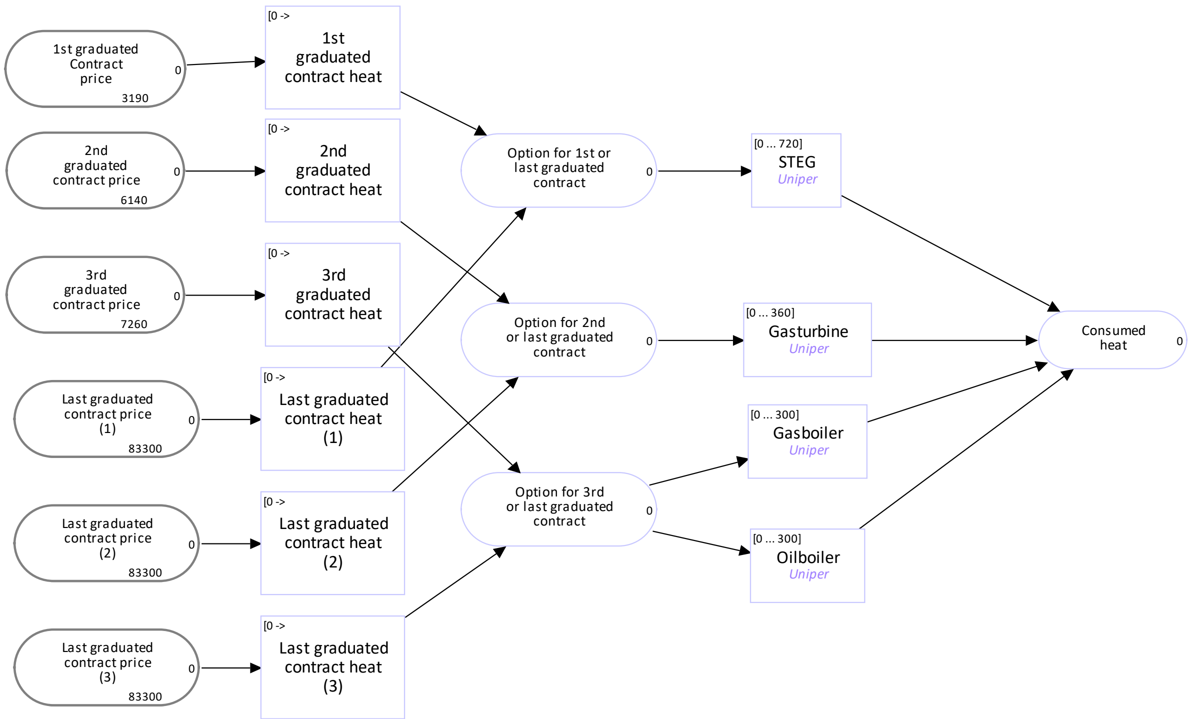

Figure 17. Simplification of the contracting levels in the single-buyer market mechanism

The consumer price of the single-buyer market mechanism arises because the independent heat trader spreads and averages the costs over the year. This is because the independent heat trader is not allowed to make a profit. This causes the settlement for both the end-to-end market mechanism and the single-buyer market to be equal (Equation 1 and 2).

6. Results

The results reflect the output of the 546 scenarios. For reasons of confidentiality, all values have been normalised. As do the result not show the real names of the contracted actors but they are depicted as producer A, B, C & D. First, the results discuss the model behaviour of the different market mechanisms. Next, the first results are outlined based on the 2018 base case. Then the markets are compared per market performance indicator in 2023, 2030 and 2040. These results are then integrated to give an overview of the most important findings. Finally, a risk analysis is described to determine whether there is a preference for investment decisions.

6.1 Model behaviour of market mechanisms in Linny-R

The models and the results of the models have been validated with experts within Eneco. This showed that the behaviour of the models and outcomes was in line with expectations of the current system and the potential markets. This section discusses for each model the behaviour based on hourly merit order and dispatch, yearly dispatch and consumer price and behaviour of graduated contracts. It provides more insight into the functioning of the models and the different market mechanisms.

6.1.1 Model behaviour of the end-to-end market

This subsection deals with the behaviour of the end-to-end market (E2E) in Linny-R. It assesses whether this is following the intended and expected behaviour. Figure 18 shows the merit order of the contract prices in the E2E market. This merit order does not change throughout the year and most probably does not change over the years due to fixed contract prices. The prices used for the merit order are not the actual prices of the contracts but are fictitious prices scaled to the agreed dispatch order in the contracts. This is because Linny-R optimises on prices and the correct fixed merit order would not be simulated. All columns in Figure 18 colour green, which means that for all three-time steps in Figure 19, the contracts deliver heat to the system.

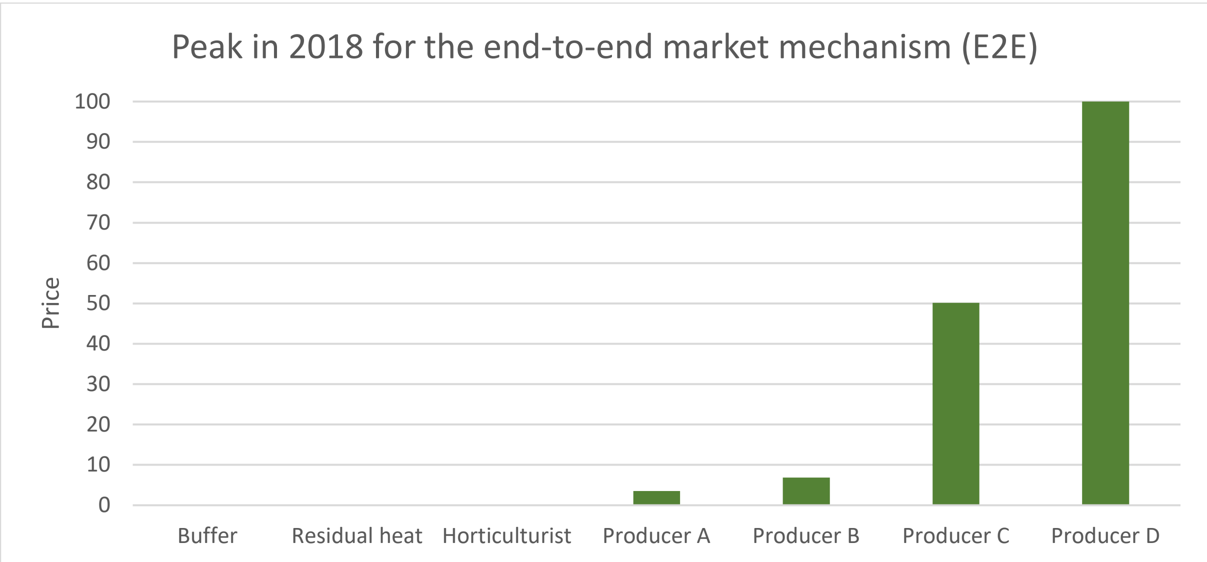

Figure 18. Merit order based on contract prices during peak demand in winter for E2E

Figure 19 shows three-time steps during the highest peak during winter with the corresponding production levels of the contracts. First, the diamond at the top of the columns gives the same value as the production levels. This means that production meets the heat demand in the E2E market. It also shows, as the merit order also predicts, that producer A, B & C produce at full load in all three-time steps. Producer D accommodates the higher peaks, as can be seen from the shift between time steps to 100 and back.

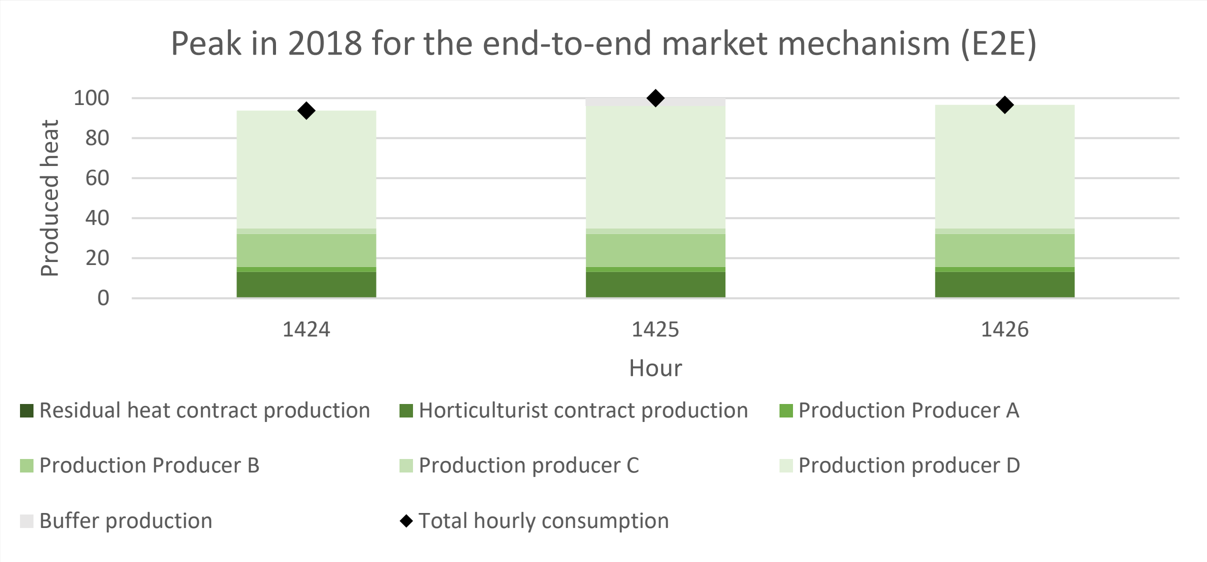

Figure 19. Production levels at three hours during peak demand in winter for E2E

Figure 20 is the same as figure 19, except producers C and D, who have a red colour. This is because they are too expensive during the three-time steps in the lowest production hours of summer and therefore do not produce.

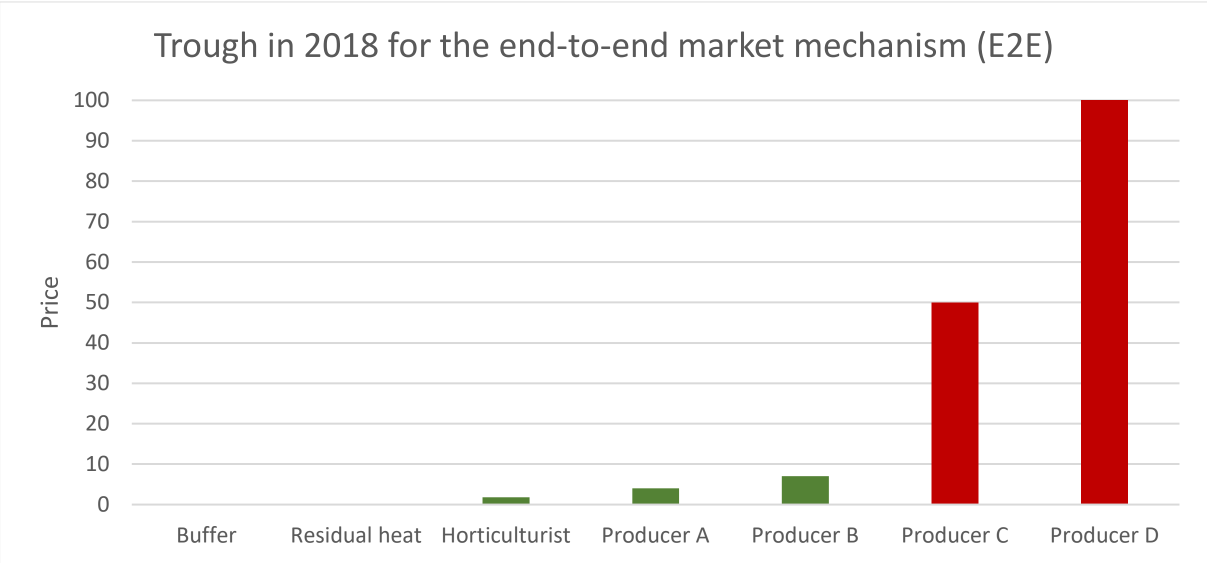

Figure 20. Merit order based on contract prices during low demand in summer for E2E

Figure 21 shows the production levels of the various contracts for the lowest heat demand. Again, the heat demand (diamond) is equal to the production (column). Notable is the large production of heat from buffers in the first two-time steps. This is probably because the heat is stored more cheaply at an earlier period. Furthermore, it shows that at the last stage, the horticulturists will start producing while they did not before. This is remarkable given that the horticulturists are at the front of the merit order and are expected to produce before producer A or B. However, the buffers are positioned at specific points in the system so that the buffers can provide heat to specific areas and some cannot. The horticulturists have a large buffer tank that meets the demand for heat. As a result of congestion in the network, the horticulturists are unable to produce as well. In this way, the buffers push the horticulturists in that area out of the market as they were at that time.

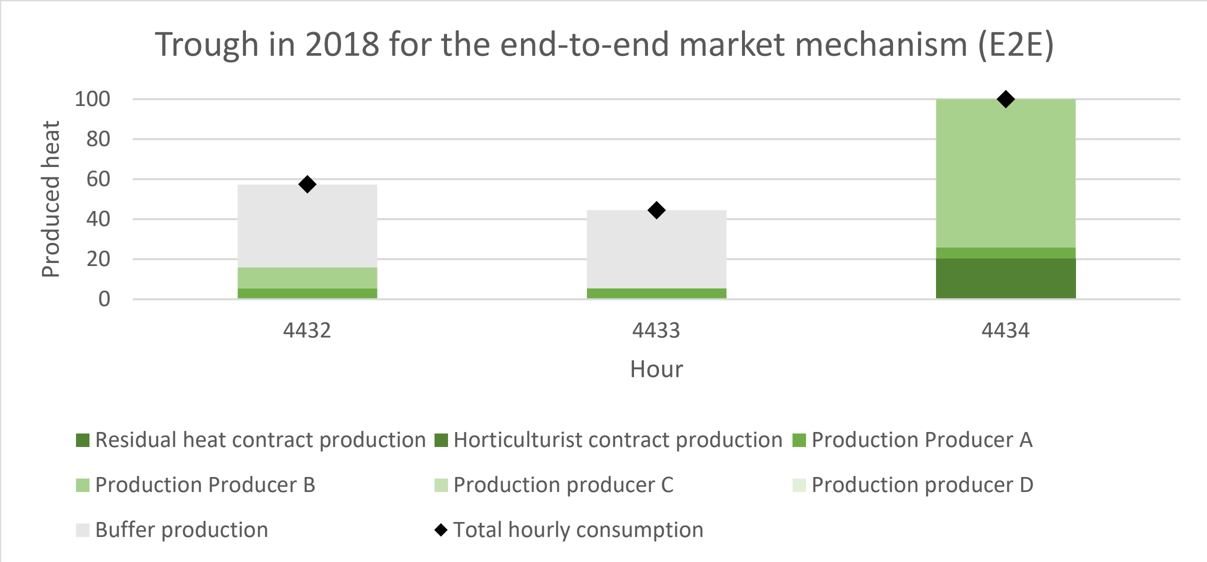

Figure 21. Production levels at three hours during low demand in summer for E2E

In addition to the hourly dispatch based on the contract prices, figure 22 shows a longer-term phenomenon. This is due to the graduated contracts of producer D, which contain a certain amount of heat at a specific price. This corresponds to the costs of base, flexible and peak load. Figure 22 shows the consumption of the cheapest graduated contract. This shows that producer D does not produce in the summer and that in 2018, the graduated contract is not fully consumed in the E2E market. If this had been the case, a shift in consumer price would have been visible in figure 23.

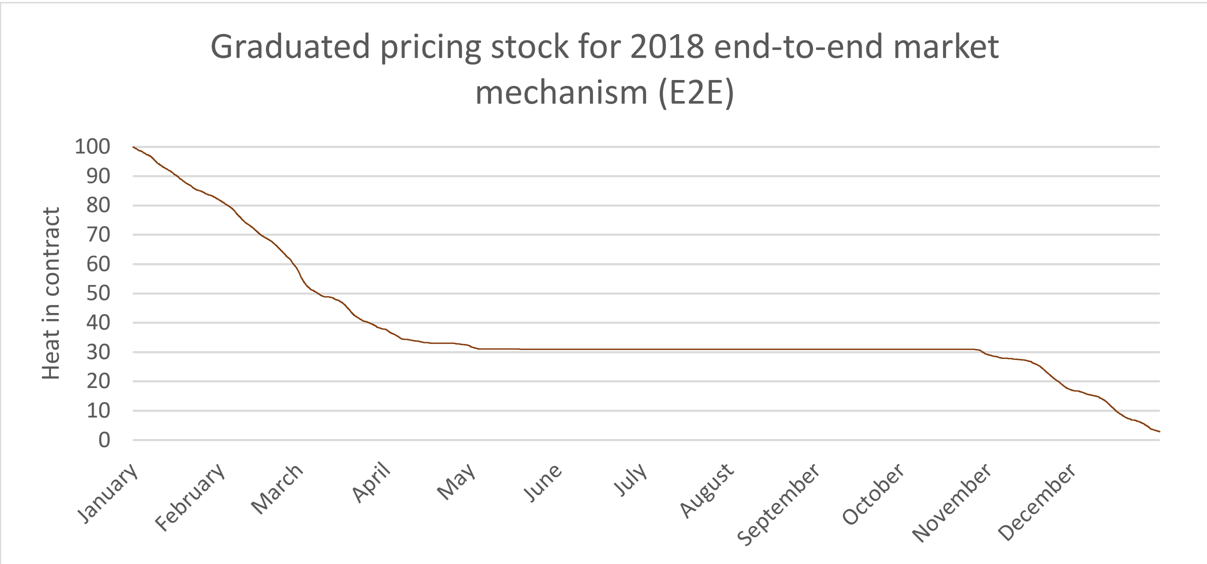

Figure 22. Heat in stock in end-to-end market mechanism first graduated contract producer D.

