LEARNING AND COMPETITIVE BEHAVIOUR IN DISTRICT HEATING NETWORKS

AN AGENT-BASED SIMULATION STUDY TO EXPLORE THE INFLUENCE OF LEARNING AND COMPETITIVE BEHAVIOUR BY ACTORS IN OPEN DISTRICT HEATING NETWORKS IN THE NETHERLANDS

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Abstract

To decrease the dependence on fossil fuels and strive for a more sustainable heat provision in the Netherlands, district heating is a solution. Although district heating networks are not novel, the Dutch ministry of Economic affairs desires a change in the district heating sector: 'open' district heating networks in which competition between multiple heat producers is introduced. In order to allow access for multiple (new) heat producers and fair competition a suitable market design is required. An agent-based model of a competitive market design is created to explore how multiple heat producers and greenhouse owners (as consumers) will behave, learn and adapt in open district heating networks. Results shows that in an open district heating network with insufficient supply and elastic demand, strategic behaviour of greenhouse owners prevents producers from exercising their market power and the ability to drive market prices up. However, this behaviour is only possible in theory since in an actual district heating network, producers will respond aggressively on strategic behaviour of greenhouse owners to prevent them to influence losses in profits for producers. Further research needs to include sufficient production capacity in a network to explore whether greenhouse owners are still able to predominate producers' strategic behaviour. In addition, further research should include greenhouse owner acting as both producers and consumers and allow them to trade heat between each other.

Keywords: District heating; Competition; Bidding strategy; Agent-based modelling, Learning agents

1. INTRODUCTION

According to the Dutch Ministry of Economic Affairs (2015) the focus on sustainable heat provision is necessary to realize a completely sustainable energy system in 2050. In 2012 more than half of the total energy consumption in the Netherlands is due to demand for heat (CE Delft, 2016). Currently, most heat demand is provided by combustion of fossil fuels, such as natural gas. To decrease this dependence on fossil fuels and realize a sustainable heat provision, district heating is a promising alternative. District heating networks are not novel since in 2009 already 13 large-scale and 7.000 small-scale district heating networks were in use all over the Netherlands (CE Delft, 2009). But with the Dutch Heat Vision, Minister Kamp (2015) introduces a new topic for the district heating sector. He suggests to create 'open' district heating networks in which competition between multiple heat producers is introduced. In order for competition to take place, multiple heat producers are required in a district heating network. However, currently in most district heating networks only one party is responsible for heat production. Therefore, to create open district heating networks and introduce competition, access needs to be allowed for new producers.

Besides structural changes in the physical infrastructure, also changes on an institutional level are needed since different rules are required between actors when competition is introduced in district heating networks. Although extensive research has been performed on finding a suitable market design for open district heating networks, still no decision has been made (Ecofys, 2015; Ecorys, 2016; Oei, 2016; Van Woerden, 2015; Warmte Koude Zuid-Holland et al., 2015).

The aim of this is paper is to choose a market design for open district heating networks and explore how actors will behave within a competitive district heating market. To research this, an agent-based model of an open district heating network with competition between multiple heat producers and greenhouse owners is created to determine the influence of learning actors in a competitive district heating market.

This paper is structured as follows. Chapter 2 briefly explains how the introduction of competition influences current district heating networks. After that, Chapter 3 explains the methodology of evaluating a competitive market design and the influence of learning actors. In Chapter 4, two experiments are proposed to explore the influence of learning actors. In Chapter 5, results of the experiments are discussed. Lastly, in Chapter 6 conclusions are drawn on the influence of learning actors in a competitive district heating market.

2. COMPETITIVE DISTRICT HEATING MARKETS

Currently, in most district heating networks in the Netherlands, one heat producer is responsible for the production of heat in a district heating network. Besides one producer, only one supplier (single supplier) is responsible for buying heat from the producer, transportation and selling heat to consumers. The single supplier is often the owner of the network as well. Due to high capital cost for district heating infrastructure it is economically not efficient to construct a new district heating network when there is already one. Therefore, the single supplier has a monopoly position since he determines which producing party he allows access to the network (Ecofys, 2015). Besides that, district heating suppliers are often vertically integrated companies since they operate the grid and produce heat. Introducing competition in existing district heating networks ensures that the owner of the network will probably prefer supply of his own heat above other suppliers. To prevent owners of district heating networks to hinder access for new actors, the Dutch government needs to interfere.

