Comparing performance of different market structures for regional heat networks

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Abstract: This research has compared three different market mechanisms in a quantitative way. The influences of these market mechanisms on the heating system were investigated for CO2 emissions, consumer price and producer surplus. In addition, the influences of investment decisions and price and consumption growth scenarios were tested.
The research showed that the end-to-end market mechanism is the least uncertain in the future and is only influenced by consumption growth. In addition, the construction of a large source of residual heat can moderate this effect. The wholesale market is strongly influenced by price scenarios. This effect can be moderated by the construction of the pipeline through the Midden, which connects two different heating systems. Finally, there is the single buyer market. This is influenced by both scenario variables, while no investment decisions affect it.
Further research must be done into the latter market mechanism. And the models need to be extended to more specific markets because this research has used archetypes.

Keywords: *District heating network, Market mechanism, Single-buyer, Wholesale, End-to-End, Simulation, Investment decisions, Price dynamics, Consumption growth*

Nomenclature and abbreviations

$n \in N$	Time step t in simulation period N ⊂ ℕ
$i \in I$	Production unit i part of production unit set I
$j \in J$	Contract j part of contract set J
$CoPr_i$	Cost of production unit i (€/GJ)
PL_i	Production level of production unit i (MW)
Cp_w	Hourly consumer price wholesale market mechanism (€/GJ)
CPr_j	Contract price of contract j (€/GJ)
Cp_c	Hourly consumer price contract markets (either single-buyer or end-to-end) (€/GJ)
$CoPr_{ij}$	Cost of production unit i in contract j (€/GJ)
CL_j	Production level contract j (MW)
bcm	Billion cubic metres

1. Introduction

The energy transition and the aggravation of the earthquakes in Groningen have created a desire in the Netherlands to get rid of the gas as soon as possible (Wiebes, 2019). The government has even decided to stop producing gas from the Groningen-gas field (Rijksoverheid, 2019). About 40 billion cubic metres (bcm) of gas is still being extracted from this field every year. This provides the Netherlands with 55 percent of its final energy demand (CBS, 2019; Rooijers, 2014). Between 25 and 31 bcm of this 40 bcm gas will be used for the production of heat (CBS, 2015). To accommodate this gas exploitation stop a substitution for gas is needed to produce heat.

One of the solutions is to construct district heating networks. The Netherlands has already installed district heating networks to provide cities with residual heat from industries instead of gas-fired central heating boilers, making them a good substitute for gas use in residential areas (Warmtealliantie, 2018). In the province of South-Holland, district heating networks are being connected in order to increase capacity and facilitate future planned expansions. However, the district heating network in South-Holland is owned by Eneco and therefore has a monopoly on the transport of heat. The natural monopoly in a district heating network is created by the subadditivity of production costs, with these costs being lower if one company builds the physical network instead of several (Baumol, 1986; Wissner, 2014). As a result, the government wants to apply market forces/regulation to this regional district heating network with an independent transport operator as starting point (Green Deal, 2018; Heida & de Haas, 2019).

The study by Heida & de Haas (2019) shows that price regulation does not have a desired impact on the district heating network and is encouraging research into market mechanisms in the area of heat transport. The government (Green Deal, 2018; Wissner, 2014) has formulated market targets that this market must meet:

- Reliability
- Affordability
- Sustainability
- Future-proof
- Accessibility
- Feasibility

In the Scandinavian countries, Baltic States, Eastern Europe and Russia, district heating networks have been in existence for some time now and research has been carried out into market forces on these systems. The most common market mechanism is the 'single-buyer' market mechanism (Aronsson & Hellmer, 2009; Hellmer, 2013; Penkovskii, Stennikov, Mednikova, & Postnikov, 2018; Söderholm & Wårell, 2011). The single buyer is an entity that is solely entitled to trade in heat. This

entity enters into contracts with both producers and consumers. It is also responsible for arranging the dispatch of the heat in the system. Although this is a widely used market mechanism, not all literature is equally positive about this market. Research shows that this market structure is strongly influenced by corruption, results in poor behaviour of payments and causes government to be heavily invested in the market mechanism (Lovei, 2000). This means that other market mechanisms need to be examined and compared in order to be able to indicate what the best market mechanism is for a district heating network.
Comparison is possible by quantification of the system and institutional arrangements. Eladl & ElDesouky (2019) and He et al., (2019) have done research into the influences of social welfare, economic cost and/or environmental cost. However, this study focuses on the competitive Combined Heat and Power market, where the main commodity is electricity instead of heat. In the province of South-Holland the main commodity will be heat with some combined heat and power (CHP) units. Kim & Edgar (2014) and Siewierski, Pajak, & Delag (2018) carried out similar research into the additional revenues of the heat system on the electricity wholesale market. (Penkovskii et al., 2018) investigated the single buyer market mechanism. However, this study was carried out with a fixed setting of one year. As a result, the dynamic factors of the markets/institutional agreements have not been considered.

Market mechanisms are institutional arrangements that organize the market. but in order to be able to compare them, they must be quantified based on equal market performance indicators (M.P.I's). The institutional arrangements of various market mechanisms have been qualitatively examined in the literature (Oei, 2016; van Woerden, 2015). However, there has been little research into the quantification of these institutional agreements and the comparison of different market mechanisms. The aim of this study is therefore to simulate different institutional agreements for a district heating network with demand, price and storage dynamics.