As expected, figure 23 does not show an average increase in the consumer price. However, it is noticeable that in the summer months (low production) the price does spike to high prices. The fact that producer A has the highest contract price but must be used first explains these price spikes. In the case of low demand, the highest price per GJ is paid. If there is a higher demand, the cheaper contracts will also be used, as a result of which the average price per GJ will be lower.

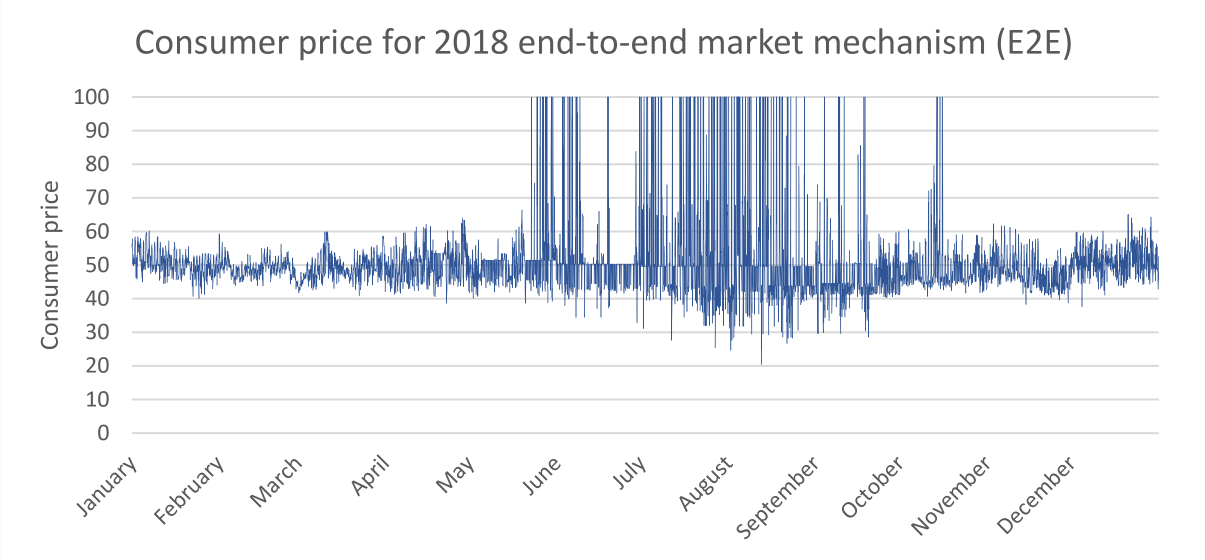

Figure 23. Consumer pricing for the end-to-end market mechanism

Figure 24 confirms that over the year, the merit order also behaves as modelled. Producer A and B generally deliver continuously at full load, and manufacturer D handles the flexible and peak loads by name. The gradations shown at producer A and B are due to contractual agreements that these producers produce less in the summer months than in the winter. However, as shown in figure 23, these moments occur frequently.

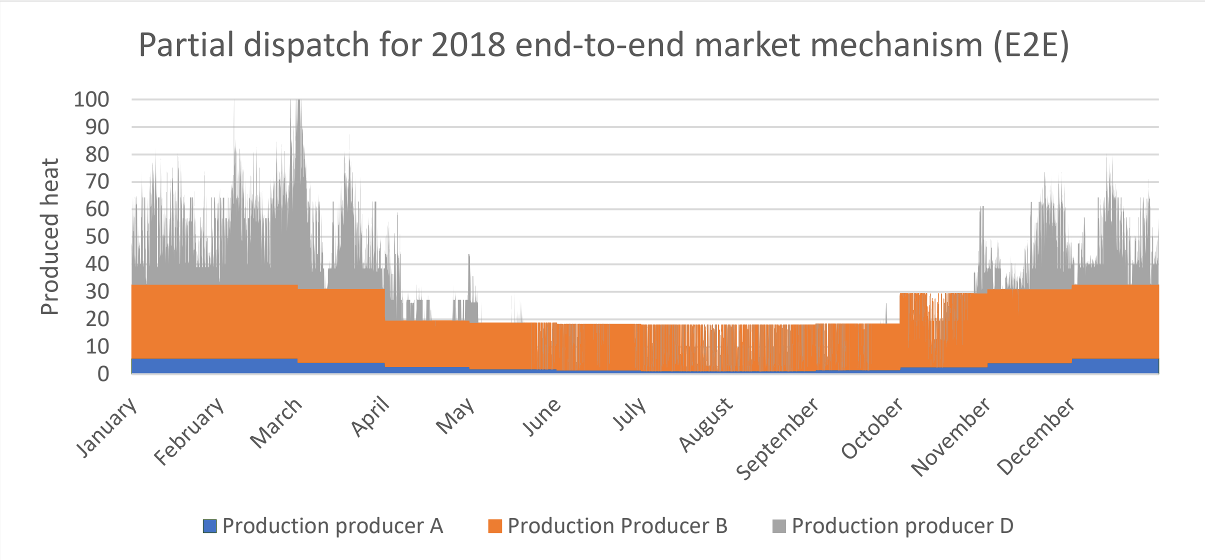

Figure 24. Partial dispatch in the end-to-end market mechanism

This subsection confirms that the end-to-end market mechanism is behaving as intended and expected. The main findings are:

- At all times, production matches demand.
- Due to congestion in the network, some contracts/buffers are not dispatched, even though they are at the front of the merit order.
- The pricing of heat in this market is unexpected since most expensive prices are at the beginning of the merit order.

6.1.2 Model behaviour of the wholesale market

This subsection deals with the behaviour of the wholesale market mechanism (WH) in Linny-R. It assesses whether this is following the intended and expected behaviour. Figure 25 shows the merit order of all marginal prices per producing unit. Green again shows which producing units are operating during the highest demand in the summer. The red columns show non-producing units. What is striking is that there are producing units that are off while they are cheaper than other units. This is due to congestion in the network and start-up costs of some units. The areas where a producing unit is located (Hor = Horticulture, ZH = divided over Zuid-Holland, RTM = Rotterdam and HAG = The Hague) indicate the areas where congestion takes place. These areas are not the only places of congestion; it is also possible that congestion will occur within Rotterdam due to, among other things, a distribution pipeline at the Boszoom.

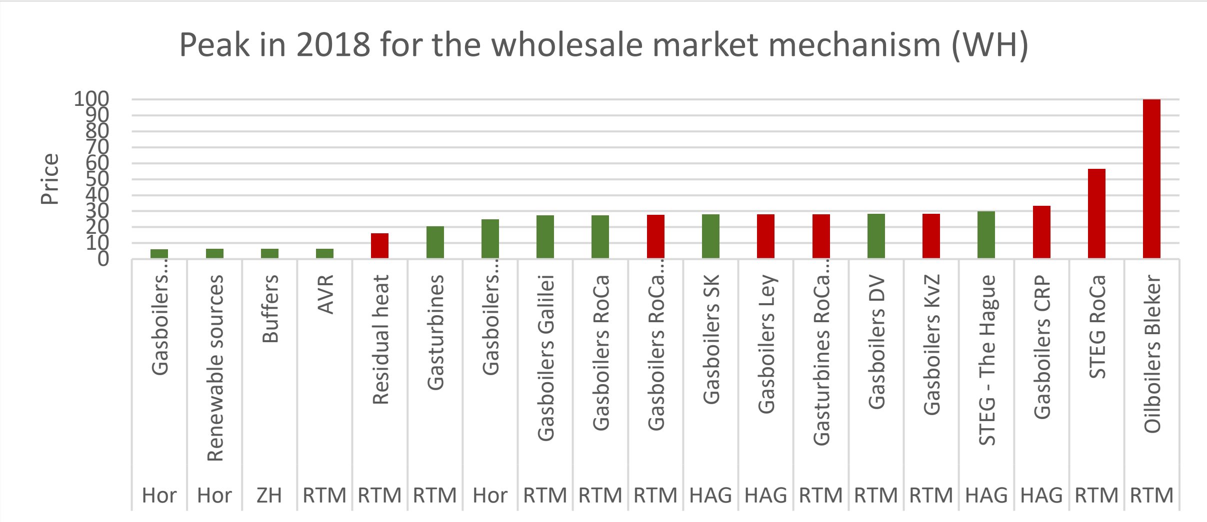

Figure 25. Merit order based on marginal prices during peak demand in winter for WH

Because of the marginal price per producing unit, it is not possible to see per contracting party whether the method of dispatch behaves correctly in the model. Therefore, in figure 26, the groups are ordered by the producing units. This is because these groups have relatively similar prices for heat production. First, the figure shows that production matches demand (diamond). Besides, it is noticeable that the cheaper units run at full load for these specific hours and that the gas boilers (relatively expensive) absorb the peak loads.

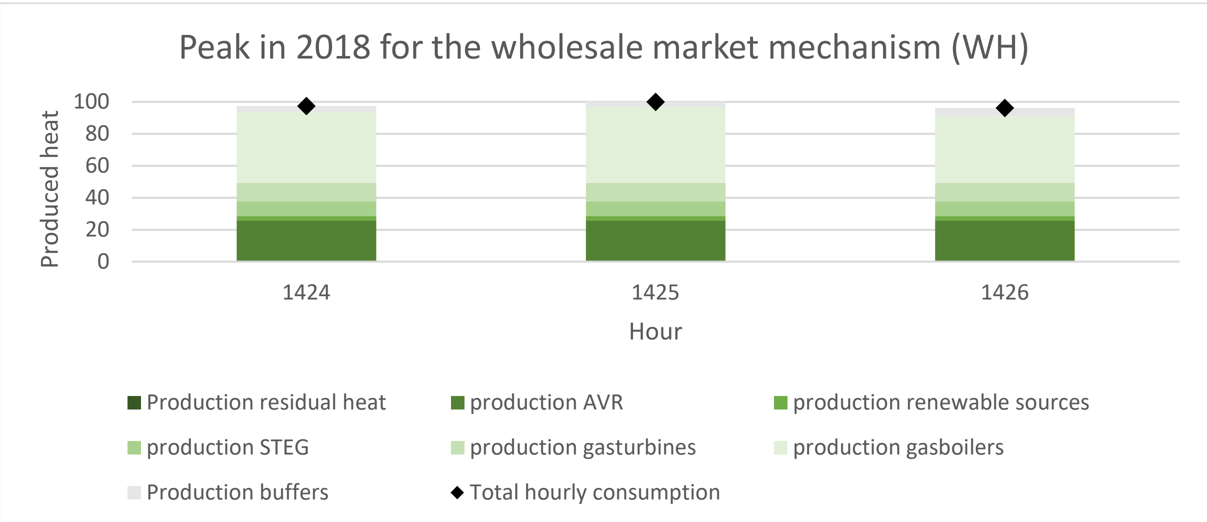

Figure 26. Production levels at three hours during peak demand in winter for WH

Figure 27 shows the merit order at marginal prices for the lowest heat demand in 2018. This figure shows that only AVR currently produces. This is in line with expectations because of the marginal price of waste incineration. If not incinerated waste piles up and this is undesirable. Besides, there is a change in merit order compared to figure 25. For example, the STEG from The Hague has become cheaper and has moved up in the merit order.

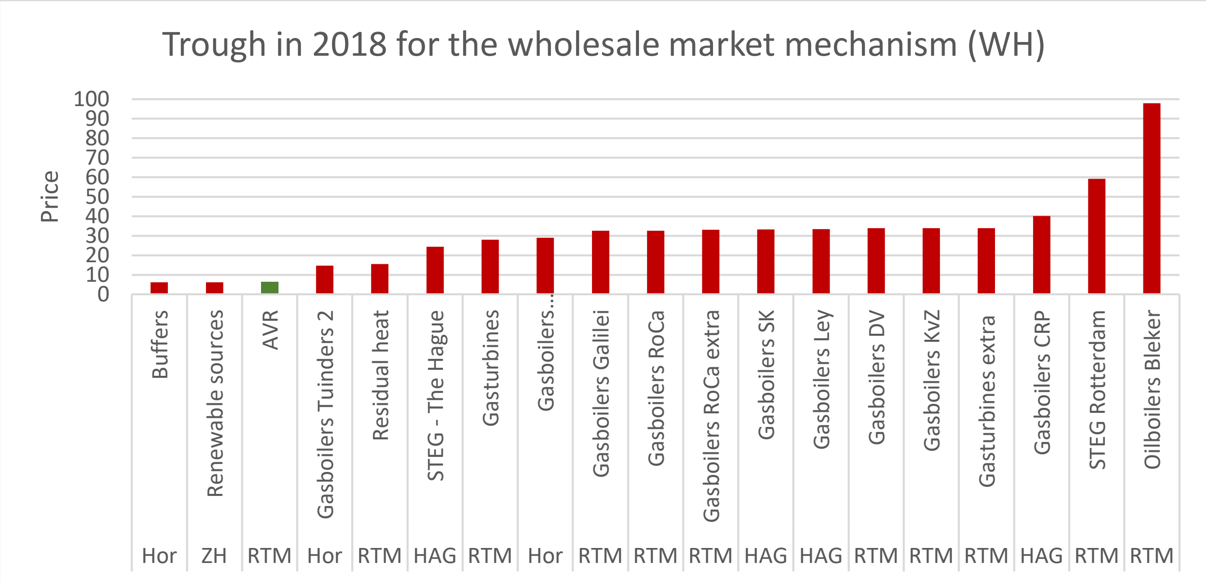

Figure 27. Merit order based on marginal prices during low demand in summer for WH

Figure 28 confirms that AVR only produces at the hours with the lowest heat demand in the year. Besides, the heat demand again matches the production. The buffers also produce during two of the three-time steps.

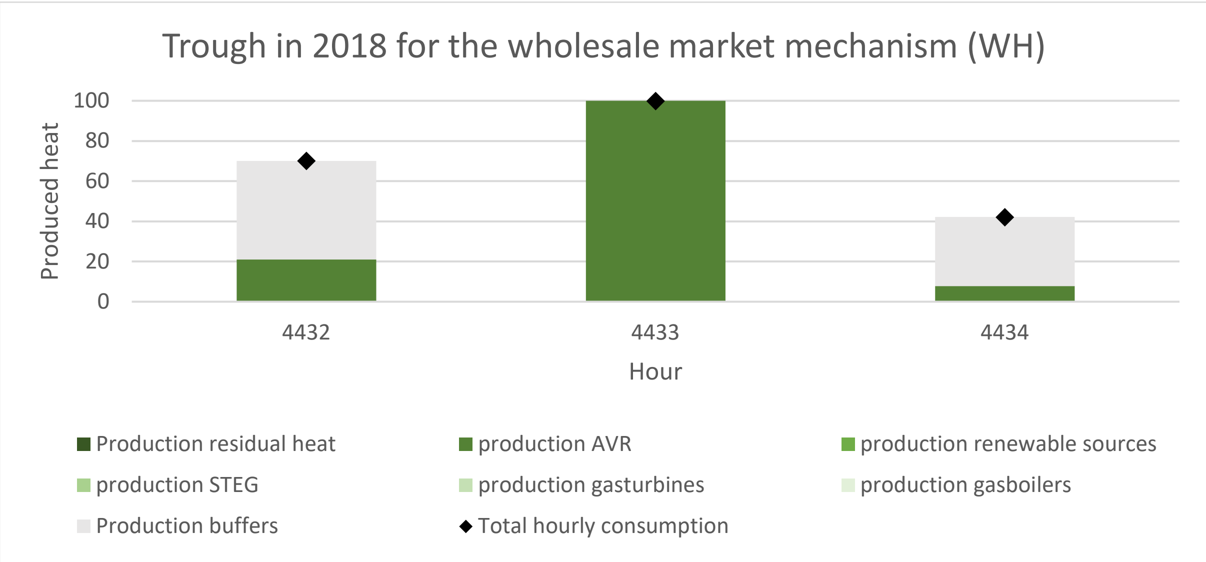

Figure 28. Production levels at three hours during low demand in summer for WH

Figure 29 shows the consumer price as expected in the implementation of the wholesale market (chapter 5.3.3). Also, it reflects the fact that prices can rise sharply in the winter months and that in the winter months, when there is relatively little demand, prices become zero for heat production.

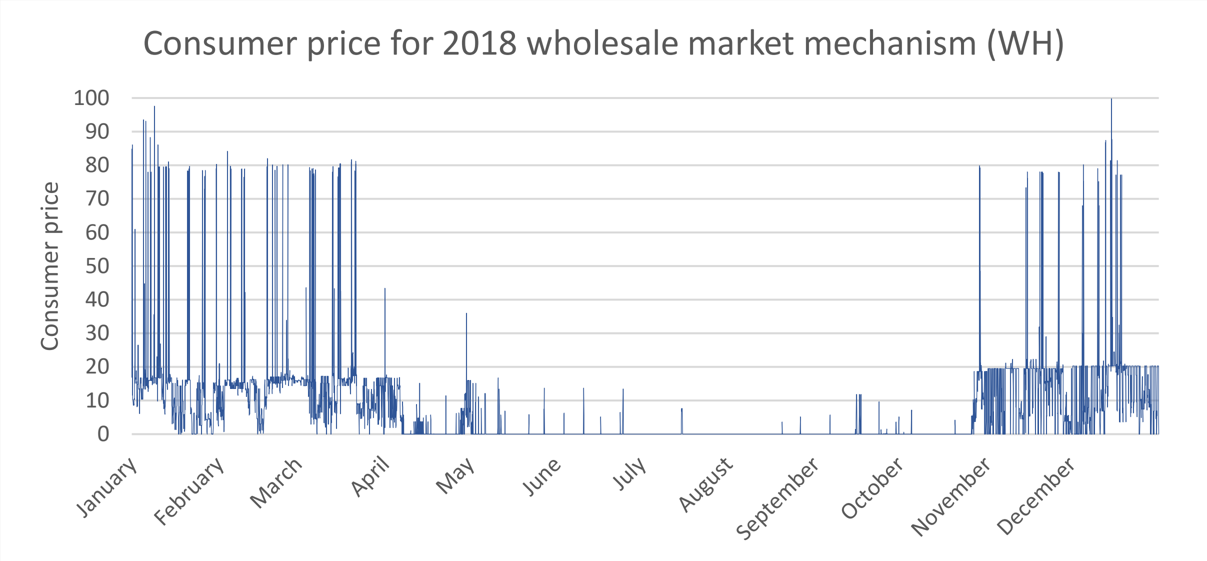

Figure 29. Consumer pricing for the wholesale Market mechanism

This subsection confirms that the wholesale market mechanism is behaving as intended and expected. The main findings are:

- At all times, heat demand is matched by production.
- Due to congestion in the network, some production units are not dispatched, even though they are at earlier positioned in the merit order.
- Prices can fluctuate significantly over the year, where the highest prices are anticipated in the winter, and lowest prices are anticipated in the summer.
- The merit order changes due to differences in fuel prices.