Literature states, that effectiveness of competition in a market is influenced by the provision of regulated or negotiated 'Third Party Access' (TPA) since it determines the competiveness of supply and the development of trade (Correljé & De Vries, 2008). According to Söderholm & Wårell (2011) generally TPA implies that "a third party can access the district heating networks in a non-discriminatory way". Access conditions can be regulated in two ways: negotiated third party access and regulated third party access. The effectiveness of negotiated third party access can be questioned, since the owner of the network can simply decide to not grant access to a certain heat producer since he cannot be forced by a regulator or other party to allow access. Therefore, regulated third party access seems required for district heating networks since the owner of the network then has the obligation to connect a producer that asks for access to the network. Besides access conditions, Correljé and de Vries also define the degree of unbundling of the networks from competitive generation is an important design variable since it prevents owners of networks to hinder access for new actors. A comparison can be made with the electricity sector since intervention of the government was required to facilitate competition in electricity markets. In 2006 the act 'Independent Grid Operation' ('Splitting's') ensured that energy companies were forced to split activities as electricity supply from the ownership of the electricity network. This ensured that the electricity network is owned by an independent organization, Tennent, which needs to allow every electricity producer access to the network to feed-in electricity and use the grid to supply electricity to consumers. Liberalization in the electricity sector required decoupling of several parts in the value chain into independent entities (Künneke, 2008). Just as in the electricity sector, district heating networks are considered natural monopolies, which might ensure conflict between the owners interest in providing equal conditions for (new and) all network users.

So based on literature, it can be concluded that an institutional environment need to be chosen that regulates third party access on a whole sale level and unbundles ownership of the network from other activities as heat production or supply. When the Dutch government enforces these rules and laws, it is unknown how actors will behave, learn and adapt within this market design. The project 'Leiding over West' is chosen as a case study to explore the influence of learning actors in a competitive market design. The project 'Leiding over West' is a district heating project with the objective to connect residual heat from the Rotterdam Harbour to greenhouse owners and residential consumers in the region Westland. Currently, greenhouse owners buy gas and use their boiler and/or a combined heat and power (CHP) installation to burn gas and receive heat and CO_2 which is required for the production of their crops. This research includes only greenhouse owners as consumers since they are able to participate in a whole sale market directly and are able to produce heat by different means which increases the competition with producers and between consumers.

3. METHODOLOGY

Since competition between multiple heat producers and large consumers has not been introduced in current district heating networks, it is unknown how actors will behave and interact with each other in a competitive district heating market. An agent-based model (ABM) is a suitable modelling approach to explore to what extent free market forces able to facilitate trading of heat between competing producers and greenhouse owners. Especially in situations where agents learn and adapt, show strategic behaviour, form alliances or cooperate and where it is unknown how the past predicts the future, agent-based modelling is recommended (Siebers, Macal, Garnett, Buxton, & Pidd, 2010). This chapter describes the conceptualisation of the competitive district heating market (section 3.1) and how this is translated into the agent-based model (section 3.2).

3.1 CONCEPTUALISATION

To conceptualise an agent-based model for a competitive district heating market as described in section 2, several core assumptions are made.

A district heating market needs to be created where producers and greenhouse owners are able to trade heat on the short-term and facilitated by only market forces. Greenhouse owners' demand for heat depends on many external influences as the outside temperature, radiation of the sun and more. They are characterised by their varying demand over the year, but also over the day. Therefore, a spot market facilitates heat trading purposes in the district heating network in the model.

The district heating network consists of two regions, A and B, which are connected by one pipeline infrastructure. Both producers and greenhouse owners are distributed between both regions. Due to high transportation losses of heat, is it more expensive for a greenhouse owner in region A to buy heat from a producer in region B. Therefore, it is most optimal when producers and greenhouse owners in the same region trade heat. However, when there is a shortage of heat and the more expensive heat from a different region still qualifies, heat is transported between regions. Therefore, supply and demand is first matched within a region (local market) by a local market operator. In case a local market cannot be cleared, or a local market can be cleared but capacity or demand remains, producers and greenhouse owners can participate in the regional market since the regional market facilitates heat trading between regions. This ensures that the regional market is cleared by a regional market operator after the local markets are both cleared. No limitations are set in the regional market concerning the capacity of the pipeline between region A and B. This allows an unlimited amount of heat to be transported between regions.