2. System Analysis

A. *District heating networks*

District heating networks can be divided into four segments: production, transport, storage and consumption.

Production - Heat can be produced from assets that use different types of fuel (Groot, Leguijt, Benner, & Croezen, 2008; Schilling, 2018). There are combined heat and power (CHP) power stations, gas boilers and oil boilers. Other producing units that are classified as sustainable by the government are waste incineration plants and residual heat from industries, mainly from the industrial clusters near the port of Rotterdam. Finally, a great deal of research is now being done into the production of heat through geothermal energy. Producing units are characterised by:

- installed capacity (MW)
- fuel costs (€/GJ)
- efficiency (%)
- ramp up/down cost (€)
- CO_2-emissions (ton/MWh)

Transport - Heat is transported in district heating systems on two different types of networks (Chiu, Castro Flores, Martin, & Lacarrière, 2016; RVO, 2018). The first network is the transport network, which transports heat over relatively long distances. The supply temperature is 120 ºC and the discharge temperature is 90 ºC. The second network is the distribution network, which supplies heat from the transport network to the consumer. This has a supply temperature of 90 ºC and a discharge temperature of 70 ºC. Characteristic for the heat transport are:

- pipeline capacity (MW)
- flow rate (m^3/s)
- heat loss (GJ/m)
- temperature difference (ΔT)
- transport cost (€/GJ)

Storage - Because heavy rain can cause a sudden drop in temperature, heat storage is required to preserve the balance in the system. There are two different types of storage that differ in storage duration: Salt caverns can store heat for other seasons whilst buffers can store heat to balance the system for a maximum of a week (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Schepers & Valkengoed, 2009). The properties that these buffers have are:

- installed capacity (MW)
- (dis)charge rate (MW/h)
- heat loss (GJ/h)
- storage cost (€/day)

Consumption – District heating system mainly provide heat to residential and office buildings. Heat can also be supplied to industries, but these often have a separate connection, such as horticulture (WarmteKoude Zuid-Holland, 2018). The consumption pattern of residential buildings characterises a so-called bathtub pattern over the year. Where consumption is high in the winter and low in the summer.

B. *Market mechanisms*

Market mechanism are market operations where supply and demand determine the price and quantity of heat offered in a free market (Long, Moore, Wenban-Smith, & Sheard, 2003). This paper discusses and compares three market mechanisms: End-to-end (E2E), wholesale (WH) and single buyer

(SB). In all markets, the independent network operator takes care of the actual dispatch, but the way in which this dispatch is arranged differs per market mechanism.

End-to-End mechanism (E2E) – This market mechanism is characterised by contracts between producers and large purchasers. They are responsible for ensuring that their demand is matched with supply. In a E2E market, the merit order of dispatch is determined by agreements in the contracts. In addition, the contracts contain the agreed prices and available capacity for each producer.

Wholesale mechanism (WH) - The wholesale market is characterised by producers and consumers who bid on heat in an open market pool. These bids are cleared every hour and the price follows from the cutting point of supply and demand (Benassy, 1986). In the electricity and gas market, the producing units bid at marginal prices which arranges the merit order (Perez-Arriaga & Meseguer, 1997).

Single-buyer mechanism (SB) - The dispatch for the single-buyer is similar to that of the E2E market. However, the dispatch orders are not fixed and the single buyer can be optimised for contract prices. The merit order is ordered from low to high contract prices (Lovei, 2000).

3. Problem formulation

To facilitate comparison of these market mechanisms, market performance indicators (M.P.I.'s) are needed. These can be derived from the market objectives described in the introduction. Accessibility and feasibility are market objectives that can only be achieved by setting up legal frameworks. Therefore, they will not be included in this simulation study. Reliability is not included in this study either because there is already an overcapacity of heat producers in the province of South-Holland and because it is assumed that enough residual heat can be retrieved from the port of Rotterdam.

Affordability, sustainability and Future-proof are included in this research. These three market objectives are changed to more concrete and measurable M.P.I.'s. The consumer price can be used to determine whether heat is affordable. Sustainability can be measured based on CO_2 emissions. And future-proof can be determined by the producer surplus. The producer's surplus encompasses what the producer retains after deducting production costs from income.

The market mechanisms differ in terms of dispatch and settlement. These differences determine the allocation of costs.

A. *Dispatch*

The E2E market mechanism is characterised by contracts. In addition to the available capacity and price, these contracts contain a fixed merit order of deployment. This means that the entire dispatch is fixed. That is why figure 1 shows a decrease in price first and then an increase in price.