6.1.3 Model behaviour of the single-buyer market

This subsection deals with the behaviour of the Single-buyer market mechanism (SB) in Linny-R. It assesses whether this is following the intended and expected behaviour. Figure 30 shows the merit order of the dispatch of the various contracts. The SB, in contrast to the E2E, optimises its contract portfolio. Therefore, the various contracts show an ascending order of contract prices. However, these prices have been multiplied by 1000 to ensure that producer D can still optimise on its assets. It is striking that outside residual heat; all contracts are producing at the highest demand of the year.

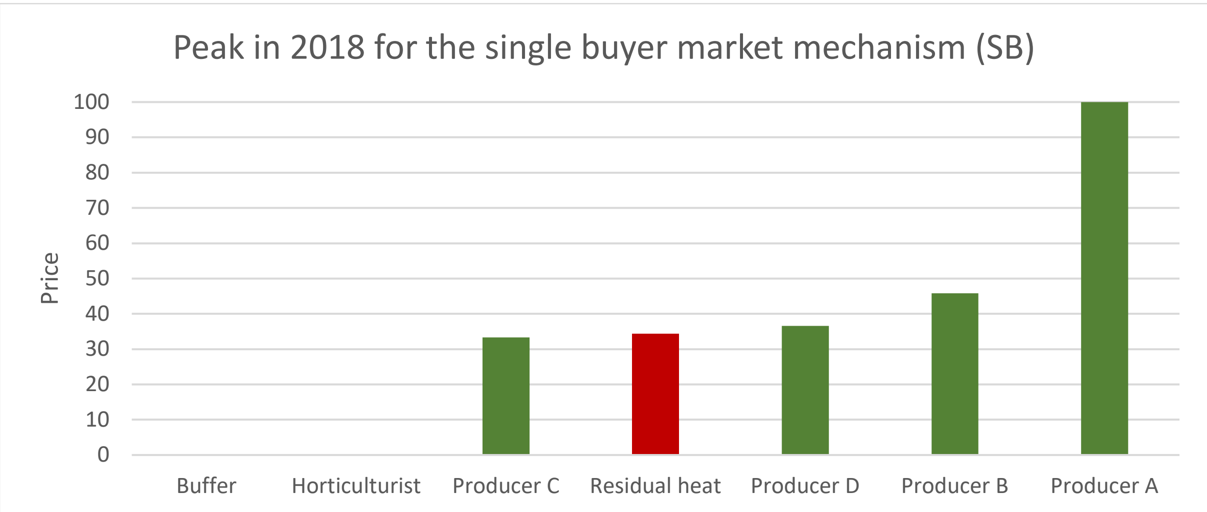

Figure 30. Merit order based on Contract prices during peak demand in winter for SB

Figure 31 shows the production per contract. First, demand (diamond) meets production. Second, Producer A, which has the highest contract price, is not called up even during the highest heat demand hours. The horticulturists, producer B and C are also called during these hours. For the horticulturists and C this is logical because they are more likely to be in the merit order. Producer D again primarily absorbs the peak loads because it has the most substantial amount of installed power. The fact that Producer B also runs continuously at full capacity can be explained by congestion in the Boszoom network, as a result of which not enough heat can be supplied to the city of Rotterdam.

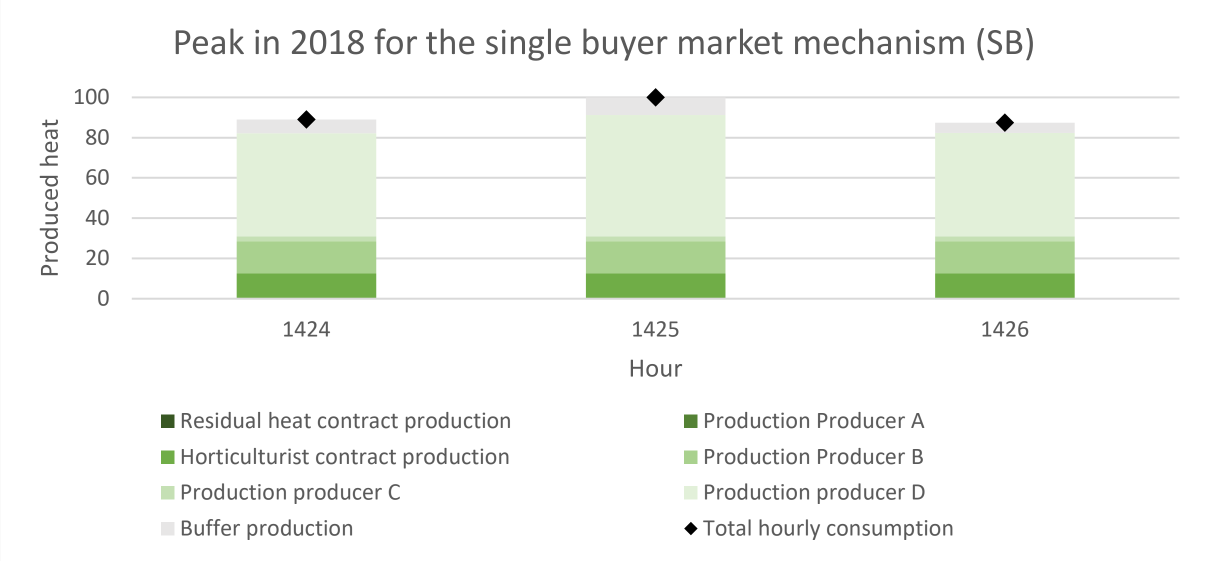

Figure 31. Production levels at three hours during peak demand in winter for SB

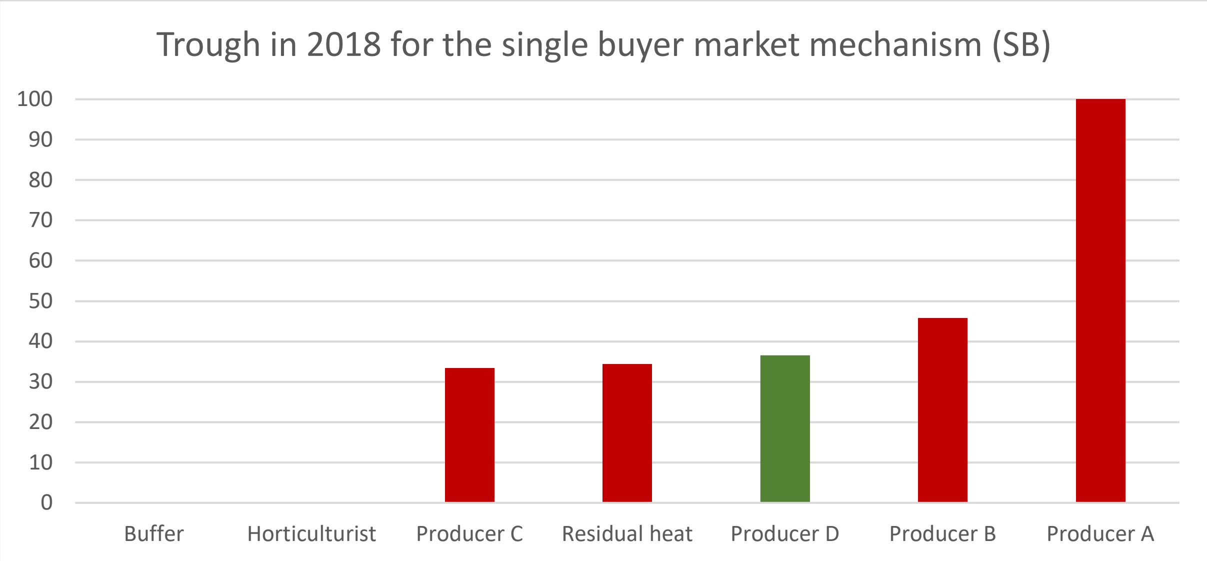

Figure 32. Merit order based on Contract prices during low demand in summer for SB

Figure 32 shows that during the lowest heat demand in 2018, horticulturist and producer D supply heat to the system (shown in green). Figure 33 confirms the production of these two producers. The horticulturist trades at the fixed gas prices and can, therefore, be cheaper at times than producer D's contract. Also, a large part of the demand is met by heat from buffers at that specific moment. Again, the demand meets the production as is supposed to be.

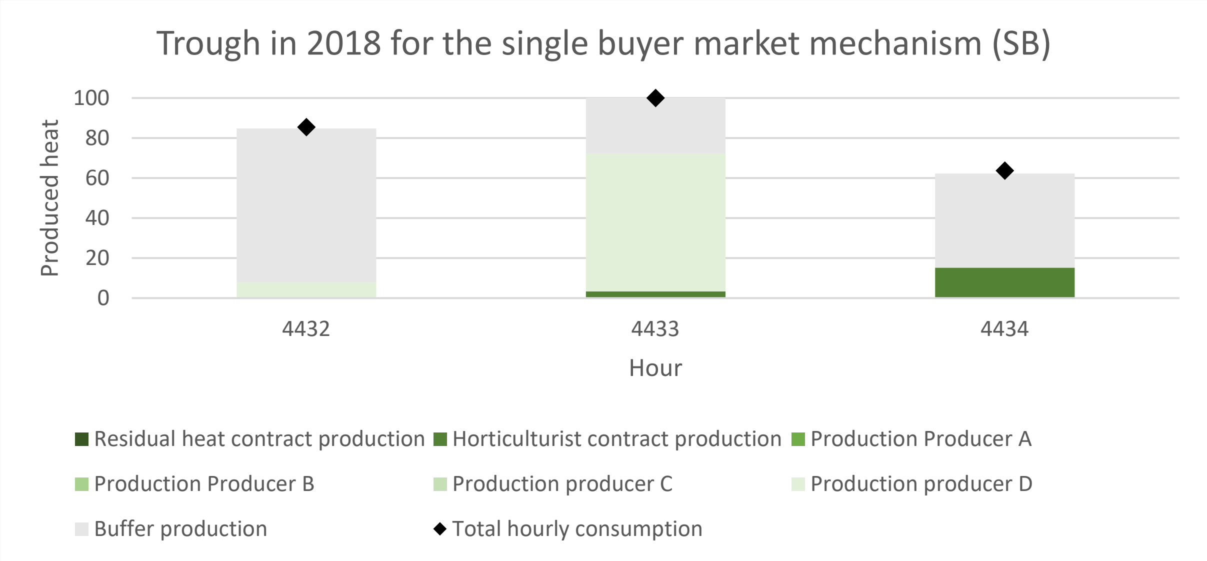

Figure 33. Production levels at three hours during low demand in summer for SB

The single-buyer market also contains the graduated contracts for producer D. These are modelled slightly different than at E2E because in the SB market they are optimised on contract prices. The dispatch method assigns these contracts to a different place in the merit order. These levels linked to different generation types. The cheapest graduated contract links to the CHP plants and the second most expensive to gas boilers. The most expensive one links to all plants in case more heat is needed. Figure 34 shows that the heat from these graduated contracts is consumed and runs out around December. Now, the most expensive graduated contract is used to supply heat to the system.

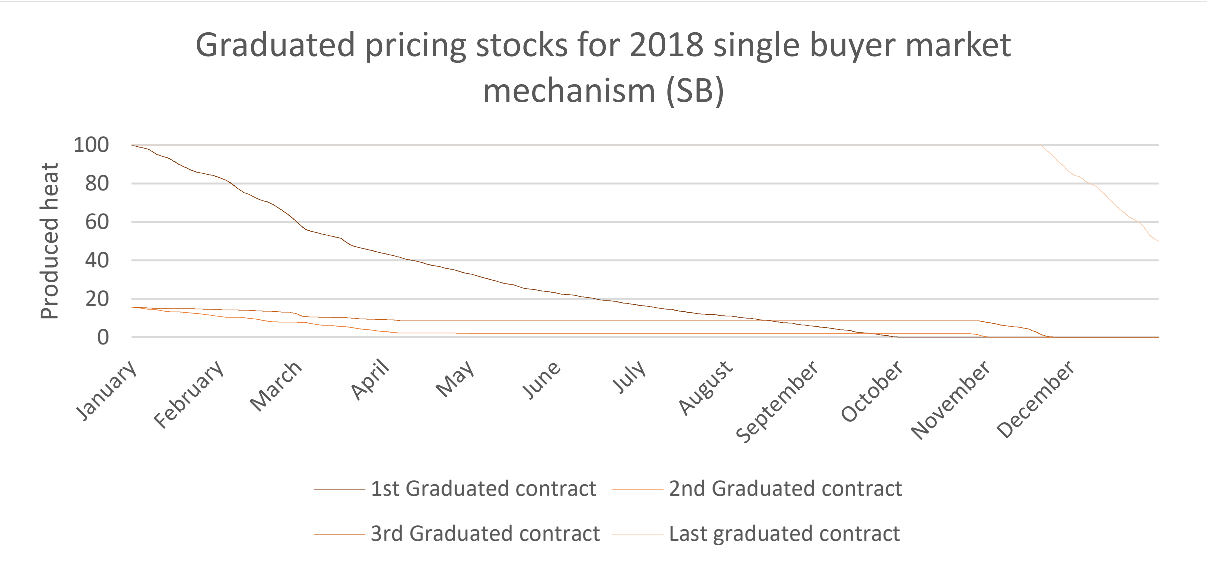

Figure 34. Heat in stock in single-buyer market mechanism first graduated contract producer D

The change in graduated contract level shows from half of November in figure 35. Producer A is at the end of the merit order but is still producing from mid-November. This is because it has become cheaper than the highest level of producer D. The fact that producer D still produces in this month is due to congestion and installed capacity of the other contracts in the network. Producer D has by far the most installed capacity and is most widely located over the province of South Holland.

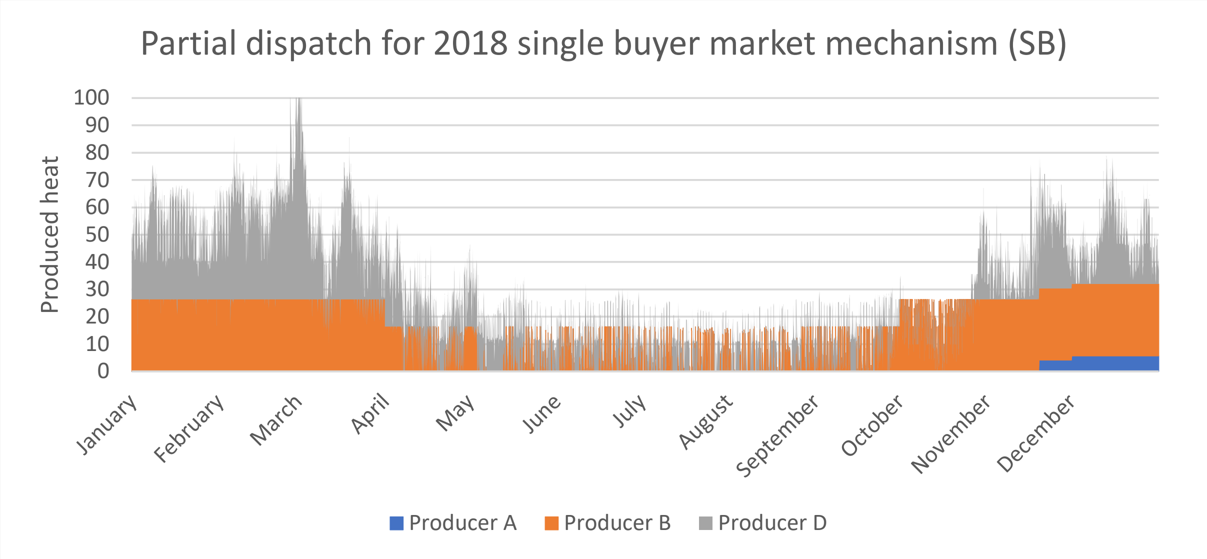

Figure 35. Part of the dispatch in the single-buyer market mechanism

Figure 36 also shows the change in the graduated contract in the graph. The light blue line clearly shows a changing trend with higher prices from mid-November onwards. Furthermore, prices can go to zero in the summer. This is because horticulturists can produce at zero euros in this market, depending on market prices. The extra heat is then filled up with the cheapest other contracts/options, such as the use of buffers.