Since this research focuses on market forces, ownership and transportation cost are not included. Therefore, access to the district heating infrastructure is allowed to multiple producers and greenhouse owners and the owner of the network does not charge them for the use of his network.

The electricity, coal and CO_2 price are of importance for a producer to calculate the production cost and determine the price he wants to receive in the heat market (Wetzels, van Dril, & Daniels, 2007). For a greenhouse owner the electricity and gas price determine the price he is willing to pay in the heat market. Therefore, full information about the aforementioned prices is given to all actors. Although actors have perfect information on the electricity price etc., they have no knowledge about the bidding strategies of producers or other greenhouse owners.

Based on the electricity price, (amount of fuel and fuel cost) and technical performance of his plant, a producer agent calculates his production cost. These costs represent the minimal price he wants to receive for his heat in the heat market. As mentioned in Chapter 2, greenhouse owners are able to produce heat on their own when they have a boiler or CHP installation (VROM-inspectie, 2010). To explore the influence of a boiler and CHP on the market outcomes it is interesting to distinguish greenhouse owners according to their facilities. Therefore, it is assumed that all greenhouse owners have a boiler, and only half of the greenhouse owners has both boiler and CHP installations. Also for greenhouse owners, their production cost for heat determine the price they are willing to pay for heat in a district heating market.

So, actors start with a bidding strategy which ensures that the price they are willing to receive or pay for heat equal to their production cost. However, due to bounded rationality and opportunistic behaviour they continuously want to optimize their profits. A different bidding strategy might be required to increase profits. Therefore, actors are allowed to change their bidding strategy.

3.2 INITIALISING THE AGENT-BASED MODEL

The core assumptions described in section 3.1 provide a general working of the ABM, but are not specific enough to perform the model simulation. Therefore, this section explains several important specification of the ABM.

Important considerations are the length of the simulation period and the time step. Greenhouse owners are characterised by their varying demand for heat during the day, but also during the year. To capture these variations a balance is found between time step and length of the study period. To include the daily variation of greenhouse owners, the chosen time step is an hour. However, choosing a simulation year of a year to include yearly variations in heat demand, the amount of calculation increases enormously. Therefore, it is chosen to simulate 12 days, representing every month in a year. So day 1 represents the month January, day 2 February and so on.

Currently, only a limited number of eligible heat producers is able to feed in heat in a district heating network (Oei, 2016). Therefore, the number of heat producers in the ABM is set at 3; one coal fired power plant, one geothermal installation and one industry plant. The capacities of the heat producers are respectively 300 MW_{th}, 20 MW_{th} and 75 $MW_{th,}$ (Nationale Energie Atlas, 2016; Uniper Benelux, 2016; Vermeulen & Waal van der, 2013). All three producers are located in region A. The region Westland contains roughly 1600 greenhouse owners, which is used as reference for the number of greenhouse owners (Hordijk, de Bruijn, Hylkema, Duijvestijn, & van der Hoeven, 2014). The number of greenhouse owners is set at 2000: 1000 are located in region A and the other 1000 in region B. In comparison with the total heat capacity of 395 MW_{th} in the network, the average greenhouse owners demand is 455 MW_{th}.

Every producer calculates his marginal production cost and uses this cost to set his bidding price. The bidding quantity is equal to the production capacity of the agent. Both bidding values combined lead to a bid containing a bid price and bid quantity as shown below.

$$[Bid_{price}\ , Bid_{quantity}]$$

with Bid_{price} = Bid price [€/MWh_{th}]
$Bid_{quantity}$ = Maximum heat production [MWh_{th}]

A greenhouse owner also calculates how much it cost to produce heat by using his boiler or CHP installation. These marginal production cost determine the bid price and his demand determines the bid quantity. In Bijvoet (2017) a specific explanation is given on how actors calculate and determine their bidding prices.