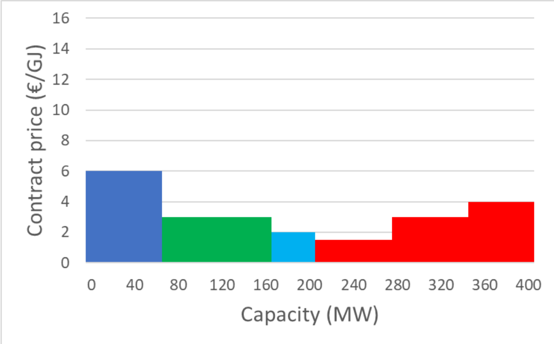

Figure 1. Dispatch End-to-End market mechanism (E2E)

Figure 2 shows the dispatch of the WH market. In this market, a heat-producing unit offers a certain amount of capacity at marginal cost. These prices are arranged by the market pool operator from low to high. The market pool operator then clears the market. The production unit at the cross-section of supply and demand is called the marginal heating plant and sets the price. The independent operator then calls upon the producing units to match supply with demand in real-time.

The merit order may change due to changes in market prices. For example, a negative marginal cost price can arise for a CHP power station when there is a high electricity price (black box at the front of the merit order). The CHP earns enough with the electricity in order to bid at a negative heat price.

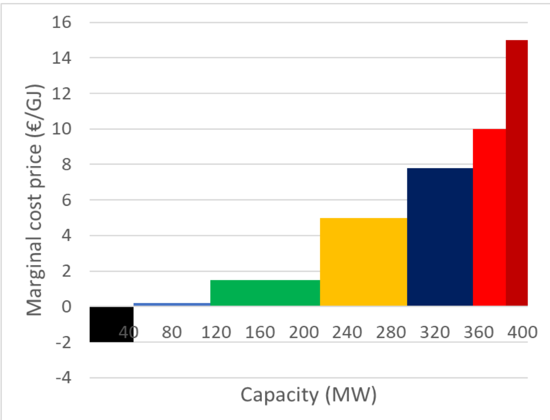

Figure 2. Dispatch of the wholesale market (WH)

The SB market mechanism operates with contracts like . In addition to the power and price offered, the contracts in this market also have a category, namely: baseload (blue), flexible load (red) and peak load (green). This is reflected in the dispatch of the single buyer market (Figure 3). The SB, as the sole trader in heat, can choose its own order from the agreed contracts. As a result, the SB first chooses the cheaper contract for each category and subsequently the more expensive one.

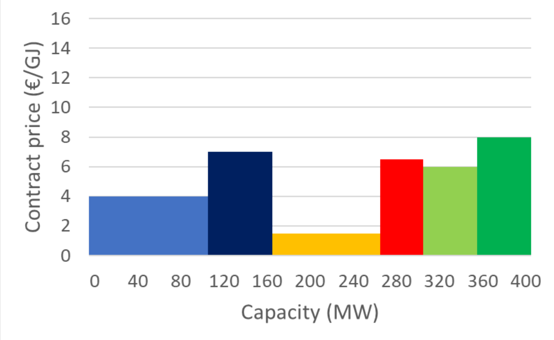

Figure 3. Dispatch Single-buyer market mechanism (SB)

B. Settlement

The government's premise that an independent network operator should manage the transport has implications for the market. This operator is not allowed to exploit profits. It can only ask for a percentage to cover costs and expansion of the network. This means that the settlement of the market is purely determined by the dispatch of the production units/contracts. In addition, this means that the independent network operator can charge an average consumer price over the year that covers all costs over the year. The way in which this consumer price is established and the way in which the independent network operator settles costs at the end of the year is explained below.

The determination of consumer price and method of settlement is the same for both contract markets (E2E & SB). The consumer price is calculated on the basis of 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 have to be taken into account. As the consumer price is a fixed price, the average over the year of all these hourly averages is taken. This ultimately covers all the contracted costs of the independent network operator.

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.

[1] $$Consumer\ Price = \frac{\sum_{n=1}^{8760}\left(\sum_{i=1\ \&\ j=1}(CoPr_i * PL_i) * \frac{1}{\sum PL_i}\right)}{n_{total}}$$

$$\forall PL_i \in \mathbb{N} : PL_i > 0$$

[2] $$Producer\ surplus = \sum_{n=1}^{8760}\left(\sum_{i=1}((Cp_w - CoPr_{ij}) * PL_i)\right)$$

$$\forall PL_i \in \mathbb{N} : PL_i > 0$$

The determination of the consumer price and the settlement for the WH market works differently from the contract markets. This is because of the hourly market clearing and due to the fact that all producing units generate their own income. The market clearing is executed by determining the marginal unit. This means that the most expensive producing plant determines the hourly consumer price. For the same reason as in the contract market, it is possible to calculate an annual average consumer price from these hourly prices (eq. 1).

What a producing unit earns is the difference between this price set by the marginal centre and its own marginal cost. The total producer surplus over the year is a sum of these hourly producer surpluses (eq. 4).

[3] $$Consumer\ Price = \frac{\sum_{n=1}^{8760}(Max\ (CoPr_i))}{n_{total}}$$

$$\forall PL_i \in \mathbb{N} : PL_i > 0$$

[4] $$Producer\ surplus = \sum_{n=1}^{8760}((Cp_c - CoPr_{ij}) * CL_j)$$

$$\forall CL_j \in \mathbb{N} : CL_j > 0$$

C. Uncertainties and scenario's

District heating networks are expected to operate for 50 years or more. In contrast, a market mechanism for about 20 years. Where it is adjusted in the meantime to the wishes of society. These timeframes are subject to uncertainties.