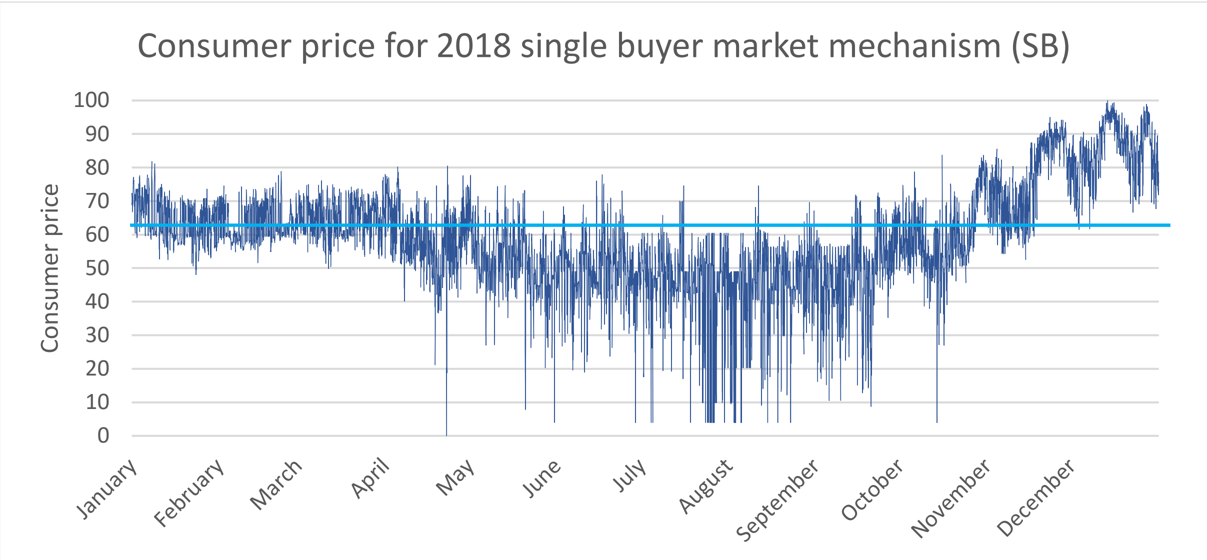

Figure 36. Consumer pricing for the single-buyer Market mechanism

This subsection confirms that the single-buyer market mechanism is behaving as intended and expected. The main findings are:

- At all times, heat demand is matched by production.
- Due to congestion in the network, some contracts are not fully dispatched, even though they are at earlier positioned in the merit order.
- Because producer D has a relatively low contract price, it places at the forefront of the merit order in the SB market. As a result, in 2018, the first three graduated contracts are fully used, and the price will rise sharply towards the end of the year.

6.1.4 Impact of capping solver time

The implementation (H5) of the market mechanism indicated that the time limit of the solver is capped at 1 minute in order to keep the simulation times relatively limited (6.5 hours). This subsection shows the impact of this cap. Each market compares, the simulation of the first 500-time steps, to a time cap of 1 minute with a time cap of 5 minutes. Table 9 shows the differences. This comparison is made on the real output and not by normalised scores. This means that the result is lower for a negative number and higher for a positive number.

Market performance indicator	**End-to-end market mechanism (E2E)**	**Single-buyer market mechanism (SB)**	**Wholesale market mechanism (WH)**
CO_2 - emission	0,99%	16,34%	4,66%
Consumer price	0,03%	-8,54%	-38,11%
Producer surplus	-6,99%	128,37%	-36,19%

Table 9. Comparison of the cap of the solver time limit (1 min vs 5 min)

Remarkable is the high value of difference for producers surplus of the single-buyer market. The way of solving and dispatch can explain this difference. The solver continuously iterates to find a better solution. In the single-buyer market, two intensive optimisations are in progress. The first is on the contract prices and the second is on the marginal costs of the assets within the contract of producer D. Because producer D has a fixed contract, but the costs can be lower than the contract price, producer D will make a loss. If the solver does not have enough time to solve the problem, he will provide sub-optimal solutions. These sub-optimal solutions can cause a substantial problem for the producer surplus. Because this producer surplus depends on the contract price minus the costs. With poorly optimised marginal costs, producer D will regularly produce while he cannot make a profit through his contracts. This means that when fully optimised, the producer's surplus can be 128 per cent higher than is currently obtained from this model.

In the wholesale market, there is a deviation of -33 per cent; this is also due to optimisation. However, there is a different orientation for the producer surplus because the dispatch at marginal costs can not result in a loss. Therefore, the values of the consumer price and producer surplus will be lower at the optimal point.

6.2 Comparison of the market mechanisms for the base case

This section presents the base case results of the three different market mechanisms for 2018. Before this section discusses the base case and full results, the following section explains how these results should be interpreted. First, the colours always are linked to the same market performance indicator (CO_2-emission = blue, Consumer price = red, Producer surplus = green) throughout this chapter. Furthermore, the results have been normalised in such a way that a low score is negative desired value, and a high score is a positive desired value.

In the base case, the actual market prices and the consumption of heat are known. The base case uses these inputs and different market models to calculate the impact on market performance indicators. Figure 37 shows the results of the different market mechanisms. Besides, the error bars show the impact of Leiding door het Midden on the base cases. What becomes apparent in figure 37 is the following:

- The E2E market performs best on CO_2-emissions and worst on consumer prices.
- The single-buyer market is underperforming on CO_2-emissions and producers' surplus, which is even negative.
- The wholesale market performs best on Consumer price and producer surplus and average on CO_2-emissions.
- The implementation of ‘Leiding door het Midden” has different effects per market model.

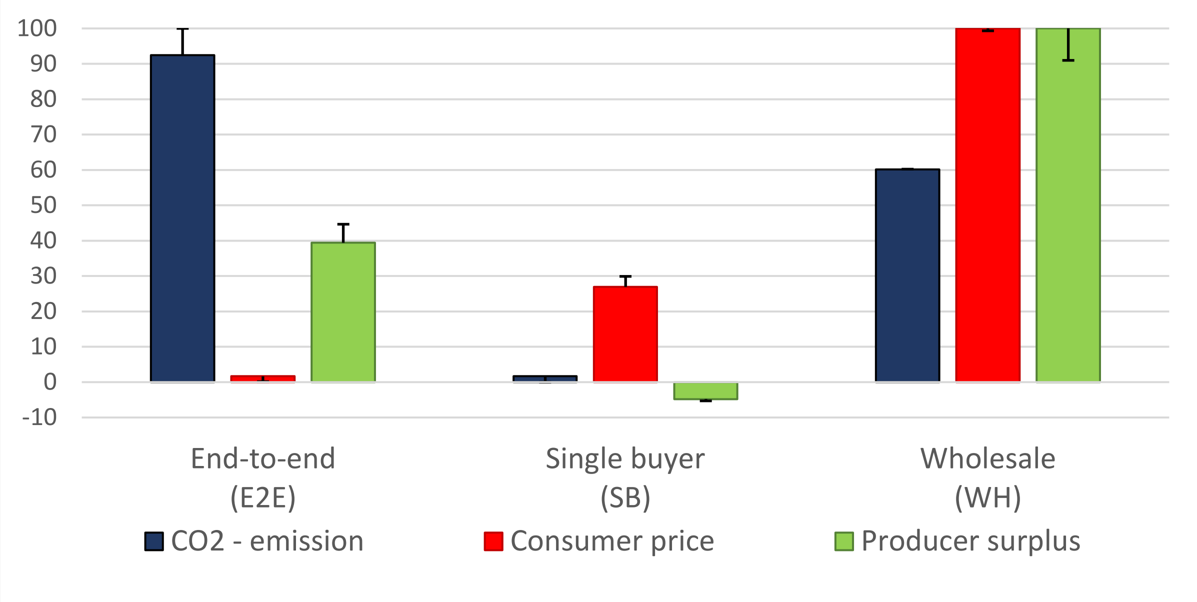

Figure 37. Comparison of the market performances for the base case (error bars depict models with “Leiding door het Midden”)

The merit order causes different scores on CO_2-emissions. Producer D has more gas-fired production units in his portfolio in comparison to the other producers and therefore emits much more CO_2. Producer D has the lowest contract price. This puts him in front of the merit order in the SB market. That is why the SB scores poorly on CO_2-emissions. The end-to-end market, on the other hand, is efficient in terms of CO_2-emissions due to the contractually established merit order.

The impact on consumer price is as expected, caused by the method of dispatch. The WH market optimises purely on the marginal costs of producing units, which is the most efficient. The SB market optimises contract costs which are lower than the established merit order of contracts in the E2E market where the most expensive contract must be used first.

The dispatch and settlement explain the differences in producer surplus. The wholesale market dispatches on the marginal cost, where the marginal unit sets the price; this means "no" loss can be made on production costs in this market. In the end-to-end and single-buyer market, a loss is possible because the order of the dispatch of the contract can cause a heat producer to be called while the production costs are higher than its contract costs. With the optimisation on contracts, this can cause a negative value for producer surplus of the single-buyer market.

The effects of “Leiding door het Midden” are different for each market. For the E2E market, it increases the performance on CO_2-emission and producer surplus. The SB sees an increase in consumer price and decreases for producer surplus. While the WH only sees a decrease in producer surplus. The effects of “Leiding door het midden” and “Vondelingenplaat” are further discussed in the results per year.

Overall, the results do not show the best practice market mechanism. However, the results of the base case scenarios show that the single-buyer market is the worst performer on two of the three market performance indicators. Moreover, it appears that the wholesale market functions quite efficiently.

6.3 The markets compared for 2023

In 2023, the 'Leiding door het Midden' and the "Vondelingenplaat" are planned for commissioning. This is the first year in which there is an expected difference in the results caused using these two assets. First, a snapshot is taken of the differences between the three different market mechanisms (end-to-end = E2E, wholesale = WH & single-buyer = SB) for the market performance indicators (M.P.I.'s) based on the low consumption and reference price scenario. Then the market mechanisms are compared on the market performance indicators.

6.3.1 Snapshot of the impact of investment decisions in 2023

Figure 38 shows the snapshot of 2023, which displays the configuration of the 'Leiding door het Midden', and 'Vondelingenplaat' in the form of off/on. The top row shows the market mechanism, and the colours on the left give the respective market performance indicators. In grey, the investment decisions are depicted by configurations (Top = Vondelingenplaat, left side = Leiding door het midden). The results are interpreted based on trends that emerge from the colour schemes. Trends that have already been observed and named are not repeated in later figures unless the trend remains strong. These colour patterns within the figure turn from red to green based on a normal distribution. This distribution is created by taking the lowest and highest value per market performance indicator and calculating the standard deviation over the three market mechanisms. This allows a comparison of the different market mechanism on M.P.I's. For the Snapshot, the normalisation compares the values within one market performance indicator over the three different market mechanisms and need to be read horizontally. For the full market performance indicator results this is done differently and explained in 6.3.2.

		E2E		SB		WH	
	Consumption low & Reference price scenario	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On
MO 1: CO_2-emission	"Leiding door het Midden" off	68	79	2	0	38	38
	"Leiding door het Midden" on	73	100	0	0	40	40
MO 2: Consumer Price	"Leiding door het Midden" off	5	100	50	57	58	59
	"Leiding door het Midden" on	0	93	31	53	82	72
MO 3: Producer surplus	"Leiding door het Midden" off	35	38	-14	-14	100	100
	"Leiding door het Midden" on	38	45	6	-12	89	92

Figure 38. 2023 snapshot of the impact of the market mechanisms and investment decisions

Several trends stand out in Figure 38:

- E2E performs best on CO_2-emissions.
- SB seems to be underperforming for both E2E and WH market mechanisms.
- WH performs best on producer surplus

- The construction of the Vondelingenplaat strongly influences the consumer price for the E2E market.
- The construction of “Leiding door het Midden” positively affects the consumer price of the wholesale market mechanism and the producers' surplus negatively.
- The construction of Leiding door het midden and Vondelingenplaat significantly improved the CO_2-emissions for the E2E market.
- The construction of the Leiding door het Midden without Vondelingenplaat seems to lower the consumer price and improve the producer surplus for the SB market.

The strong effect of the connection of the Vondelingenplaat on the consumer price in the end-to-end market mechanism can be explained by the fact that this is a new source with a new contract. The contract is cheaper compared to the other contracts, and this source is called upon first. The residual heat is supplied as baseload and therefore has priority over the other contracts.
For the wholesale market, the price decrease is caused by 'Leiding door het Midden’, which means that despite the transport costs over Leiding door het Midden of 0.5 euro per GJ, the costs of production are cheaper in the sub-regional network of Rotterdam, and it is, therefore, valuable to transport the heat produced to The Hague.

After the implementation of the market mechanism, the consumer price can be moderated. Implementation of an additional heat source at a relatively cheaper than average price can reduce the consumer price in the end-to-end market mechanism. Connecting multiple regions utilising transport pipelines in a wholesale market mechanism ensures an improvement of the price. The first application, however, is easier to achieve than the second. Connecting an additional source is relatively cheaper than expanding the heat infrastructure.

6.3.2 The impact of market mechanisms on CO_2-emission in 2023

For the full comparison of market mechanisms on market performance indicators, the colour patterns again colour from red to green using a normal distribution. However, this distribution is created by taking the lowest and highest value per market mechanism and calculating the standard deviation. This means that the trends can be compared between one market mechanism and the other. The specific values within the cells of the full M.P.I’s results cannot be compared with those of the snapshot.

Figure 39 shows the CO_2-emissions for the three market mechanisms for all scenarios in 2023. Apart from the confirmation of the observations from the snapshot, the following trends stand out:

- The implementation of both ‘Leiding door het midden” and “Vondelingenplaat” have a strong influence on the CO_2-emission of the E2E market.
- The WH and the SB show similar trends indicating a degree of dependence on price scenarios.
- The SB contains cells where CO_2-emissions deteriorate sharply for one specific scenario, while this breaks with the trend for that scenario.

		CO₂-emission in 2023																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	17	13	8	45	43	39	70	62	59	70	63	60	37	71	0	74	94	93
	Circles	12	7	3	38	34	32	7	6	0	6	5	1	1	1	1	0	56	0
	Paces	19	14	11	42	39	36	61	56	50	60	57	51	32	33	41	41	31	38
	Tides	22	18	15	45	42	40	80	76	74	80	75	75	49	75	79	84	38	77
	Reference	8	3	0	36	33	30	10	9	3	12	10	6	18	17	15	13	24	15
"Leiding door het Midden" on	Low	28	24	20	99	98	96	79	75	70	80	76	72	30	2	69	30	92	93
	Circles	25	21	17	95	93	92	20	19	13	20	18	11	68	66	1	1	64	65
	Paces	31	27	23	99	97	96	76	69	61	74	68	62	41	41	13	43	31	38
	Tides	34	30	26	100	99	97	100	91	90	100	91	89	49	79	77	22	100	77
	Reference	20	16	13	92	91	89	22	18	13	24	19	12	13	19	15	12	19	15

Figure 39. CO_2-emission in 2023 for all market mechanisms

The fact that both optimise on prices from which the dispatch follows. For the WH this is at marginal cost, and for the SB it is at contract prices, and within the contract of producer D, it is also on marginal costs of the producing units. By dispatching the contracts/producing units differently, more polluting producing units can be used sooner/later than others.

The cells that suddenly seem to change in the SB market mechanism can be explained by congestion in the network. With higher demand, more congestion occurs, so that ultimately more CO_2 polluting producing units must be transported by producer D. The WH is not tied to the use of contracts and can, therefore, optimise on each producing unit. Because the CO_2 price is included in the pricing, the market optimises on CO_2-emissions as well.

This means that these two markets (WH and SB) are a lot more uncertain when the CO_2 price drops sharply and CO_2 is produced relatively at low cost. The E2E market is through fixed merit order efficient in CO_2-emissions and robust for market changes. This means that a relatively low CO_2-emission is guaranteed in the contracts of this market.

6.3.3 The impact of market mechanisms on consumer price in 2023

Figure 40 shows the impact of the three market mechanisms in 2023 on the consumer price. Several aspects are again notable:

- The Vondelingenplaat has a strong influence on the consumer price of the E2E market.
- The fact that both the WH and SB are dependent on the price scenarios.

A new trend stands out as well:

- The consumer price in the E2E market is sensitive to one scenario, namely paces.

		Consumer price in 2023																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	47	47	46	94	94	93	95	95	93	96	96	93	98	92	84	92	89	88
	Circles	39	39	38	91	91	90	59	53	53	60	54	52	70	66	64	70	69	64
	Paces	6	6	5	62	62	61	6	1	1	6	0	0	27	10	0	8	10	6
	Tides	32	32	31	86	85	84	59	58	53	60	58	52	73	65	64	65	73	64
	Reference	55	55	54	100	99	99	52	47	46	52	49	44	96	94	91	100	99	91
"Leiding door het Midden" on	Low	44	44	45	89	88	88	98	100	98	98	99	97	94	89	84	94	83	81
	Circles	36	36	36	88	86	85	74	70	66	75	71	70	60	59	69	73	60	57
	Paces	0	0	0	58	57	57	16	14	14	18	16	11	6	5	20	6	7	4
	Tides	29	29	30	81	80	79	68	66	61	67	66	63	69	59	59	75	55	59
	Reference	52	52	53	97	96	95	59	53	53	56	54	53	87	81	82	98	81	82

Figure 40. Consumer price in 2023 for all market mechanisms

The Vondelingenplaat has a significant impact on the E2E market because a relatively large amount of heat is offered at a lower price. Besides, the Vondelingenplaat is contracted at the beginning of the merit order because the amount of waste heat produced cannot easily be adjusted without discharging it. This means that the Vondelingenplaat pushes up the more expensive contract of producer A. This means that in the winter months the most expensive contract can no longer be produced, which has a strong effect on the price.

The WH and SB are again dependent on the consumer price. For the WH, this follows logically, but for the SB, it is less evident because it uses contracts that should offer more certainty. However, the contracts are indexed to the gas price, which may cause differences in this model. Because the SB optimises on contracts, the dispatch can be different, resulting in a different consumer price.