4. EXPERIMENTAL DESIGN

To explore the influence of learning agents in a competitive district heating market, two experiments are performed with the agent-based model (ABM) as explained in section 0. First, section 3.1 explain the experiments in more detail. After that, section 3.2 presents the performance indicators to measure the performance of the experiments.

4.1 EXPERIMENTAL SETUP

The first experiment allows both producers and greenhouse owners to learn and adapt their bidding strategy. For the first bidding (Day 1 00:00) none of the agents has received any information from a local or regional market operators, so producers and greenhouse owners are not able to learn yet. Therefore, the bidding prices for their first biddings are equal to the calculated marginal production cost. From then on, agents are able to learn since they receive information about the market price and quantity. The decision to change a bidding strategy differs between producer and greenhouse owner agents. A producer's bidding strategy depends on the following aspects:

- ***Production previous bidding***

Since a producer wants to receive a high price for his heat production, he continuously increases his bidding price for the next bidding. Literature about gaming in energy markets shows that if electricity generators exceedingly increase their bidding prices, they will sell smaller quantities, resulting in lower profits (Visudhiphan & Ilic, 1999). This ensures that generators stop increase their bidding prices when they are satisfied with their profits. Based on this, a producer agent in this research decrease his bidding price for the next bidding when less than 70% of his production capacity is sold.

- ***Highest received bidding price***

A producer remembers the highest bidding price with which he was able to sell more than 70% of his production capacity. When he decides to increase his bidding price a random value between 0 and 10% is added to this highest bid price. When an agent decreases his bidding price, a random value between 0 and 10% is subtracted from the highest bid price.

- ***Estimated heat demand***

Producers are able to predict greenhouse owners' heat demand in an adequate way (deviation about 5% deviation). Since a producer agent knows what type and how many competitors he has, he can predict whether his production is needed during baseload or peak load. When an agent predicts that he will not be dispatched for the next hour, he does not increase or decrease his bidding price.

- ***Marginal production cost***

Since a producer agent does not want to make losses, he never decreases his bidding prices below his production cost. The decision for a greenhouse owner to change the bidding price depends on the following aspects:

- ***Received heat previous bidding***

A greenhouse owner continuously decreases his bidding price for the next bidding unless less than 70% of his heat demand is received. When a greenhouse owner is not able to fulfil more than 70% of his heat demand, he increases his bidding price for the next bidding to ensure that he will receive his entire heat demand.

- ***Lowest received bidding price***

A greenhouse owner remembers the lowest bidding price with which he received more than 70% of his heat demand. When a greenhouse owner decreases his bidding price for the next bidding, he subtracts a random value between 0 and 10% from this lowest bidding price. When the bidding price is increased, a random value between 0 and 10% is added to the lowest bidding price.

- ***Marginal production cost***

A greenhouse owner does not want to make losses, so never bids bidding prices that are higher than his production cost

In line with the first experiment, the second experiment adds one behaviour rule for greenhouse owners: greenhouse owners are allowed to collaborate with each other. Greenhouse owners are able to collaborate with other greenhouse owners to collectively bid low prices in the heat market in order to prevent producers from increasing the market price for heat. Every greenhouse owner is connected to 10 other greenhouse owners in the region. When a greenhouse owner learns that producers are influencing the market price, he asks greenhouse owners in his network to collaborate and jointly bid lower prices in the next bidding. Since not every greenhouse owner is willing to collaborate and fierce competition between greenhouse owners exist, it is assumed that only 20% of his network is persuaded to join a collaboration. A greenhouse owner has two reason to stop with a collaboration:

- The market price for heat is equal to the bidding price of a greenhouse owner. This happens when heat is scarce and the market increases to the bidding price of a greenhouse owner, which indicates that a lower bidding prices can be offered.
- A greenhouse owner has not received any heat during two successive hours.

4.2 PERFORMANCE INDICATORS

The performance of the experiments with learning actors in a competitive district heating market is determined by four performance indicators:

- ***Price for heat [€/MWh$_{th}$]***

This performance indicator is of importance since it determines to what extent a competitive district heating market is able to provide affordable heat for greenhouse owners. Affordability is an important indicator to determine the energy security in energy systems (Hughes, 2012). The price for heat is calculated by dividing the total cost made by greenhouse owners by the total production of heat.