This simulation study considers uncertainties as scenario variables and decision variables. Scenario variables are fuel prices and consumption. For the future fuel prices this research considers five different worldviews developed by Eneco; low, reference, paces, tides & circles. The predictions are made for CO_2, gas and electricity prices. In addition, this research looks at growth in consumption, which is also estimated by Eneco for a low, medium and large scenario. Decision variables encompass investment decisions. In the province of South-Holland two different types of assets are planned for construction in 2023. The first is Leiding door het Midden, which will connect the district heating network of Rotterdam with The Hague. And the second is connection of the Vondelingenplaat, which will supply residual heat from petrochemical clusters in the port of Rotterdam to the district heating network. Table 1 gives a clear overview of these scenario variables

We have chosen a time span from 2018 to 2040. The data for 2018 (prices and heat consumption) are known. And after 2040, consumption growth and price scenarios are so uncertain that they do not add much value to the results.

In addition, the decision was made to run three different years. In order to then extrapolate this information. The choice was made for 2023 because the construction of the various investments will then be completed and for 2030 and 2040.

Table 1. *Scenario variables for experimental design*

Scenario variable	Setting
Fuel prices	Low, Reference, Tides, Paces, Circles
Consumption	Low, medium, high
Leiding door het midden	Off, on
Vondelingenplaat leiding	Off, on

D. Simulation

The simulation of the dispatch for the different market mechanisms can be characterised by a Unit Commitment problem (UCP) (Tahanan, van Ackooij, Frangioni, & Lacalandra, 2015). This problem can be solved with Mixed Integer Linear Programming (MILP). A graphical specification language which solves UCP's with MILP is the program Linny-R (Steep Orbit, 2019).

This graphical language uses products (1a & b), links (2a & b) and processes (3) to model for example a heat system (figure 4).

Figure 5 shows the products in a greatly simplified heating system. In the heat system, products can be used as fuel, CO2, produced heat, stored heat or contracted heat. The name of the product is shown in the middle of the two figures, 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 the product is produced by a different process. The heat product (1b) shows a =100 number. This is the target that has been set. In the heat system this is used to indicate a fixed amount of heat consumption. The green colour indicates the target is met.

Figure 6 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. And in yellow (700) the costs associated with the commodity flowing over the link are shown.

In the heat system, a process (figure 7) 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 quantity of heat at a certain price. This means that when heat from a contract is asked for, the quantity of heat must be injected into the system at the given contract price.

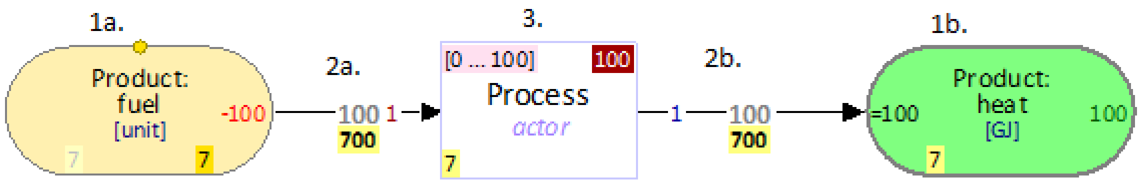

Figure 4. Abstract and simplified heat system

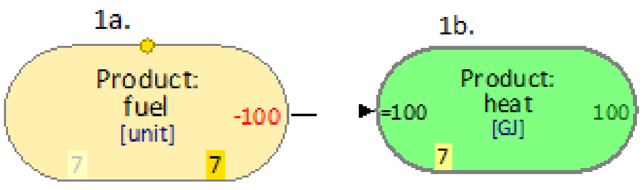

Figure 6. Products in Linny-R (left as input, right as output)

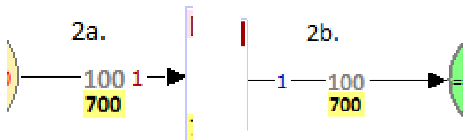

Figure 7. Links in Linny-R (left from product to process, right from process to product)

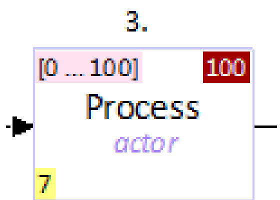

Figure 5. Process in Linny-R

The name of the process is displayed in the middle of the process. The owner of the process is shown in italics below. 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 heat 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.

Linny-r can solve a UCP by matching supply and demand. For this, the program uses a decision variables, constraints and objective function. The decision variables in the heat network consist of the capacity used per producing asset and the capacity transported per pipeline. Constraints limit the basic load and maximum load that a producing unit can handle. In addition, it also limits the possible amount of heat in transport lines.
The objective function dissolves the UCP based on these decision variables and constraints. It maximizes the revenues of the system (minimizes costs), by adjusting the decision variables and by matching the heat demand with the production as cheaply as possible in this way.

6. Results

For reasons of confidentiality, all results have been normalized and the actual names of the producers have been changed to producer A, B, C & D. During 2018 the residual heat is not yet connected to the system and is not included in *A. model behaviour and B. Base case comparison*

A. Model behaviour of the three market mechanisms

The data of the physical system, including installed capacities, topology, prices and consumption, are obtained from Eneco. For clarification, this section represents the dispatch behaviour per market mechanism.