That the paces scenario is terrible for all markets is because this is a scenario where fuel prices rise sharply, and energy becomes expensive. However, it is expected that this would have little impact on the E2E market mechanism due to a contract structure where prices are relatively fixed. The phenomena are explained by heat from the horticulturists, which was cheap compared to the contracts. Moreover, these were, therefore, the first to be used. Because the agreement is that horticulturists always produce for themselves, but they are included in the total consumer price, in this case, the consumer price rises because of them.

These observations, in turn, indicate that the E2E market is the most robust at uncertain market prices. When market prices rise, the contract market endures problems as well, but to a much lesser extent than the other two markets. Furthermore, the construction of the Vondelingenplaat can significantly improve the consumer price in the E2E market while the other markets experience hardly any influence by investments in new production or transport assets.

6.3.4 The impact of market mechanisms on producer surplus in 2023

Figure 41 shows the impact of investment decisions and market mechanisms on the producers' surplus. Several trends stand out here:

- Once again, the combination of Vondelingenplaat and Leiding door het midden has a positive impact on the E2E market mechanism.
- The WH again follows a pattern that shows that it depends on the price scenarios.
- The difference, however, is that the SB and the WH no longer follow the same pattern for producer surplus as they did for the consumer price.
- The producer surplus for the SB market experiences a positive impact for the two investment decisions.

		Producer surplus in 2023																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	75	73	72	69	70	71	38	38	40	38	38	40	-13	-7	-14	1	79	76
	Circles	84	84	80	87	88	89	67	70	71	67	70	72	-21	-28	-32	-20	4	-31
	Paces	69	68	62	79	80	81	95	99	99	95	99	100	-55	0	83	47	1	40
	Tides	75	73	71	73	74	75	58	60	63	58	59	64	-19	-9	-3	15	-32	-11
	Reference	71	72	66	76	77	78	71	75	77	71	73	77	-37	-38	52	-37	-48	53
"Leiding door het Midden" on	Low	81	81	79	97	98	100	38	37	38	38	37	39	-10	-9	-6	-10	61	85
	Circles	88	89	87	91	92	93	57	60	64	57	60	61	100	97	-33	-23	75	95
	Paces	71	69	66	86	86	86	86	88	89	84	87	90	56	56	-67	62	10	50
	Tides	81	81	79	94	96	97	53	55	58	53	54	57	-13	5	-3	-31	93	-2
	Reference	77	76	73	89	91	91	63	68	69	65	67	69	15	97	63	-33	96	63

Figure 41. Producer surplus in 2023 for all market mechanisms

An interesting result from this figure is the difference in outcomes for the WH and SB markets. The determination of dispatch explains this phenomenon. The SB settles its contract prices by reducing its production costs. It is possible to include negative scores. The producers' surplus will, therefore, differ in positive or even negative, depending on the time of deployment and market prices. In the WH market, negative returns are not possible. The price is set by the most expensive producing unit, and the rest also receives this price for its produced heat. As a result, the producer surplus in terms of the score is inversely proportional to the consumer price score.

That there is an effect on the producer surplus by one of the investment possibilities can be explained by the fact that a more extensive infrastructure or cheaper large quantity of production can both influence the SB market. In the end, it is a hybrid market containing features of both E2E and WH market mechanisms. However, in this case, the high values of 100 give a wrong impression because the market still performs poorly on producer surplus compared to the others.

This means that the producer surplus and therefore, the investment climate is better for the WH market. However, it appears that after implementation of this market, no influence can be exercised by making certain investments. This means that it is strongly dependent on the environmental factors while investments can moderate the effects in the system for two of the markets.

6.4 The markets compared for 2030

6.4.1 Snapshot of the impact of market mechanisms and investment decisions in 2030

The snapshot of 2030 (Figure 42) is almost entirely equal to that of 2023. Two notes can be added to the comparison.

- The identified trends have become more pronounced.
- The influence of investment decisions on the SB market is no longer visible in the snapshot.

		E2E		SB		WH	
	Consumption low & Reference price scenario	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On
MO 1: CO_2-emission	"Leiding door het Midden" off	78	93	2	1	37	37
	"Leiding door het Midden" on	79	100	2	0	40	41
MO 2: Consumer Price	"Leiding door het Midden" off	0	99	25	25	49	50
	"Leiding door het Midden" on	0	100	26	25	80	77
MO 3: Producer surplus	"Leiding door het Midden" off	35	31	-28	-28	100	100
	"Leiding door het Midden" on	34	38	-29	-32	90	91

Figure 42. 2030 snapshot of the impact of the market mechanisms and investment decisions

6.4.2 The impact of market mechanisms on CO_2-emission in 2030

CO_2-emissions in 2030 (Figure 43) in the first respect show different trends compared to 2023:

- Consumption affects the emissions noticeably for all three market mechanisms
- The most substantial impact of consumption growth on CO_2-emission is visible in the E2E market.

		CO_2-emission in 2030																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	60	32	15	84	63	50	60	40	29	60	39	30	57	38	32	59	43	0
	Circles	48	17	0	72	49	36	24	9	0	24	10	0	25	9	4	25	9	4
	Paces	56	25	8	80	58	45	39	22	14	39	23	14	26	12	6	26	6	0
	Tides	72	44	28	91	71	60	93	76	65	93	76	65	100	54	45	100	63	56
	Reference	53	23	6	78	57	44	43	26	17	43	25	17	38	21	12	38	21	12
"Leiding door het Midden" on	Low	61	32	17	94	79	71	67	47	36	67	47	36	60	36	33	57	75	31
	Circles	50	19	3	83	67	58	26	11	2	25	11	2	25	9	4	25	10	4
	Paces	57	27	10	92	76	67	42	25	16	42	25	16	23	6	6	24	13	0
	Tides	72	44	29	100	86	77	100	81	71	100	81	71	100	52	45	75	64	79
	Reference	55	25	8	89	74	65	47	28	19	47	28	19	38	19	12	36	19	12

Figure 43. CO_2-emission in 2030 for all market mechanisms

The influence of consumption growth for CO_2-emissions can be explained by the following: Producer D is at the end of the merit order, which means that all 'clean' producing units are used first. This means that any additional gigajoule of heat required will be produced by a polluting gas-fired unit.

The findings in Figure 43 imply the effects on the heating system. The E2E market appears to be highly dependent on consumption growth based on CO_2-emissions and is therefore uncertain for the future in this area. However, this growth can be corrected by adding a relatively clean production unit to the system. The impact of consumption growth on the other two markets is much less. However, it is not possible to reduce this impact by implementing an extra unit.

6.4.3 The impact of market mechanisms on consumer price in 2030

The impact of the market mechanism on the consumer price in 2030 (figure 44) varies considerably.

- The E2E is influenced by consumption, but this is poorly visible due to the large impact of the Vondelingenplaat.
- The consumer price in the WH market is influenced by the price scenarios.
- The consumer price in the SB market is influenced by both consumption and price scenarios.

		Consumer price in 2030																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	36	33	30	90	83	80	92	90	89	91	91	89	92	82	76	94	86	32
	Circles	47	41	36	99	90	86	70	61	56	70	59	56	100	85	75	100	85	75
	Paces	20	15	11	74	66	62	44	34	23	44	34	24	55	42	38	56	40	32
	Tides	9	4	0	68	59	55	17	5	0	16	5	0	17	8	0	18	9	5
	Reference	38	33	29	89	81	77	68	61	56	68	61	57	85	73	64	85	74	64
"Leiding door het Midden" on	Low	36	33	31	90	84	82	100	97	97	100	98	97	93	82	75	92	96	73
	Circles	47	41	36	100	91	88	75	68	62	77	69	61	99	85	75	100	85	75
	Paces	20	15	11	75	67	64	50	39	30	49	39	30	54	40	38	54	43	32
	Tides	9	4	0	69	60	56	41	28	21	40	28	21	18	8	0	17	10	8
	Reference	38	33	29	90	82	79	77	69	64	76	69	64	86	73	64	86	73	64

Figure 44. Consumer price in 2030 for all market mechanisms

By 2030, the expected difference in consumer price between the different markets becomes evident. This is because the market must put a certain amount of heat into the system before any difference can be observed between the markets. The uncertainty in consumption growth in 2030 becomes large enough to demonstrate a difference in the performance of the market mechanism.

6.4.4 The impact of market mechanisms on producer surplus in 2030

Figure 45 shows compelling confirmations and findings for the producer surplus in 2030:

- The trends for E2E is the opposite of the WH market mechanism.
- The producer surplus for the SB market is mainly determined by the growth in consumption.

		Producer surplus in 2030																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	79	71	63	61	67	68	31	34	35	31	33	35	-8	-40	-45	-1	-27	-76
	Circles	55	36	20	52	53	50	58	69	75	58	70	75	-17	-50	-56	-17	-50	-55
	Paces	45	16	-4	48	46	40	76	89	100	76	89	99	-16	-55	-63	-16	-67	-76
	Tides	42	8	-16	43	34	24	74	86	91	74	86	91	22	-90	-100	22	-69	-87
	Reference	59	38	23	53	52	48	51	61	67	51	61	66	-21	-56	-64	-21	-56	-64
"Leiding door het Midden" on	Low	78	71	62	73	82	84	29	32	33	29	31	32	-4	-42	-46	-8	30	-44
	Circles	53	33	19	61	63	60	53	64	70	52	63	72	-16	-50	-56	-16	-49	-56
	Paces	43	14	-5	57	57	51	70	83	93	70	84	93	-29	-68	-63	-27	-48	-76
	Tides	42	8	-16	60	59	53	68	79	85	68	79	85	22	-97	-101	-38	-70	-35
	Reference	56	36	21	64	67	64	46	56	62	47	56	62	-22	-58	-64	-24	-58	-64

Figure 45. Producer surplus in 2030 for all market mechanisms

The reverse trends between E2E and WH explain the same trend as the difference in 2023 between WH and SB. This has to do with making a loss when a contract is called when it cannot run profitably. For the E2E market, this only becomes clear later because the most expensive contract is used first. As a result, the average contract price is higher than in the SB market.

The SB market, on the other hand, shows a difference this time mainly for the producers surplus based on the growth in consumption. This is because producer A is the cheapest contract with the most producing assets. While it is precisely these assets that can become expensive as a result of market prices. The more heat is required, the more often it happens that these assets produce above the contract price, as a result of which the producers' surplus is significantly reduced.

This means that the wholesale market mechanism remains the best market to generate a healthy investment climate. In the other two markets, there is a high risk that not enough producers surplus is generated. In the E2E market, investing in the Vondelingenplaat moderates this effect.

6.5 The markets compared for 2040

6.5.1 Snapshot of the impact of investment decisions in 2040

The snapshot of 2040 gives a similar but even more pronounced picture as portrayed in 2023 and 2030 (figure 46). However, it shows a new trend:

- The Vondelingenplaat affects all M.P.I's for the E2E market in 2040. This has a positive effect on CO_2-emissions and consumer prices and a negative effect on producer surplus.

		E2E		SB		WH	
	Consumption low & Reference price scenario	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On	Vondelingenplaat Off	Vondelingenplaat On
MO 1: CO_2-emission	"Leiding door het Midden" off	75	95	1	0	33	33
	"Leiding door het Midden" on	72	100	1	0	45	45
MO 2: Consumer Price	"Leiding door het Midden" off	0	98	20	20	35	34
	"Leiding door het Midden" on	0	100	20	20	84	84
MO 3: Producer surplus	"Leiding door het Midden" off	51	28	38	36	100	100
	"Leiding door het Midden" on	50	32	37	36	84	85

Figure 46. 2040 snapshot of the impact of the market mechanisms and investment decisions

This is because a substantial change (higher score equals lower consumer price) in consumer price results more often when a cheap contract is called upon while it is unprofitable. This is due to the large amount of relatively cheap heat that the Vondelingenplaat can supply. Next to, the fixed merit order which characterises the E2E market.

This means that problems may arise in the future when cheap contracts with a large quantity of heat are placed at the front of the merit order. Although this is advantageous for the consumer price, it creates problems for a healthy investment climate. Therefore, the established merit order in this market must be considered, and when adding new producing units, an assessment must be made of the influence on the system.

6.5.2 The impact of market mechanisms on CO_2-emission in 2040

The influence of investment decisions and market mechanisms on CO_2-emissions (Figure 47) do not differ much in 2040 compared to 2030. However, two things come to the fore:

- The WH and SB markets do show different scores for CO_2-emissions influenced by the price scenarios.
- The SB scores on medium consumption growth lower than for low and high consumption growth for the price scenarios low and reference.

Ratios between gas, electricity and CO_2 prices explain the first trend. These differ over the years per price scenario because of the world view they give.

		CO_2-emission in 2040																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	80	35	15	95	62	45	90	64	51	90	64	51	100	67	100	99	68	100
	Circles	68	22	0	86	51	32	61	41	30	61	42	30	71	42	28	71	42	28
	Paces	78	28	5	95	57	38	56	34	22	57	34	22	57	27	14	57	27	14
	Tides	67	22	1	84	51	34	30	12	0	30	12	0	40	16	0	40	15	0
	Reference	76	30	10	93	60	41	80	55	42	80	55	42	87	56	86	87	56	86
"Leiding door het Midden" on	Low	81	36	15	99	75	62	100	74	61	100	74	61	100	67	99	100	67	99
	Circles	69	23	1	90	65	51	64	44	34	64	45	34	71	42	29	71	42	29
	Paces	79	29	6	100	72	57	60	36	25	60	36	25	56	27	14	57	27	14
	Tides	69	23	1	89	64	50	33	13	2	33	13	1	40	13	24	40	13	0
	Reference	76	31	10	97	73	59	87	63	51	87	63	51	87	56	86	86	56	86

Figure 47. CO_2-emission in 2040 for all market mechanisms

The second observation has already been explained in the case of CO_2-emissions in 2023. In some price scenarios, CO_2-emissions in the single-buyer are sensitive to changes in consumption patterns. This can be traced back to congestion within the network. As soon as there is more demand than producer D can transport to the consumption clusters, other producers will start producing that emit mainly less CO_2. That is why this dip can also be explained for the single-buyer.

From a policy perspective, this means that the single-buyer market can behave unpredictably when specific prices and consumption scenarios interact. Furthermore, it appears that the WH and SB markets can change significantly in scores under different price scenarios.

From a policy perspective, this means that the single-buyer market can behave unpredictably when prices and consumption scenarios interact. Besides, the WH and SB again appear to be highly dependent on the price scenarios for CO_2-emissions. On the other hand, the E2E is only dependent on consumption growth which makes it a more robust market is in case of uncertainty.

6.5.3 The impact of market mechanisms on consumer price in 2040

Figure 48 shows the scores for the consumer price in 2040. In terms of trends, this figure is also the same as in 2030. Again, the same dip in medium consumption growth for the SB is striking as in figure 47 CO_2-emissions. The price is, therefore, also influenced by congestion in the network.

		Consumer price in 2040																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	35	29	26	90	79	75	83	80	79	84	81	80	88	67	91	88	68	91
	Circles	43	33	28	96	82	77	66	52	49	66	50	49	92	68	60	92	69	60
	Paces	18	6	0	76	60	53	34	10	0	34	10	0	27	7	0	27	7	0
	Tides	49	38	33	99	86	80	92	83	80	92	82	80	100	78	66	100	76	66
	Reference	32	24	20	86	74	68	57	50	45	57	50	46	73	52	72	73	52	72
"Leiding door het Midden" on	Low	35	29	26	91	82	77	100	95	92	100	95	92	88	68	91	88	68	91
	Circles	43	33	28	97	84	79	85	71	67	85	70	67	92	69	59	92	68	59
	Paces	18	6	0	77	62	56	40	14	4	40	14	3	27	7	0	27	7	0
	Tides	49	38	33	100	88	83	96	87	84	95	87	84	100	76	97	100	75	66
	Reference	32	24	20	87	76	71	77	66	61	77	66	61	73	52	72	73	52	72

Figure 48. Consumer price in 2040 for all market mechanisms

6.5.4 The impact of market mechanisms on producer surplus in 2040

The scores of the producer surplus in 2040 (Figure 49) also show the trends shown above. The essential confirmation of a higher score for consumer price equals a higher score for producer surplus in the E2E and SB markets. The WH, on the other hand, has the opposite relationship.

This means that the implementation of the E2E and SB markets at the same time results in a desired effect of the producer surplus. While in the WH market, a trade-off must be made between a more desired score on the consumer price or producer surplus.

		Producer surplus in 2040																	
		End-to-end (E2E)						Wholesale (WH)						Single buyer (SB)					
		Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On			Vondelingenplaat Off			Vondelingenplaat On		
	Price \ Consumption	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
"Leiding door het Midden" off	Low	100	90	71	52	63	61	20	24	26	20	24	26	67	23	100	67	24	100
	Circles	83	53	23	46	46	37	38	53	57	38	55	57	58	8	-20	59	8	-20
	Paces	67	5	-47	42	27	3	65	91	100	65	91	100	28	-41	-79	27	-41	-79
	Tides	94	82	60	52	63	59	26	36	38	26	36	39	69	38	3	69	37	3
	Reference	83	51	20	46	43	33	38	48	53	38	48	52	50	-12	89	47	-11	88
"Leiding door het Midden" on	Low	100	89	71	59	76	78	16	20	22	16	20	22	66	23	99	67	23	99
	Circles	81	52	23	51	56	49	31	47	51	31	47	51	59	8	-18	59	8	-19
	Paces	63	2	-48	45	32	10	60	88	97	61	88	97	26	-42	-79	26	-41	-78
	Tides	91	82	60	54	69	68	22	32	35	22	32	35	69	31	96	69	31	4
	Reference	82	50	19	52	58	51	32	43	48	32	43	48	49	-11	90	48	-12	88

Figure 49. Producer surplus in 2040 for all market mechanisms

6.6 Integration and summary of the most important findings

The findings from the base case, snapshots and full results per market performance indicator are grouped below into four groups: overall performance of market mechanisms, scenario variable influencing the individual market mechanism, similarities between market mechanisms and investment decisions.