- ***Market share [%]***

To provide insights on the competition between producers, a market share is required. A producers' market share shows the share of his production is comparison with the total production in the network.

♦ ***Production/demand ratio [ratio]***

Reliability of the district heating supply is an important indicator for the successfulness of the system (Ministerie van Economische Zaken, 2015). Therefore, this performance indicator shows to what extent the heat production in the network is able to meets greenhouse owners' demand.

♦ ***Profit [€]***

Learning and competitive behaviour is caused by actors' willingness to optimize their profit rates. Therefore, this performance indicator calculates the profit made by each actor and shows how an agent is able to perform under certain market conditions. Producers' profit is calculated by multiplying the total production with the difference between the received market price the marginal production cost. For a consumer, the performance indicator saving is more appropriate since if not received any heat in the heat market, natural gas is bought. The savings are calculated by multiplying the total received heat with the difference between the production cost minus paid market price.

5. RESULTS

To determine the influence of learning and competitive behaviour in open district heating network the results for the two experiment are compared with a base line experiment (experiment 0) in which agents are not able to learn and change their bidding strategy. All four performance indicators are presented and discussed in this section.

PRICE FOR HEAT

The average price for heat in the network during the entire simulation period is shown in Figure 1. As explained in Chapter 3, 12 individual days are simulated, representing every month in a year. So day 1 represents the month January, day 2 February and so on. Since the simulated days are not consecutive days, the results are shown for every day separately. In addition to Figure 1, the average price for heat per year is shown in Table 1. The ability for agents to learn and adapt their bidding strategy ensures a decrease in the average price of heat. In experiment 1, without collaboration between greenhouse owners, a decrease of 28% in the average price is realized due to strategic behaviour by actors. When greenhouses are able to collaborate, in experiment 2, a decrease of 32% in the average price for heat in a year in realized.

MARKET SHARE

Based on the results shown in Table 2, it can be seen that actors' ability to change their bidding strategy, ensures a small increase in the market share of the industry plant and geothermal installation, and a decrease in the market share of the coal fired power plant. However, these changes are only caused by the fact that the total production per year of the coal fired power plant is decreased. This ensures that the other two type of producers are responsible for a larger part of the total production per year. Therefore, these results for this performance indicators are not very useful since the market power between the three producers has not really changed.

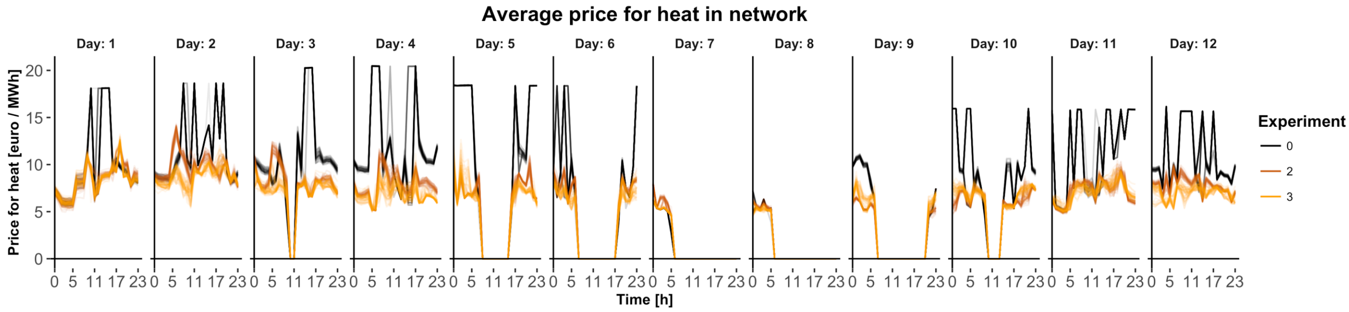

Figure 1: Average price for heat in network

Experiment	Average heat price per year [€/MWh$_{th}$]	Difference [%]
0	7.92	
1	5.73	- 28
2	5.73	- 32

Table 1: Average price for heat per year in network

	Market share		
Experiment	*Industry plant*	*Geothermal installation*	*Coal fired power plant*
0	0.22	0.06	0.72
1	0.26	0.07	0.67
2	0.27	0.07	0.66