The E2E market has a fixed merit order. Because Linny-R optimizes costs, fictitious costs are used per contracted producer, simulating the correct merit order. Figure 8 shows the merit order, the green colours indicate production of the producers.

During the winter peak load, it is clear that producers A, B & C produce at full load (Figure 9). Producer D also accommodates the peaks in the demand. This is in line with the merit order from figure 8. In addition, the system matches demand with production. The diamond is equal to the production. This observation applies to all three market mechanisms and will not be repeated below.

Figure 10 shows the merit order from the E2E market for low heat demand in the summer. The merit order does not change because it is fixed in this market. In addition, the figure shows that producers C and D do not produce.

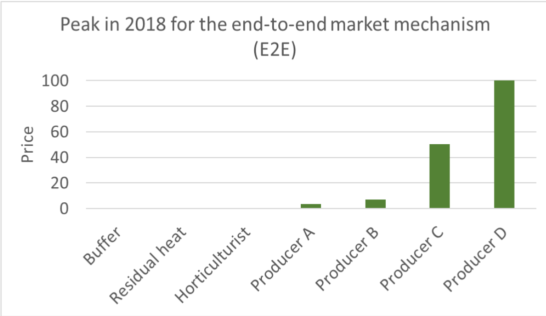

Figure 8. Merit order end-to-end market mechanism high demand

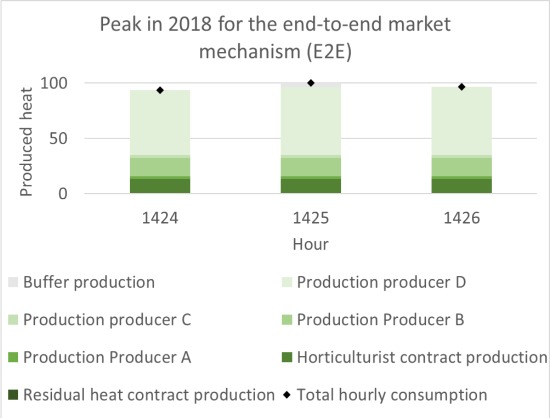

Figure 9. Dispatch end-to-end market mechanism winter

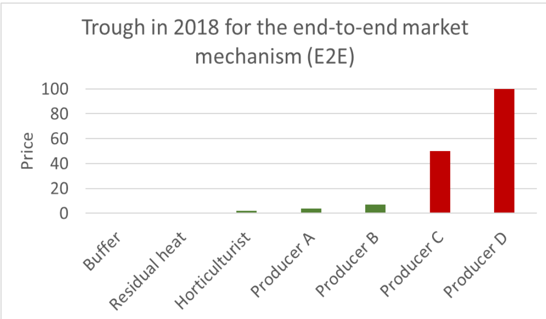

Figure 10. Merit order End-to-end market low demand

Figure 11 shows the dispatch in the summer for the E2E market. This indeed shows that producers do not produce C & D. It is also noticeable that in the first two hours of production from buffers, a large part of the heat demand is met.

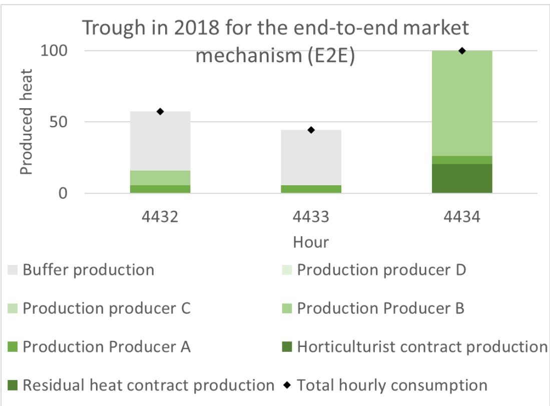

Figure 11. Dispatch end-to-end market mechanism in summer

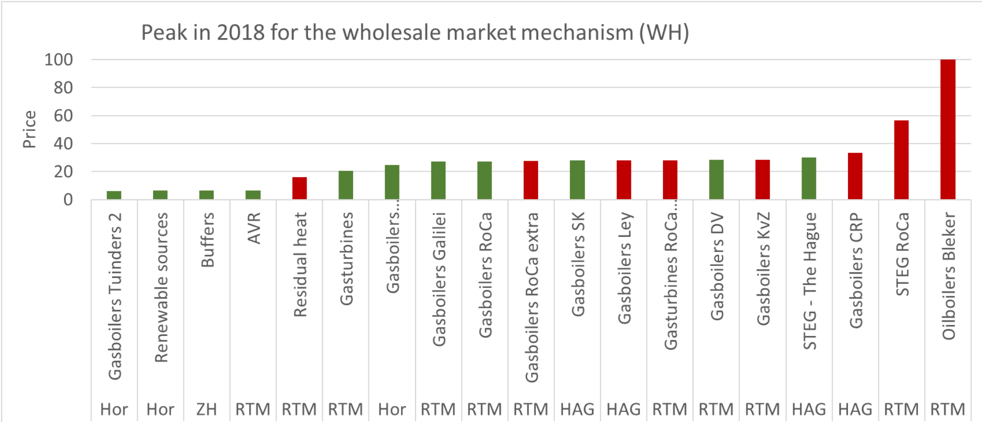

Figure 12. Merit order peak demand wholesale market.