1. Overall performance of the market mechanisms
   - The E2E market performs best on CO_2-emissions and worst on consumer prices.
   - The wholesale market performs best on Consumer price and producer surplus.
   - SB seems to be underperforming for both E2E and WH market mechanisms.
   - Consumption growth affects the emissions noticeably more and more in the future for all three market mechanisms

2. Scenario variables influencing the market mechanisms
   - The consumption growth influences the E2E market the most.
   - The WH market is influenced by price scenarios.
   - The SB market is influenced by both consumption and price scenarios.

3. Similarities between market mechanisms
   - The WH and the SB show similar trends for the difference in price scenarios.
   - SB and E2E show opposite patterns for producer surplus compared to the WH market

4. Investment decisions and their impact
   - For the WH market
     - The construction of "Leiding door het Midden" positively affects the consumer price of the wholesale market mechanism and the producers' surplus negatively.
   - For the E2E market
     - The Connection of Vondelingenplaat significantly improved the CO_2-emissions and consumer price but diminished the producer surplus for the E2E market.
     - The Leiding door het midden influences a lesser extent.
   - For the SB market
     - Is not influenced by any of the investment decisions.

6.7 Risk analysis of the market mechanisms and investment decisions

This section discusses the risk analyses performed in the study. First, it discusses the robustness of the results per market mechanism over the years. It then discusses investment decisions based on decisional theories: the maximin by Wald and de minimax regret by Savage.

6.7.1 Trend analysis and robustness in the future

The trend analysis shows the average value and the 95 per cent confidence interval of all values scored per market mechanism per year. Figures 50, 51, 52 show the trend analysis for CO_2-emissions, consumer price and producer surplus, respectively.

Trend analysis of CO_2-emissions (figure 50) shows that the E2E market is the most robust for CO_2-emissions, and this confirms the earlier findings that this market performs better than the WH and the SB market. Besides, it appears that the scores of CO_2-emissions vary the most for the SB market. This means that despite uncertainty in scenarios, the E2E market is the most robust against these uncertainties and performs best. The SB market, on the other hand, is susceptible to uncertainties.

Figure 51 shows the trend analysis for the consumer price. Once again, the E2E market is the most robust against uncertainty. As expected, the WH market is strongly influenced by uncertainty (especially price scenarios). What is remarkable is the increasing low score of the SB market on consumer prices.

Optimisation of contract prices creates the expectation that the SB would perform better than the E2E regarding the consumer price. However, this high price can be explained. Three parts of manufacturer D are responsible for this increase. Producer D is widespread throughout the system with a large amount of installed power, the contract price of producer D is the lowest, and he uses graduated contracts. As more consumption is needed, the cheaper graduated contracts are exhausted earlier. As can be seen in figure 34, this was already mid-November in 2018, with more consumption in 2030 and 2040, this is even sooner the case. However, it is precisely in these months that there is a high demand for heat. Because producer D is so distributed across the network, congestion forces producer D to operate despite the high prices. This, in turn, drives up the total consumer heat price.

The E2E market offers the most secure consumer prices in the system (figure 51), even though some of these prices are less desirable than those of the WH market. However, this market is highly dependent on the price scenarios and therefore, highly uncertain. For the SB market, the currently agreed contracts are not efficient enough. However, these contracts are also not negotiated for an SB market but an E2E market. So, when implementing the SB market, the contracts will first have to be renegotiated after which the effects will have to be determined again.

Trend analysis of the producer surplus (figure 52) again shows the E2E as the most robust market mechanism. It is also noticeable that the SB market achieves predominantly negative scores and therefore, never creates a sufficient investment climate.

From a policy perspective, the producer surplus must be carefully examined. This study assumes that a higher producer surplus is more desirable. However, producers can also earn too much. For this reason, it is necessary to consider whether the E2E market already generates sufficient producer surplus or whether there is a need for more which the WH market achieves in any case.

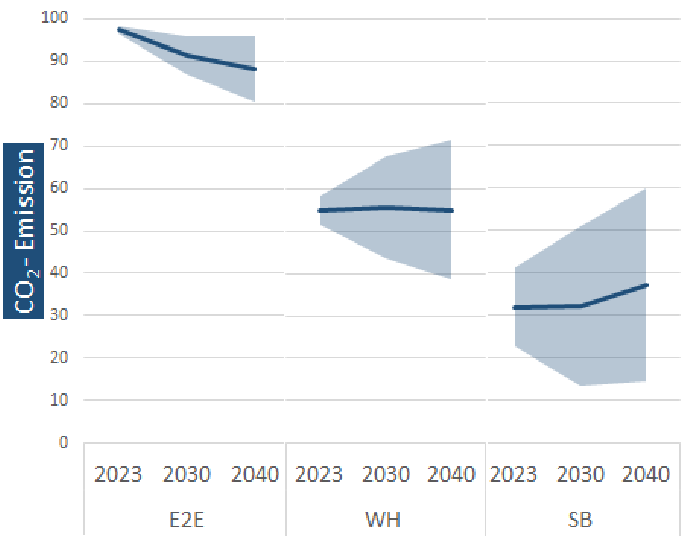

Figure 50. Trend analysis of the CO_2-emission

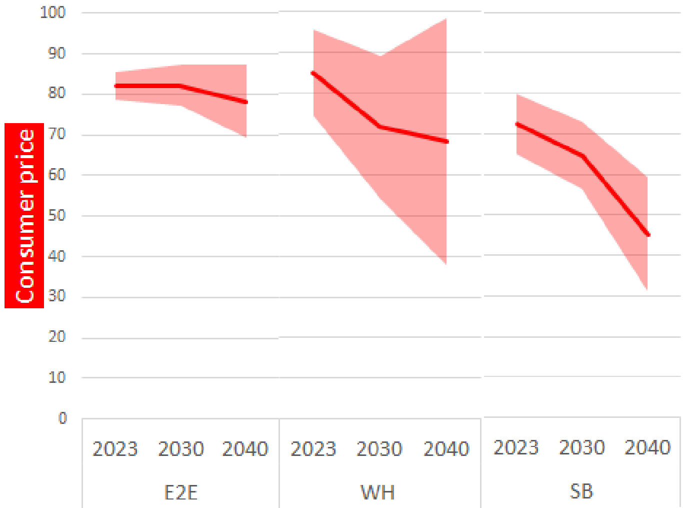

Figure 51. Trend analysis of the consumer price

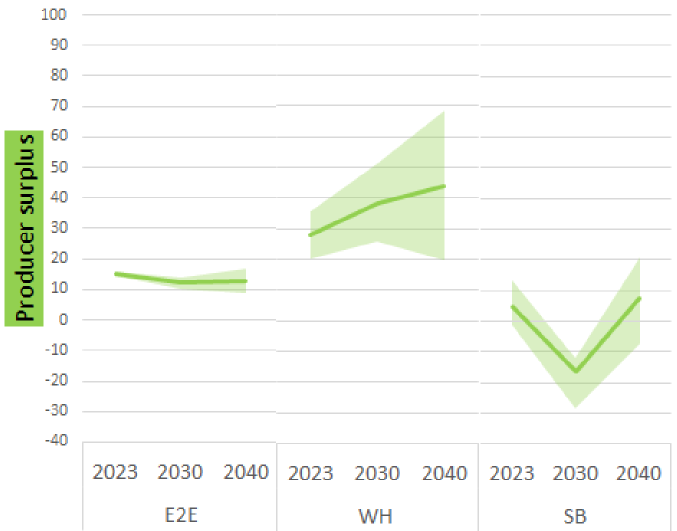

Figure 52. Trend analysis of the producer surplus

6.7.2 Regret analysis of investment decisions

The risk analysis is performed in four different ways. First, it distinguishes between the market mechanisms as scenario variable or as a decision variable. Since the ultimate decision for market mechanism lies with the government, Eneco has no influence on the outcome, and the market mechanism must be considered as an uncertainty in the system. However, Eneco can lobby for a preference for a specific market mechanism. The analysis of market mechanism as a choice variable gives a direction in which Eneco should lobby. Besides, risk analysis uses two different decision theories. The first is Savage's with the minimax regret. This shows which investment decisions have the least regret. Besides, the analysis uses Wald's maximin. This theory chooses the best investment decision for the worst case.

The least regret analysis of savage in which market mechanism is a variable scenario does not give a dominant investment decision (figure 53). The least regret for the CO_2-emission and consumer price is always achieved when the Vondelingenplaat is connected. With a preference to construct the Leiding door het midden as well. However, the result is different for the producer surplus. For 2023 and 2030, investment in the Vondelingenplaat and Leiding door het midden give the least regret as well. However, in 2040, this will cause much regret.

This means that, in terms of good strategy based on regret, the best decision would be to invest in both the Leiding door het midden and the Vondelingenplaat. However, this is not a dominant strategy, and there is a possibility that uncertainty will lead to more regret in the future.

The maximin analysis (figure 54) in which the market mechanism is a variable scenario does not give the dominant investment decision of the worst cases. Up to and including 2030 it is the right decision concerning CO_2-emissions to install the Vondelingenplaat. However, this becomes uncertain after this. For the consumer price, no correct decision can be made concerning the Vondelingenplaat. However, the Leiding door het midden seems to be a good investment here. The producer surplus prefers to build the Vondelingenplaat. There is a slight preference for also laying the Leiding door het midden.

Again, the investment in both assets seems to be the right choice concerning the worst-case scenarios. However, account must be taken of the possible impact on CO_2-emissions in these scenarios, as a result of which extra measures must be taken in this area.

Market is a scenario variable						
Minimax regret (Savage)						
2023			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,74	1,82	0,14	1,82
		Ldm on	1,49	1,81	0,01	1,81
	VP on	Ldm off	1,17	1,33	0,14	1,33
		Ldm on	0,00	1,32	0,02	1,32
Consumer price	VP off	Ldm off	1,06	0,34	0,50	1,06
		Ldm on	1,16	0,35	0,11	1,16
	VP on	Ldm off	0,00	0,33	0,52	0,52
		Ldm on	0,10	0,36	0,09	0,36
Producer surplus	VP off	Ldm off	5,11	17,91	0,69	17,91
		Ldm on	3,78	19,98	5,74	19,98
	VP on	Ldm off	5,25	19,28	0,70	19,28
		Ldm on	0,00	16,33	6,19	16,33
2030			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,54	1,73	0,21	1,73
		Ldm on	1,48	1,81	0,01	1,81
	VP on	Ldm off	0,57	1,51	0,24	1,51
		Ldm on	0,00	1,14	0,02	1,14
Consumer price	VP off	Ldm off	1,76	0,27	1,20	1,76
		Ldm on	1,76	0,28	0,08	1,76
	VP on	Ldm off	0,04	0,85	1,21	1,21
		Ldm on	0,00	0,11	0,06	0,11
Producer surplus	VP off	Ldm off	14,89	33,97	0,73	33,97
		Ldm on	14,89	34,84	5,02	34,84
	VP on	Ldm off	6,22	27,79	0,67	27,79
		Ldm on	1,34	29,24	5,05	29,24
2040			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,60	6,00	0,42	6,00
		Ldm on	1,58	6,00	0,03	6,00
	VP on	Ldm off	0,60	1,18	0,43	1,18
		Ldm on	0,00	1,17	0,02	1,17
Consumer price	VP off	Ldm off	3,27	6,96	1,51	6,96
		Ldm on	3,27	6,97	0,04	6,97
	VP on	Ldm off	0,16	1,08	1,59	1,59
		Ldm on	0,00	1,08	0,07	1,08
Producer surplus	VP off	Ldm off	15,22	30,74	1,94	30,74
		Ldm on	15,54	2,38	9,74	15,54
	VP on	Ldm off	12,78	30,62	0,53	30,62
		Ldm on	11,06	30,43	9,35	30,43

Figure 53. Minimax regret analysis for the markets as a scenario variable

Market is a scenario variable						
Maximin (Wald)						
2023			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,15	4,71	3,85	1,15
		Ldm on	1,40	4,73	3,94	1,40
	VP on	Ldm off	1,73	4,71	3,86	1,73
		Ldm on	2,88	4,72	3,92	2,88
Consumer price	VP off	Ldm off	2,74	3,04	1,69	1,69
		Ldm on	2,65	3,11	2,07	2,07
	VP on	Ldm off	3,80	3,13	1,68	1,68
		Ldm on	3,71	3,10	1,99	1,99
Producer surplus	VP off	Ldm off	11,20	-7,39	19,47	-7,39
		Ldm on	11,89	-8,89	18,78	-8,89
	VP on	Ldm off	12,58	-6,38	19,33	-6,38
		Ldm on	15,50	-4,39	18,95	-4,39
2030			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,10	2,88	2,37	1,10
		Ldm on	1,17	2,87	2,42	1,17
	VP on	Ldm off	2,03	2,71	2,38	2,03
		Ldm on	2,59	2,71	2,43	2,43
Consumer price	VP off	Ldm off	2,35	3,51	1,83	1,83
		Ldm on	2,35	3,51	2,88	2,35
	VP on	Ldm off	3,97	3,60	1,85	1,85
		Ldm on	4,01	3,66	2,88	2,88
Producer surplus	VP off	Ldm off	-3,44	-48,35	21,43	-48,35
		Ldm on	-3,43	-48,97	20,23	-48,97
	VP on	Ldm off	5,23	-41,99	21,95	-41,99
		Ldm on	10,89	-36,82	20,23	-36,82
2040			**E2E**	**SB**	**Wh**	
CO_2-emission	VP off	Ldm off	1,06	0,01	2,03	0,01
		Ldm on	1,09	0,63	2,11	0,63
	VP on	Ldm off	2,05	0,00	2,03	0,00
		Ldm on	2,59	0,01	2,09	0,01
Consumer price	VP off	Ldm off	2,20	0,00	1,66	0,00
		Ldm on	2,21	0,00	2,00	0,00
	VP on	Ldm off	5,14	0,00	1,66	0,00
		Ldm on	5,29	0,00	1,92	0,00
Producer surplus	VP off	Ldm off	-12,55	-26,05	22,84	-26,05
		Ldm on	-12,87	-26,03	18,00	-26,03
	VP on	Ldm off	0,93	-25,87	22,61	-25,87
		Ldm on	2,67	-25,79	18,10	-25,79

Figure 54. Maximin analysis for the markets as a scenario variable

Also, the least regret analysis for market mechanism as a choice variable (Figure 35, left side) does not bring to the fore a dominant strategy. The choice here is extremely varied for different market performance indicators. The CO_2-emission indicator prefers the E2E market. Regarding the consumer price, it is uncertain and unclear over the years what strategy to choose. For the producer surplus, it is the WH market that has a preference.

The worst-case analysis gives a similar picture. The consumer price does give a better preference for the E2E market to which the Vondelingenplaat must be connected.

It is not possible to express a preference for a strategy on market mechanisms and investment decisions based on the risk analysis because they are too divergent. In order to make a choice, a trade-off must be made regarding the preference of the market performance indicators. If there is a difference in the desirability of these indicators, more specific investment decisions can be made for a particular market.

Market is a decision variable

				Minimax regret (Savage)			Maximin (Wald)		
				2023	2030	2040	2023	2030	2040
CO2-emission	E2E	VP off	Ldm off	1,74	1,54	4,12	4,72	4,78	3,80
			Ldm on	1,49	1,48	4,10	4,97	4,85	3,82
		VP on	Ldm off	1,17	0,57	3,13	5,31	5,71	4,79
			Ldm on	0,00	0,00	2,59	6,46	6,27	5,33
	SB	VP off	Ldm off	5,45	5,15	6,00	1,15	1,28	0,01
			Ldm on	5,45	5,35	6,00	1,18	1,26	0,63
		VP on	Ldm off	5,42	5,49	5,80	1,15	1,11	0,00
			Ldm on	5,41	5,42	5,89	1,16	1,10	0,01
	WH	VP off	Ldm off	3,26	3,14	6,27	3,25	3,13	1,65
			Ldm on	3,17	3,08	6,19	3,34	3,18	1,73
		VP on	Ldm off	3,27	3,13	6,27	3,26	3,14	1,65
			Ldm on	3,18	3,08	6,21	3,33	3,19	1,71
Consumer price	E2E	VP off	Ldm off	1,97	2,43	7,75	1,99	3,35	1,55
			Ldm on	2,02	2,42	7,75	1,90	3,35	1,55
		VP on	Ldm off	1,10	0,96	4,81	3,05	4,97	4,49
			Ldm on	1,19	0,91	4,66	2,96	5,01	4,64
	SB	VP off	Ldm off	1,59	2,01	6,96	1,68	3,19	1,41
			Ldm on	1,59	2,02	6,97	1,75	3,19	1,41
		VP on	Ldm off	1,55	2,86	4,15	1,77	3,28	1,40
			Ldm on	1,66	2,05	4,15	1,74	3,34	1,40
	WH	VP off	Ldm off	1,10	3,18	9,30	1,96	1,83	0,00
			Ldm on	0,72	2,13	8,96	2,33	2,88	0,33
		VP on	Ldm off	1,11	3,16	9,30	1,94	1,85	0,00
			Ldm on	0,79	2,14	9,04	2,26	2,88	0,26
Producer surplus	E2E	VP off	Ldm off	40,04	71,04	127,64	11,20	-3,44	-12,55
			Ldm on	39,35	71,33	127,96	11,89	-3,43	-12,87
		VP on	Ldm off	36,62	61,65	114,15	12,58	5,23	0,93
			Ldm on	35,57	59,31	112,42	15,50	10,89	2,67
	SB	VP off	Ldm off	56,10	112,22	130,44	-7,39	-48,35	-26,05
			Ldm on	60,13	112,84	130,42	-8,89	-48,97	-26,03
		VP on	Ldm off	50,62	106,76	130,26	-6,38	-41,99	-25,87
			Ldm on	49,33	107,02	130,18	-4,39	-36,82	-25,79
	WH	VP off	Ldm off	0,69	0,73	5,31	19,47	21,43	22,84
			Ldm on	5,74	5,02	9,76	18,78	20,23	18,00
		VP on	Ldm off	0,70	0,67	5,70	19,33	21,95	22,61
			Ldm on	6,19	5,05	9,84	18,95	20,23	18,10

Figure 55. Risk analysis with the markest as a decision variable (Left minimax regret analysis and right maximin analysis)

7. Discussion

The most important result of this investigation is to enable a quantitative comparison of market mechanisms rather than a qualitative comparison. This allows the implementation of a market mechanism and the various consequences for a particular heat system to be identified and assessed. This research is an exploratory study into the quantitative comparison of market mechanisms for heat systems and can =therefore be elaborated in the future. The discussion, therefore, discusses the results in the context in which the research was carried out. It examines the results in terms of the method, the modelling programme used, and the choices made. It identifies the shortcomings of the research and draws a more general picture for the conclusions.