Table 2: Market share for each type of producer

PRODUCTION/DEMAND RATIO

Based on Table 3, it can be concluded that the production/demand ratio decreases when agents perform strategic behaviour. When agents are not able to change their bidding strategy (and supply is sufficient) every greenhouse owner receives heat from the heat market since they are willing to pay a price that is much higher than the production cost of the marginal producer. However, when agents are able to change their bidding strategy, a greenhouse owner decreases his bidding prices until he learns that this bidding price was too low and not receives heat from the heat market. Since every agent learns on a different time in the year, there are always greenhouse owners who bid a price lower than the production cost of the marginal producer. This results in a lower production/demand ratio compared to a network in which agents are not able to learn.

Collaboration between greenhouse owners ensures that a greenhouse owner is willing to accept that his bidding price might be too low and ensures that he does not receive heat from the heat market. This collaboration needs to force the coal fired power plant to decrease his bidding price to ensure larger production quantities. However, due to changing electricity prices, the marginal production cost of the coal fired power plant vary. But since greenhouse owners have no information about bidding prices of producers, they often bid prices that are lower than the marginal cost of the coal fired power plant. This ensures that the coal fired power plant produces smaller quantities and a decrease in the production/demand ratio when greenhouse owners collaborate.

Experiment	**Production/demand ratio per year** [ratio]	**Difference** [%}
0	0.55	
1	0.47	- 15
2	0.45	- 18

Table 3: Production/demand ratio in network

	Difference in total profits per year [%]			
Experiment	*Industry plant*	*Geothermal installation*	*Coal fired power plant*	*Greenhouse owners*
1	-39	-48	-65	16
2	-38	-47	-77	29

Table 4: Difference in total profits per year

PROFIT

Based on hourly profits producers and greenhouse owners make, the total profits during the simulation period are shown in Table 4. Due to the insufficient production capacity in the network to meet greenhouse owners' demand, heat is often scarce. Scarcity of heat ensures that the market price is equal to the bidding price of greenhouse owners. When agents are able to learn, greenhouse owners decrease their bidding prices and as a result the market prices (scarcity prices) decrease as well. Therefore, strategic behaviour of greenhouse owners in the simulation model prevents producers to exercise their market power and drive market prices up. However, in an actual district heating network producers will not allow greenhouse owners to predominate their own strategic behaviour. Producers will ask a price that is just below the production cost of a greenhouse owners in order to prevent greenhouse owners from decreasing their bidding prices.

6. CONCLUSION

Based on the results in chapter 5, the following conclusion can be drawn. In a district heating network with insufficient supply and elastic demand, strategic behaviour of greenhouse owners prevents producers from exercising their market power and the ability to drive market prices up. However, in an actual district heating network producers will prevent greenhouse owners from predominating their own strategic behaviour by aggressively increase the price they want to receive for their heat production. Eventually, greenhouse owners are in need for heat for the production of their crops. Although greenhouse owners have the ability to produce heat by own means, when heat is only offered for a price that is just below their own production cost, greenhouse owners will buy heat from the district heating market since that is more profitable for them in the end. Therefore, in theory strategic behaviour by greenhouse owners is able to predominate strategic behaviour of producers, but in practice producers will prevent this and exercise their market power anyhow.

Since insufficient production capacity ensures that heat is often scarce, resulting in high market prices and increasing profits of for the supply side, producers in existing district heating networks might withhold capacity to drive prices up. However, producers are only capable of withholding capacity if current bilateral contracts between produces and the owner of the network allow this behaviour. If these bilateral contracts allow withholding capacity, suitable regulation is required to prevent producers from premeditating insufficient production capacity in open district heating networks.

FURTHER RESEARCH

Actors' ability to learn and adapt their bidding strategy is only simulated in a district heating network with insufficient production capacity. Therefore, future research could explore the influence of sufficient production capacity in a network. When heat becomes less often scarce, it drives the market price down and probably limits the influence of competitive greenhouse owners. In addition, this research assumed that greenhouse owners only act as a consumer, but they are able to behave as a producer as well. Therefore, it would be interesting to explore the effect of trading heat between greenhouse owners and their dependence on large producers in the network.

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