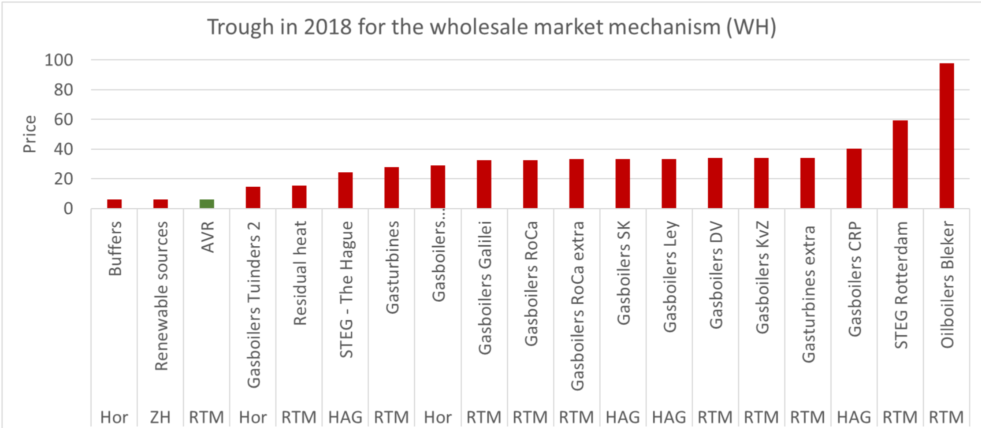

Figure 13. Merit order low demand wholesale market

In the WH market, the marginal cost price determines the merit order and dispatch. The merit order of the wholesale market contains many green and red columns (Figure 12). These colours alternate, which shows congestion in the network. This means the independent grid operator dispatches more expensive generating units in order to meet the demand for heat. This is also clear from the name under each production unit (Hor = horticulture, ZH = spread across the province, RTM = Rotterdam, HAG = The hague). However, the figure also shows congestion within Rotterdam. This is caused by a distribution line at the forest edge.

The dispatch is grouped together due to the large number of producing units which is based on marginal cost per production type. Gas boilers are generally the most expensive and are used to accommodate peak demand. Then follow the gas turbines, CHP, Renewable sources, AVR and residual heat. Figure 14 shows that the merit order from figure 12 is followed. In addition, it is noticeable that the gas boilers indeed absorb the peak loads.

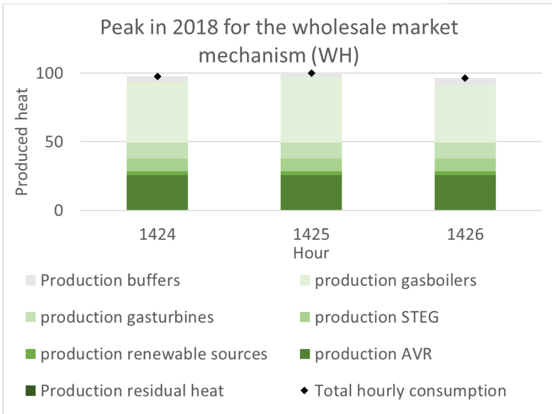

Figure 14. Dispatch peak load wholesale market

Figure 13 shows the merit order of the wholesale mark for low demand. This seems to be the same as during peak load, however, the STEG -The hague is moving up the merit order due to changes in prices. During the low demand, only AVR produces heat. Figure 15 confirms that only AVR supplies heat to the system. In addition, the buffers are used.

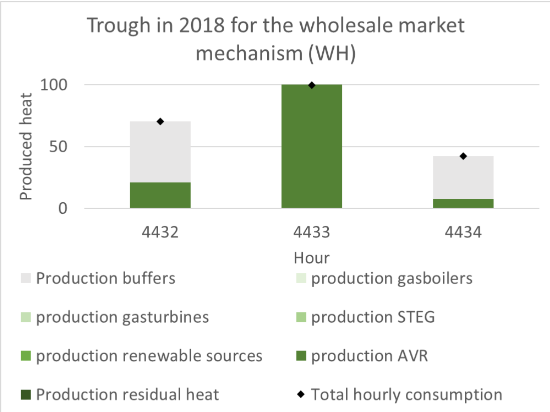

Figure 15. Dispatch wholesale market during low demand

In the SB market, the contract price determines the merit order and dispatch. This is why the order of the merit order is different from that of the E2E market (Figure 16). During the peak load, all units produce heat, except the residual heat, because it is not constructed.

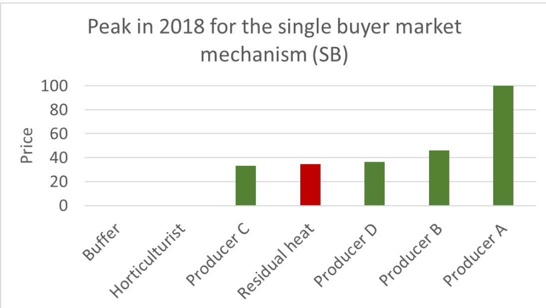

Figure 16. Merit order peak demand single buyer market.