7.1 Contract & Pricing

The results show that the single-buyer market generates a negative producer surplus. This implies that when introducing this mechanism on the district heating network in South Holland market parties are going to withdraw from the heat market because the market as a whole runs at a loss and therefore business is not profitable. This phenomenon arises primarily as a result of the method used to include prices and contracts in this study. First of all, the contracts included in this study were negotiated by the market parties for the current end-to-end market mechanism. By copying these contracts to the single-buyer market, several aspects are lost. For example, producer D's contract is the cheapest but is contractually placed last in the merit order. When you remove the contractually determined merit order and only perform optimisation on the contract price as is the case with the single-buyer market mechanism, then information from the original contract is lost, and essential information for the single-buyer market mechanism is lacking. Besides, this contract would possibly be more expensive if producer D knew that it had to negotiate against a single-buyer, with the possibility of optimising the price of contracts themselves. This means that contract negotiation and information in the contracts are an essential aspect of using the contracts for these market mechanism optimisations.

Secondly, the contracts are indexed at the gas price. In this study, these contract prices are only indexed according to the reference price scenario for all the different scenarios. This means that a difference in real results will occur for the producer surplus. However, this impact can be viewed as minor because the CO_2 price and electricity price also have a strong influence. Besides, the dispatch does not change because all contracts in the heat market are indexed to this gas price. So the price differences are cancelled out. However, it may result in the producer surplus being more positive for all three market mechanisms in some scenarios.

Furthermore, the results of CO_2-emissions are most favourable for the end-to-end market mechanism. This is not entirely in line with expectations. Arguably, a wholesale market mechanism would work best in terms of CO_2-emissions. Because of this market prices, CO_2 and thus an incentive is present to discourage the market in CO_2 polluting production units. Because less CO_2 production would save costs, CO_2-emissions are already efficiently included in the contracts of the end-to-end market mechanism. This efficiency is brought about through the fixed merit order. Therefore, the single-buyer market is very inefficient since it optimizes on contracts and changes the merit order.

Then some prices and costs are not included in this heating system. Amongst others, it does not include the transport and distribution costs outside of Leiding door het Midden. These costs include pumping and system regulation and control costs. The independent network operator must also maintain the network and be able to bear any future investments. This entity is therefore also going to ask for a commission on top of the transport costs. This means that consumer prices, in reality, are higher than those obtained from this study. However, because these costs for the entire system are distributed among all users, no major differences in the rise of heat prices are expected. What the level of this price should be, however, can be investigated with the models that have been designed because this can be added as an extra cost component to transport, whereby it can be assessed for various scenarios at the expected costs of investments and system control.

This research has shown the different influences of the market mechanism and investment decisions on the heating system. Despite the shortcomings described above, the results of the end-to-end and wholesale markets are very relevant and can be used to make choices for a future market organisation of the heating system in the province of Zuid-Holland. The end-to-end market is modelled after its practical functioning by taking the existing contracts into account. The wholesale market represents reality to a lesser extent. However, the use of real marginal production prices causes the model to give a preliminary assessment of its impact on the heating system indication, which comes close to reality. For the single-buyer market, however, this is not the case; the model uses the contracts from the end-to-end market. As indicated before, information is lost, and the single-buyer market functions worse than would otherwise be the case. It is possible to add the shortcomings mentioned in this section to the models in order to model the behaviour of the market mechanism in the field of contracts and pricing more precisely.

7.2 Behaviour of the market mechanisms

Another important aspect of this research is the behaviour of market mechanisms. The results show that the end-to-end market mechanism behaves as expected and is influenced in particular by the consumption pattern. This is in line with expectations since there is no optimisation of contract prices. Therefore, with a fixed merit order, if the heat demand increases, it is more likely that one contract is fully utilised and the next one has to be called upon for production. The wholesale market, on the other hand, is entirely influenced by the price scenarios. Once again, this can be explained by the merit order, which is organised by optimising the cost price per production unit. The single-buyer seems to be influenced by both price and consumption. This makes it look like it has a hybrid effect compared to the wholesale market. This appears to be due, on the one hand, to the fact that the contracts contain fixed quantities of installed capacity and, on the other hand, to the fact that even though Producer D contract is the cheapest, the fuel prices influence the dispatch of producer D's assets.

Earlier research by Eladl & ElDesouky (2019), He et al. (2019), & Kim & Edgar (2014) optimised the electricity wholesale market and used heat as a by-product. On this basis, the functioning of the heat market was examined. Even though this study looked at the heating system, it appears that a number of the large production units in the regional heating system are dependent on electricity prices. So also in this investigation a certain degree of interconnection with the electricity market. It appears that the functioning of the heat market is similar to that of the electricity market, as described in the literature. This would mean that despite other literature describing that it is not possible to introduce market forces into the heating system, this is possible concerning the archetypes. This could be because the literature has mainly analysed local district heating systems. The heating system analysed in this study is a regional network that has a large scale and a large variety of producing units.

The fact that the influences on the market mechanisms are relatively clear is due to the use of archetypes of these market mechanisms. In reality, there is more regulation in place, and even hybrid forms are possible. In the Netherlands, for example, the electricity sector makes use of the imbalance market and the day-ahead market, which mainly operate based on the wholesale principle. However, there is also a long-term market that functions just like the end-to-end market mechanism. This means that any hybrid forms can provide better market performance.

As discussed earlier in this discussion, the single-buyer has a hybrid form but underperforms. In light of the literature, as described in chapter 2, it is particularly striking that a market mechanism which literature researched much and implemented in district heating system is in this study inferior to other market mechanisms. This implies that possibly wrong market mechanisms are in place in those district heating systems. On the one hand, it is possible that this is the most prominent and known system for the heat market and therefore, has been used so much while it is not the optimal market mechanism. On the other hand, it may also be because there are only four contracting parties in this research, which create an oligopoly of producers on the supply side. In the optimisation process, this translates into few choice possibilities for cheaper contracts. Besides, because the single-buyer is a monopolistic heat trader, much regulation for this market mechanism is needed. This study does not model these regulations. However, it is possible to include these regulations by translating them into prices.

Finally, two aspects can change the way the market operates. First of all, hot water is both fed into the transport system and discharged. During transport over the Leiding door het Midden, water is transported by 120 ^{o}C to The Hague, where it is consumed, and at full consumption, the water is returned by 90 ^{o}C. However, with less consumption, hotter water is left over. This heat, which was initially sold to The Hague, could be sold back to the Westland on the way back. This creates a second-hand heat market, which can influence the operation of the market mechanism above. Besides, there is also demand management. For the contract market, this is expected to have little effect on the functioning of the market, except for the independent network operator. It is highly probable that this system will be used more optimally. However, in the case of a wholesale market mechanism, this will undoubtedly have an impact on the operation of the market. This is because if prices are higher, people will not be able to take advantage of the fact that a system can regulate this. Hence, consumer prices are expected to fall.

7.3 Asset investments and regulation

The results showed that especially for the contracts markets, the addition of a sizeable producing unit affects market performance. For the wholesale market mechanism, connecting two cities via the Leiding door het Midden achieves a moderating effect on the consumer price. This ensures low-cost producing units to provide heat to another area. This shows that the market mechanisms are influenced by investments in assets of both transport and production. A risk analysis has been carried out concerning the best options for the market. However, these options can be further developed. By using (Sarma & Bazbauers, 2017) methodology, investment incentives can be better mapped out, but overinvestment risks can also be included in the market models already made.

Besides, the regulation of the producing units also has an impact on market mechanisms. At present, for example, biomass power stations and geothermal energy sources are subsidised. This means that they bid in the market at zero costs for the wholesale market and a low contract price for the contract and market mechanisms. However, at the moment, these technologies are still costly. So if the government discontinues subsidies, a quick disappearance of these units from the market is anticipated. Besides, there is also uncertainty in the policy on CO_2-emissions. At the moment, the regulation defines waste heat and waste incineration as CO_2-neutral. This means that if this policy on grants and CO_2-emissions changes, it will have a significant impact on the heat markets and the heating system.

Finally, a policy is currently in force that relates to the Energetic Generation Efficiency (EOR) (Chapter 4). In Eneco's current market models, this efficiency is first optimised in order to determine heat flows. These heat flows could be entered into the market mechanism models but would leave no room for optimisation on cost within the Linny-R models. This means that for this study, either an optimisation should take place on two objectives: costs and EOR or it could be modelled intrinsically in the market mechanisms. Because the EOR functions based on scores, this system can incorporate the EOR in the cost system of the market mechanisms. By having producing units produce a score for each quantity of heat produced. This is translated into costs in the model and can, therefore, be optimised on both costs and EOR.

7.4 Modelling and simulation

Finally, there is the process of doing research. The modelling of the market mechanisms in Linny-R has resulted in relatively normal-sized models. However, the running time of the market mechanism differed between 2 and 6.5 hours. This while the solver time of Linny-R stops at 60 seconds. This means that the simulations could have taken even longer. Threshold variables these long simulation times are caused by where one process could only be switched on when another process was producing at full load. This threshold provides a binary variable that doubles the solver capabilities. This also increases the simulation time considerably. By capping this simulation time to 60 seconds, the solver regularly stops at sub-optimal results. This means that the results obtained are also sub-optimal.

Furthermore, due to the long simulation times, it was decided to look at four different years instead of the entire 24 years. What is striking from the price scenarios is that in some years they come close to each other. As a result, the distinctive value of these price scenarios cannot be fully estimated for each year. On the other hand, the analysis of an additional 20 years would generate a large amount of additional data, which in turn would need to be analysed in a correct and orderly manner.

8. Conclusion

The market mechanism strongly influences the performance of the district heating system. Uncertainties, in turn, strongly influence the various market mechanisms. Each market mechanism is influenced differently by its specific market operation and thus influences market performance. The end-to-end mechanism is primarily influenced by consumption growth and experiences a significant improvement when investments are made in additional production assets. The price scenarios drive the wholesale market mechanism and investing in transport capacity improves the market performances in this market. The single-buyer market is driven to a lesser extent by both scenario variables investment in heat assets influence the market limited. The comparison clearly illustrates that the single-buyer underperforms in comparison with the wholesale and end-to-end market mechanism. Between the latter two, however, there is no preference for optimal performance.

Through market performance indicators, it is possible to compare the overall performance of the markets. These are derived from the market targets set by the Dutch government: Reliability, Affordability, Sustainability, Future-proof, Accessibility & Feasibility. Accessibility & feasibility can be achieved by creating legal frameworks. Overcapacity and the addition of 250 MW of residual heat in the port of Rotterdam (Vondelingenplaat) ensure the reliability of the system. This study therefore only requires the formulation of the following three MPI's:

1. Affordability is translated into consumer price.
2. Sustainability according to the amount of CO_2 emitted
3. Future-proof according to the producer surplus

Subsequently, it appears that the market mechanisms differentiate on three different aspects of economic functionalities: Usage, contracts & pricing, Availability and Information exchange & payment. First, the difference in usage, contracts & pricing, the end-to-end market mechanism is characterised by contracts between producer and customer. These contracts contain all kinds of agreements about the capacity to be delivered, the order of production with growing demand and delivery arrangements such as transport costs and times. The single-buyer market is characterised by an entity with the sole right to trade in heat. This is the only one to enter into contracts with the various producers. The wholesale market mechanism does not use contracts. In this mechanism, each production unit bids at the marginal cost on a market platform. The difference in availability arises from the characteristics mentioned above. For the end-to-end, agreements must be made with the independent network operator by the producer or the consumer who has entered into a contract with each other. In the single-buyer market, the single-buyer is the independent network operator, or he is the one who must buy it from the network operator. For the wholesale market mechanism, the market pool purchases the transport from the independent system operator. Finally, the exchange of information and payment. For the end-to-end market, the Producer and Consumer deal with the payment themselves. In the case of the single-buyer, the payment is between the producer and the single-buyer and the consumer and the single-buyer. In the wholesale market, the market pool operator settles the costs.

The district heating system must match supply from producing units with demand. In other words, this is a unit commitment problem. A Unit Commitment Problem can be solved using mixed-integer linear programming. This study uses a graphic modelling program called Linny-R to solve this problem. This program can automatically calculate the CO_2-emission per production unit; however, it does not automatically apply the market mechanisms. These market forces of the different market mechanisms must be translated into a unit commitment problem. Therefore, a distinction is made between the different mechanisms in the way of dispatch and settlement. The dispatch of the end-to-end market mechanism is contractually defined, and the prices do not affect the merit order. The settlement of this mechanism takes place by taking the average contract price. Based on this, the producers' surplus describes the contract price minus the production costs. For the single-buyer market, the settlement works the same. However, the dispatch is different from the end-to-end market mechanism. This is done by optimising the contract portfolio. So cheaper contracts are more likely to be dispatched. In the wholesale market, both dispatch and settlement are different. The dispatch takes place purely based on marginal costs. This means that the cheapest producing production unit is the first to enter into service. The marginal production unit determines the consumer price and the producer surplus is calculated by reducing the consumer price by the cost price of production.

Because the dispatch of the end-to-end and single-buyer mechanism results from contracts, it is clear that consumption has the most significant impact. This is because contracts offer a certain amount of power. If there is more consumption, the dispatch switches to the next contract, in the wholesale market, the price scenarios have a strong influence because this price is decisive in the dispatch and the merit order can change. It also appears that mutual relationships differ per M.P.I. The producer surplus increases proportionally with a higher consumer price for the wholesale market mechanism. This is because the price is set by the marginal producing unit and a production unit always generates turnover when it produces. For the contract markets this connection is not noticeable, and for some price scenarios it is even the opposite. This is because of the fixed contract prices and the contracted party's commitment to supply the demanded heat. This means that there are times when the production costs are higher than the contract costs, and thus losses are made.

Furthermore, a certain investment decision in heating infrastructure affects a market mechanism. Because the end-to-end market mechanism is mainly consumption driven, investment in the Vondelingenplaat (250MW of heat production) ensures that this growth in consumption can be accommodated. In the case of the wholesale market mechanism, the construction of a Leiding door het Midden leads to improvements because it connects two cities and thus reorganises the merit order. The influences on the market mechanism become increasingly more evident in the future. The risk analysis has pointed out that there is no dominant strategy of investing which covers for the uncertainty. However, my advice would be to opt for an integral investment in both production and transport because this brings about the most significant improvement in all mechanisms. In the case of choice of market mechanism, there is no dominant strategy. Besides, the choices made for the various types of M.P.I.'s vary widely so that no advice can be linked to them.

This research has shown that it is possible to simulate institutional arrangements such as market mechanisms. This means that it is possible to determine in advance which market mechanism functions optimally for a particular heat network. By simulating scenarios, the most robust market mechanism for this heat market can be examined. The market mechanisms modelled in this study can still be improved and extended to a wide range of other institutional arrangements. For example, for the single-buyer market, optimisation can be done for the contract prices and sequence. By filling in different contract prices and adding different entities, it is possible to make this market mechanism more complex and to approximate an accurate single-buyer market mechanism.

Also, after the implementation of a specific market mechanism, the developments and their influence on the market mechanism regarding regulation and grants can be simulated. It would also be possible to use the EOR (see chapter 7) as an objective. As a result, the market goal of sustainability can be explored in greater depth, and the comparisons between market mechanisms are more meaningful.

Concerning the designation of a more effective market mechanism in the province of South Holland, more research should be done into the single-buyer market mechanism. Even though it scores lowest on the M.P.I's, they are not sufficiently representative of reality. In any case, for all three market mechanisms, the exact price mechanisms and market form to be implemented need to be thought out and made more concrete. Once this has been further explored, the method used in this study could be used again to carry out the comparison of the market mechanism.

9. Recommendations

This section discusses two different topics. First, it defines follow-up steps for researchers and policymakers. Secondly, it makes recommendations for companies involved in the district heating network and Eneco.

9.1 Follow-up steps for researchers and policymakers

The first recommendation addresses government policymakers. The government plans to implement a new market mechanism. However, it appears that the current contracts market functions reasonably efficiently compared to the other markets. Moreover, risk analysis cannot find any dominant strategy to take, but the end-to-end market comes out preferable in most of the causes. It would, therefore, be better to consider decoupling the No More than Otherwise (NMDA) principle in order to prevent heat from becoming much more expensive when gas prices rise. Besides, the currently designed market models can be expanded with the NMDA principle and other forms of regulation (e.g. tax schemes & subsidies). Using this, the influence of these regulations on the current market contracts market can be examined. Moreover, estimates can be made in advance for the impact in the future based on the formulated uncertainties. An example of the expansion and testing of the effect of the NMDA is calculating the linking of heat prices to the NMDA with which a desirable consumer price and producer surplus are generated in the system. Based on this, a choice can be made as to how robust these revenues are, but also as to whether they are sufficient.