The dispatch of the single buyer during peak load also reflects this dispatch (figure 17). However, producer D again absorbs the peaks. You wouldn't necessarily expect this if it were to be used first. This phenomenon can be explained by congestion in the network at Boszoom and the fact that heat outside only runs downstream. As a result, producer D cannot lose its heat at all places in the network at the same time, and the other contracts have to be used to capture this.

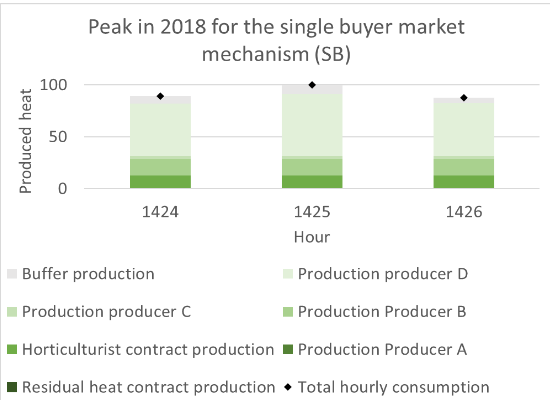

Figure 17. Dispatch single buyer market during peak load.

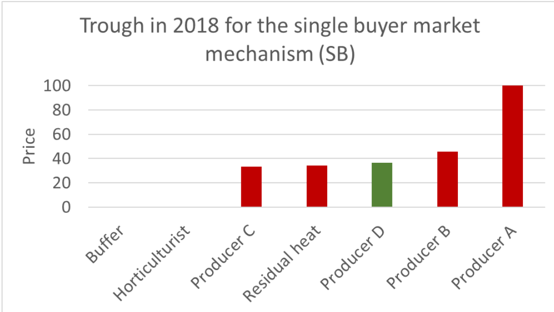

Figure 18. Merit order low demand single buyer market

Also for the SB, the merit order of the contracts does not change within a year. This is shown in figure 18, the merit order during low demand for the SB. During low demand, only producer D delivers to the network. This is remarkable since producer C is cheaper. The dispatch during low demand for the SB shows (figure 19) that the horticulturists are also on the move. Producer C and the horticulturalists supply the same distribution network, thus pushing each other out of the market. You can also see that buffer and producer D are supplying heat to the system during this time.

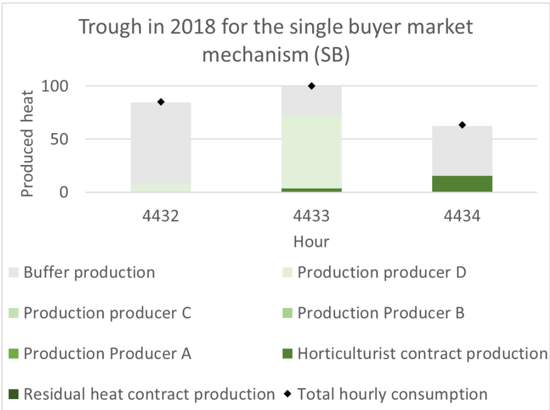

Figure 19. Dispatch single buyer during low demand

The discussion of the merit order and dispatch provides insight into the model behaviour and follows the expected patterns. In addition, the behaviour of the market models and outcomes were reviewed and tested with experts from Eneco in the heat sector. This demonstrates that the models model the behaviour as intended and expected.

B. Base case comparison of market mechanisms

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 M.P.I.'s (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 represent negative desired value, and a high score represent 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 M.P.I.'s. Figure 20 shows the results of the different market mechanisms. Besides, the error bars show the impact of Leiding door het Midden on the base cases.

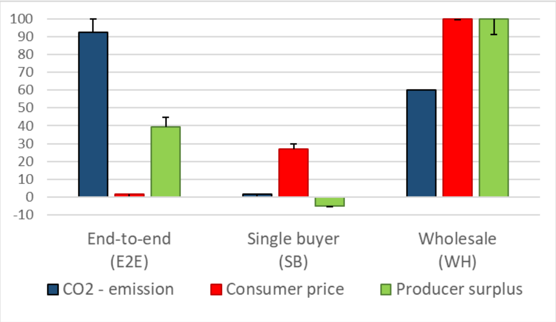

Figure 20. Base case comparison

These are the most important findings from the base case comparison (figure 20):

- 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.

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 M.P.I.'s. Moreover, it appears that the wholesale market functions quite efficiently.

C. Brief overview of impact of investment decisions

Figure 21 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 is outstanding. 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.

Normalisation of the Snapshot 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 *D. In depth analysis of M.P.I's.*

	Consumption low & Reference price scenario	Vondelingen-plaat Off	Vondelingen-plaat On	Vondelingen-plaat Off	Vondelingen-plaat On	Vondelingen-plaat Off	Vondelingen-plaat 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 21. Snapshot impact investment decisions 2023

Several trends stand out in Figure 8:

- 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.

The snapshots of 2030 and 2040 of the investment decisions are not shown. They further accentuate the trends shown in Figure 21.