For further research, market mechanisms need to be further specified. This research has made use of archetypes, but in reality there are hybrid forms and more regulation of these archetypes. Besides, the study showed that the single-buyer market mechanism is underperforming. Because this market did not have the right contracts as input, it is interesting to apply the market models from this study to a district heating network in one of the Baltic States or Scandinavian countries. Moreover, to investigate the effects of the different market mechanisms on the performance of these district heating systems. First of all, qualitative research must be carried out into how these markets would be shaped and what the best form of these markets would be. Based on this qualitative research, these qualitative requirements can be modelled in Linny-R. In this way, more precise market forms can be modelled, including hybrid forms such as a combination of the wholesale and end-to-end market.

The last recommendation is technical modelling. The long simulation time should be looked at and how it can be shortened. In order to ensure that the optimal results are found within a considerable amount of time.

9.2 Recommendations for Eneco

First of all, Eneco wants to build a Leiding door het Midden and needed more financial insight into the future regional district heating system and so issued this study. This research shows that the pipeline only affects the wholesale market mechanism. Therefore, the advice is not to commit to the construction of the Leiding door het Midden unless a contract with Vondelingenplaat has been concluded. This guarantees in the future that a relatively cheap and large volume of heat is fed into the system and be transported to The Hague.

Besides, the market models can be used for various applications. First of all, when negotiating contracts, it is useful to compare the end-to-end market mechanism with that of the wholesale market. This makes it relatively easy to estimate the actual costs of the other party and to negotiate a more advantageous contract for Eneco. Namely, the difference between the end-to-end market and the wholesale market makes it clear how much the producers consider necessary to hedge their risks. This can be determined based on the average marginal cost to a producer, which can be compared with the contract price.

Finally, to give more insights into the current policies in place, an addition of the analysis of the Energetic Generation and Efficiency is needed. This is not included in this study because this is methodologically not possible with Linny-R. By adding the EOR, a dual optimisation method is needed. The EOR is path-dependent because each producing unit and transport line has its EOR score. In addition, both must be optimised over a year, because in a year you can achieve a maximum of EOR score. However, it is also necessary to optimize per week to see what the optimal EOR is for the system during that time. You could use Linny-R to optimise on this. However, you cannot optimise on costs at the same time. Using dual optimisation, the impact of this EOR could still be mapped out.

10. Reflection

This chapter reflects on the process of the research. This chapter reflects on the research process. During the process, I experienced the major obstacles to the running of the 546 scenarios. I have described this below.

The implementation of the market mechanism in Linny-R worked reasonably well and was straight forward. However, difficulties arose due to the extensiveness of the models and a large number of chosen scenarios. For example, the simulation time of one market model took between 2 - 6.5 hours. Because 540 scenarios had to be run, a program was needed that could quickly enter the correct scenario values and put the models one after the other. Besides, enough computing capacity had to be found to be able to simulate these models in a considerable amount of time. Using a Python script designed by Dr Pieter Bots it was made possible to enter data of the scenario variables from Excel into the Linny-R model in question. This script also ensures that the results are written to a .csv file. After which the next scenario was run. However, no computer/server was found that could be used with a large computing capacity. That is why it was decided to run 27 desktops at the Faculty of Technology, Policy and Management, each with 20 scenarios to ensure that all results could be obtained within four days.

The results of these scenarios also needed to be presented clearly. An Excel macro designed by Dr Pieter Bots was used to read all statistics per scenario in an excel file. Moreover, to display these in tables in a clear manner. Trends can be read based on colour scales. This excel macro has helped me a lot with the overview of the large amount of data generated by the market models.

In retrospect, I could have better analysed the expected impact of scenarios before the simulation process. This would have allowed me to make a selection of scenarios that would have reduced the total simulation time. However, it has been possible to present this large amount of data clearly, and interesting trends have been found concerning investments and uncertainties in the heat market for the various market mechanisms. Also, through perseverance, I can now show the full picture of what I had thought of in advance of what I wanted to show.

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Appendices

A. Literature search and results

This appendix shows the different literature search terms iScopusus and its results. It describes the selection of the articles/book sections. Scopus was used as the default search engine. First of all, the term "district heating" was used. This resulted in 8854 results. To make a better selection, several words have been added to this research term.

1. Market

First, the emphasis was placed on market mechanisms in the field of the heating system. By using "district heating" AND market as a search term, 850 search results were generated. In order to get even fewer articles, the "limit to" function in scopus was used. The years 2010-2019 are selected and the subject area energy. This generated 322 articles. Therefore it was decided to first search for document types for review. This generated 24 search results. By researching these reviews it was possible to find other articles by means of backtracking.

The articles which have been found by this search inquiry are:

- Li, Sun, Zhang, & Wallin (2015) – A review of the pricing mechanisms for district heating systems.
- Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi (2019) – 5th generation district heating and cooling systems: A review of existing cases in Europe.
- Lund et al. (2014) – 4th generation District heating (4GDH)

2. Market mechanisms

In addition, the market mechanism defined in the background has been taken into account. Together with the term heat. For the wholesale market this resulted in 175 articles. Under the search term (wholesale AND heat) In order to further limit the number of results, it was decided to use the "limit to" function, whereby the years 2010 - 2019 were chosen. This resulted in 84 documents. The following two articles have been selected:

- Siewierski, Pajak, & Delag (2017) – Optimisation of cogeneration units in large heating systems.
- Kim & Edgar (2014) – Optimal scheduling of combined heat and power plants using mixed-integer nonlinear programming
- (Eladl & ElDesouky, 2019) – optimal economic dispatch for multi heat-electric energy source power systems.

For the single-buyer market this resulted in 13 articles. Under the search term (single AND buyer OR "single-buyer" OR "single buyer" AND heat). These have been chosen from among them:

- Penkovskii et al. (2018) – Search for a market equilibrium of Cournot-Nash in the competitive heat market
- (Andrey V. Penkovskii et al., 2017) – Search for a market equilibrium in the oligopoly heat market
- (Söderholm & Wårell, 2011) – Market opening and third party access in district heating networks

For the end-to-end contracts market this resulted in 372 documents. Where, at first glance, little was actually about heat networks. This is obtained by means of the following search term; (E2E OR "end-to-end" OR "bilateral contracts" AND heat) After this, the focus is again on the years 2010-2019 and the subject area energy. This resulted in 28 articles. However, non which proved to be about district heating and the market mechanism which was looked for.

B. Market mechanisms detailed description

B.1 End-to-end Market mechanism

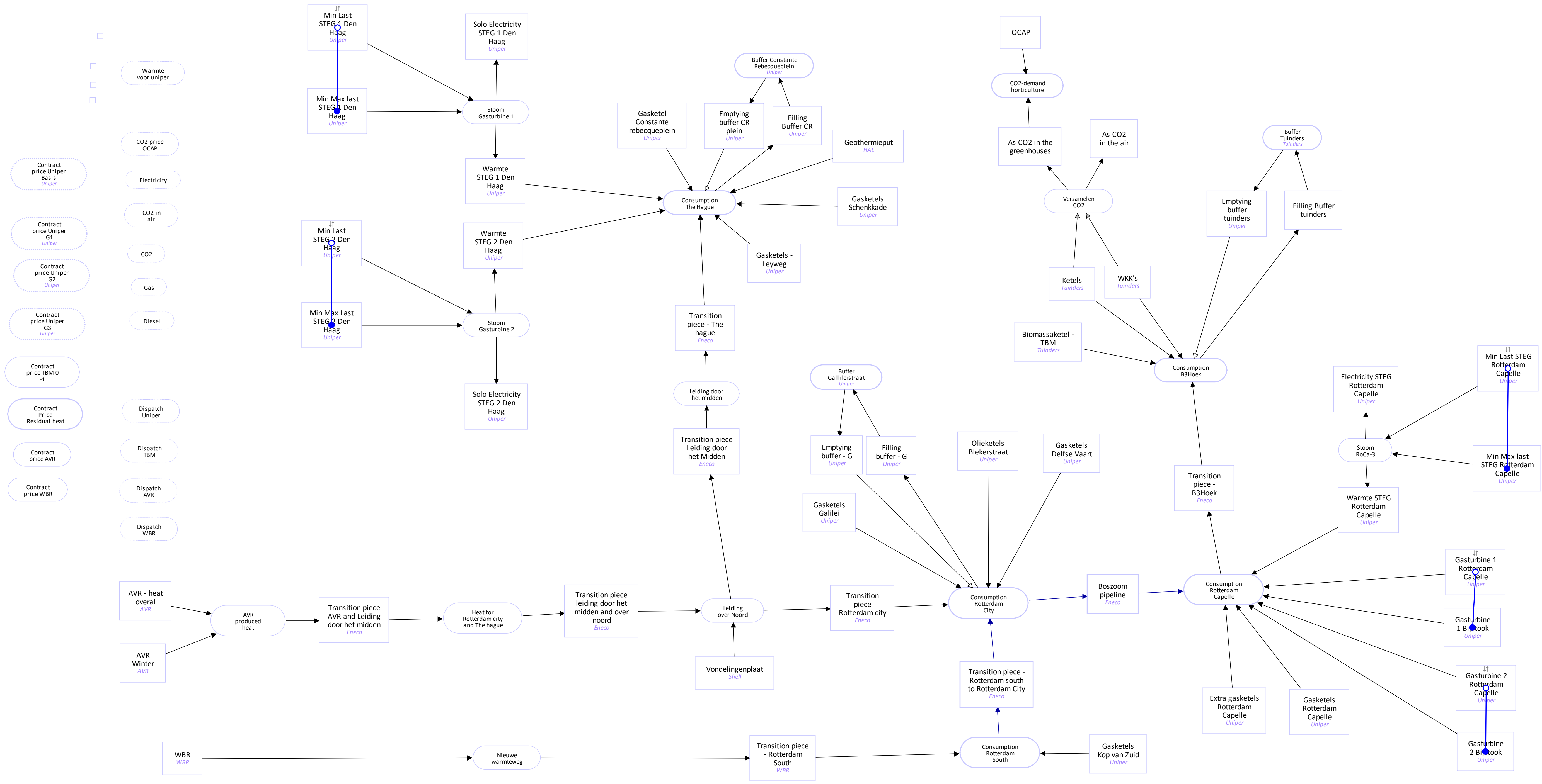

Figure 56. Full end-to-end market mechanism model

B.2 Single-buyer Market mechanism

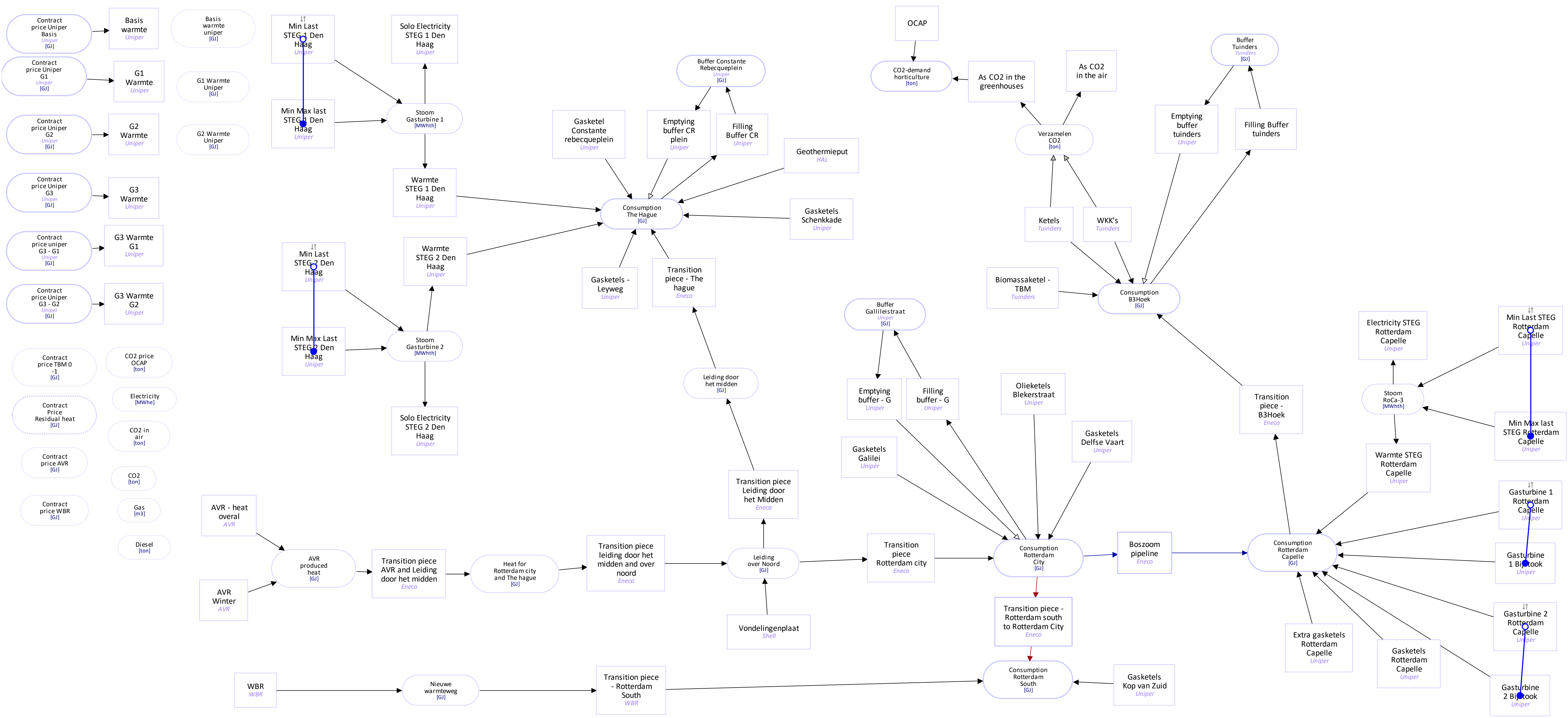

Figure 57. Full single-buyer Market mechanism

B.3 Wholesale Market mechanism

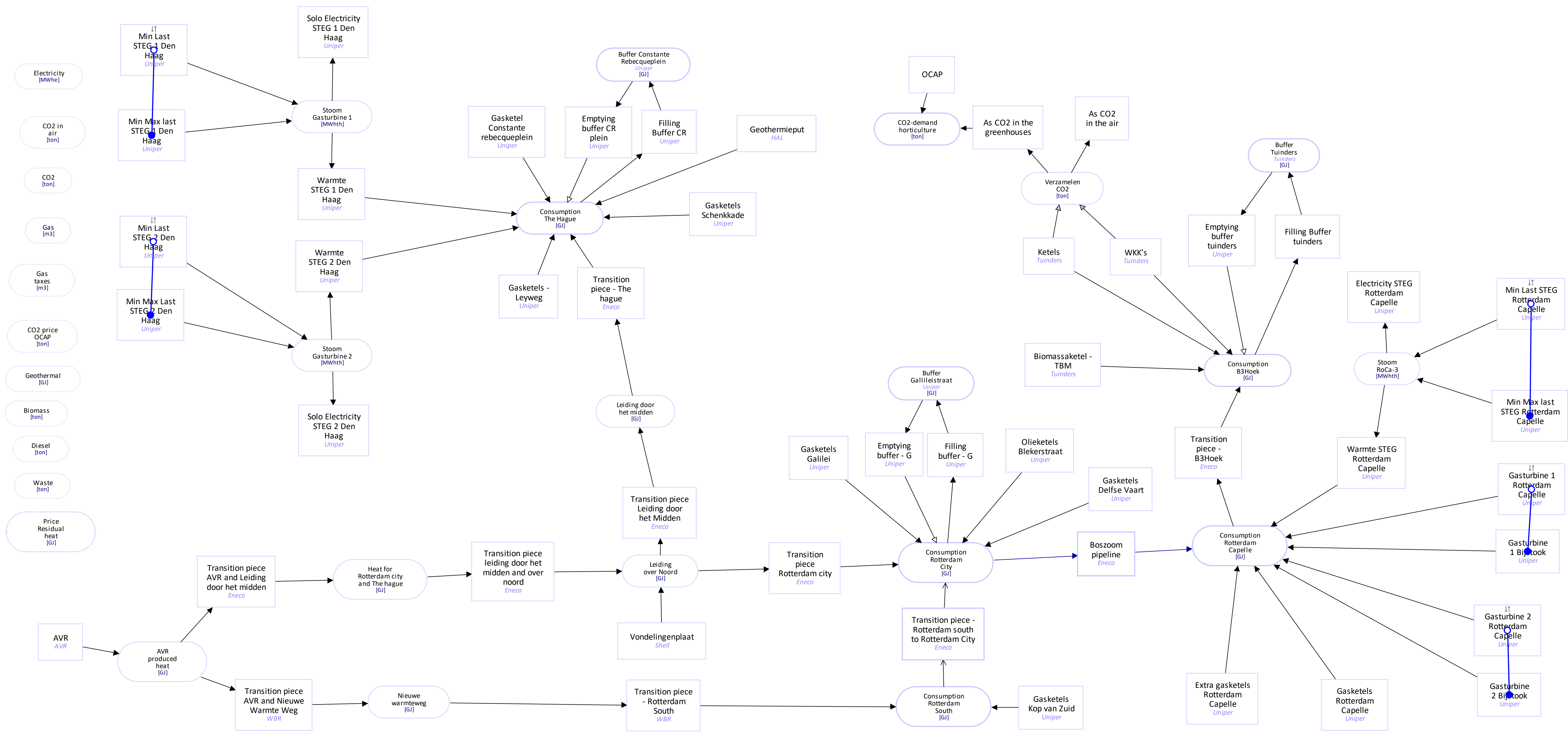

Figure 58. Full wholesale market mechanism

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