D. In depth analysis of the impact the market mechanisms on the M.P.I's

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. This section only discusses one market performance indicator per year because the trends do not differ much over the years.

D.1. Consumer price in 2023

Figure 22 shows the impact of the three market mechanisms in 2023 on the consumer price. Trends which stand out are:

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

For the full comparison of market mechanisms The Vondelingenplaat has a significant impact on the E2E market because a relatively large amount of

		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"	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

Figure 22. Full results of the impact of the market mechanisms and investment decisions on the consumer price in 2023

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 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.

D.2. Producer surplus in 2030

Figure 23 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.

The reverse trends between the contract markets (E2E & SB) and WH can be explained because of the manner of settlement. 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.

D.3. CO_2-emission in 2040

The influence of investment decisions and market mechanisms on CO_2-emissions (Figure 24) shows two trends:

		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 23. Full results of the impact of the market mechanisms and investment decisions on the producer surplus in 2030

		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 24. Full results of the impact of the market mechanisms and investment decisions on the producer surplus in 2030

- Consumption affects the emissions noticeably for all three market mechanisms
- Once again, the combination of Vondelingenplaat and Leiding door het midden has a positive impact on the E2E market mechanism.
- 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.

The third phenomenon can be explained by the following; 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.

7. Discussion

This study has successfully compared three market mechanisms on three market performance indicators. This comparison showed that the single buyer market is actually the worst functioning market. This is in sharp contrast to what has been researched in the literature. The single buyer market is the most implemented of all markets and the most researched. This suggests that it must be a well-functioning market. As mentioned in the literature, it is difficult to just apply market mechanisms in a heat system. Therefore, it is possible that this explains the difference. First of all, the heat system in the province of Zuid-Holland is of a regional nature. In addition, the literature mentions that a lot of regulation is needed in a single-buyer market because, after all, it is a monopolist. This may mean that the negative effects of producers' surplus are remedied by regulation. In addition, one of the limitations of this study is that no contracts are negotiated in a single buyer market. This could also mitigate the problem of producer surplus.

The wholesale market has also been tested several times on the network as a market mechanism. However, this was with producing units that had electricity as their main commodity, where heat is a by-product. This research uses heat as a main commodity. However, the results show that the markets function in the same way. This means it does not matter what the main commodity is. However, it is not known what will happen if both are seen as main commodities and there is scarcity of both commodities.

Finally, this research has made it possible to model institutional agreements such as contracts. The influence on consumer price and producer surplus, among other things, has been examined. However, this can be extended to parameters of Sarma & Bazbauers (2016) who in their research into an existing SB heat market investment incentives and overinvestment risks have investigated. By taking into account the ideas of this research, more insight into market influences can be gained.

8. Conclusion

This investigation shows no best market mechanism. The single buyer market is underperforming compared to the other two markets. Therefore, when implementing the market mechanism, a balance must be made between the performance of the end-to-end and wholesale markets.

This study shows that the measurable indicators are CO_2 emissions, consumer prices and producers surplus, which allows the market mechanism to be compared. In addition, the similarity between the market mechanism and the market mechanism are market operations. However, when it comes to dispatch and settlement, there are differences between the market mechanisms. This makes it possible to simulate these models separately from each other and to compare them.

The results show that the market mechanism functions and reacts as intended. The Wholesale market is highly sensitive to price scenarios because it has a dispatch at cost price. The Single Buyer market is less influenced by the price scenarios because it contains contracts. However, the order of these contract prices is optimised. And last but not least, the end-to-end market, which is not very dependent on the price scenarios because the merit order of the contracts is fixed. The end-to-end market mechanism appears to be very sensitive to the growth in consumption. This is because the contracts offer a certain amount of power. If the capacity of one contract is exceeded, the next contract is immediately called up for production. In which case the price changes. In comparison, the single buyer market is moderately influenced by the method of dispatch and the wholesale market the least. The influence of the investment plans also reflects what has just been described above about the influence of price or consumption scenarios. On the single buyer market, both scenario variables have a mediocre influence, and this can also be seen in the implementation of the assets, which also have little influence on the improvement of the market performance indicators. But because the Vondelingenplaat delivers more power to the system, the influence on the end-to-end market mechanism is significant. Leiding door het midden, on the other hand, provides a link between two district heating systems so that cheaper units can now also deliver heat in The Hague. This makes it beneficial to the wholesale market mechanism.

9. Further research

Because this research has shown that institutional agreements can be simulated with dynamic forms, it is interesting to look further at other institutional agreements that have an influence on market forces. This could include research into the influences of subsidies, CO_2 pricing systems, demand response, etc.

Further research into contracts negotiated for the single buyer market can provide insight into the actual performance of the single buyer market mechanism.

In addition, mixed integer linear programming can be used to conduct research into other contract markets, structures and mechanisms. To see whether it is also possible to simulate the institutional arrangements in these systems and what the usefulness of these simulations are. For example, subsidies can be tested on the basis of these models. If the government wants to subsidise biomass, they can investigate the difference in the use and effect of this subsidy on the market. For example, they can determine how high the subsidy should be, but also whether it will serve sustainability objectives such as CO2 emissions.

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