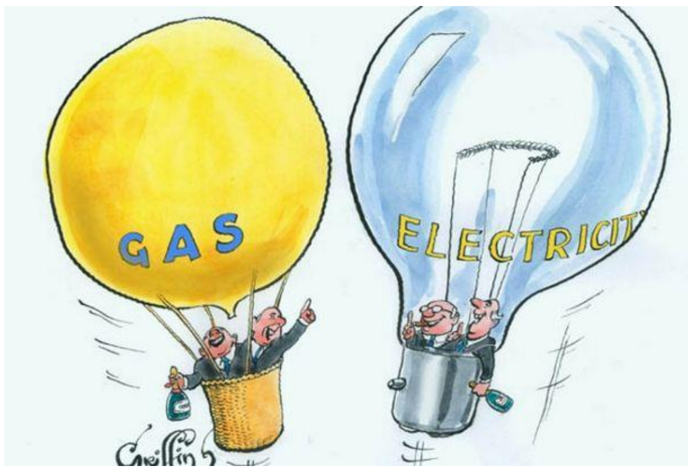
Thesis

Development in space heating using Agent Based Modelling

A collective incentive or an individual choice

Oscar Kraan



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Abstract

Heat demand in the Netherlands is responsible for 38% of primary energy use and almost half of it (49%) is used in the built environment. The EU goal to cut greenhouse gas emissions by 80-95% below 1990 levels by 2050 will impose large changes is the used space heating technology of households. The energy demand mix for space heating in the built environment will therefore change. An agent based model has been created to model the behaviour of home owners and their decision for a space heating technology. It was assumed that a space heating energy demand mix with electricity as dominant energy carrier will impose great challenges on the grid with large costs, costs that exponentially enlarge with higher demand from relatively low prices now. Clean gas, an overarching term for biogas, a mix of hydrogen and other CO_2 neutral gasses, distributed via the existing natural gas network, could lower the overall system cost for space heating as clean gas costs are assumed to go exponentially down from a high start price now. As the network can only distribute one kind of gas, this distribution is only possible when home owners decide together to use clean gas. Especially the interaction between agents possibly forming a collective incentive to switch to clean gas has been investigated to see if a gaseous energy carrier can be a sustainable energy carrier in the energy mix. The results show that a collective incentive can arise and a gaseous energy carrier can be sustainable if the price difference between clean gas and electricity is kept small. Other policy possibilities are encouraging neighbourhood interaction and forcing small neighbourhood to switch to clean gas. For this last policy option, the timing of the policy is important.

1. Introduction

Heat demand in the Netherlands is responsible for 38% of primary energy use and almost half of it (49%) is used in the built environment (Nationaal Expertisecentrum Warmte, 2013). Therefore it is not surprising that the heat supply in residential and commercial buildings is of great importance in the energy use of the built environment in The Netherlands. In the residential sector, the heat demand is three times as large as the electricity demand and it is more than twice as large in the commercial sector (KEMA, 2012) (Centraal Bureau voor de Statistiek [CBS], 2011). In the built environment, this energy demand for heating is predominantly supplied by the distribution of natural gas (Ministerie van Economische Zaken, 2012). Both the EU goal to cut greenhouse gas emissions by 80-95% below 1990 levels by 2050 (European Commission, 2012) to tackle the issues of global warming, security of supply and increasing energy prices will have serious implications for the heating technology used in the built environment.

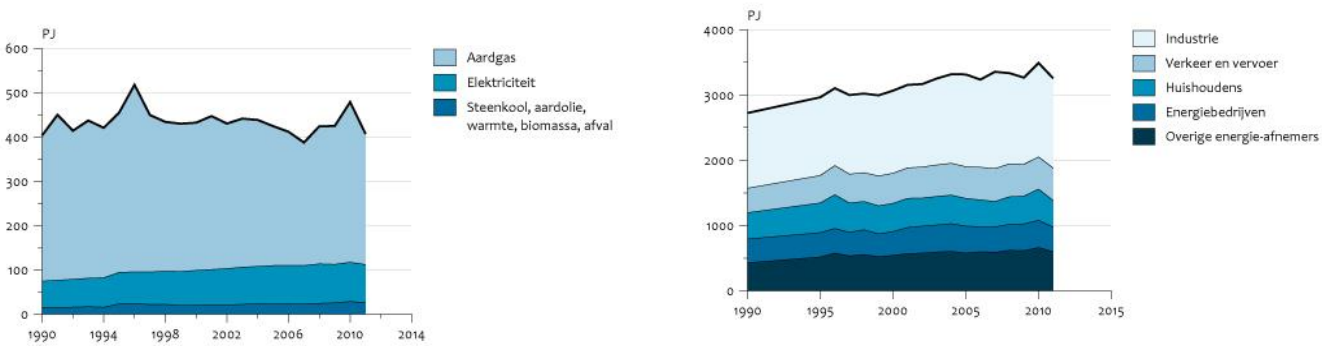


Figure 1. Primary energy use of households (left) and Primary energy use by sector (right) (Centraal Bureau voor de Statistiek [CBS], 2011)

Emissions from space heating in the built environment will have to go down and therefore the type of energy carrier we use for our space heating will change. This research aims to give insight in the role any gaseous energy carrier can play to meet the heat demand and CO_2 emission reductions in the built environment in 2050 in The Netherlands. It will identify several individual behavioural factors of building owners that shape the emergent behaviour, the energy demand mix and overall system costs. It especially addresses the choice of building owners between a collective incentive to use clean gas and an individual decision to use electricity to meet the space heating demand. As will be explained later, the choice for electricity looks at first very promising to the individual customer but the collective incentive to switch to clean gas will lead to lower overall system costs. This research will identify what behavioural factors are crucial in the different emergent system outcomes.

This problem will be modelled in a computer model with a modelling method called agent based modelling (ABM) that has a bottom up approach and aims to analyze the actions of individual stakeholders (agents) and the effects of these agents on their environment and on each other. The overall emergent behaviour follows from the behaviour of these individual agents and factors that influence the emergent behaviour of the system can be identified. (Mitchell Waldrop, 1992) (Ligtvoet, 2013).

2. Important background

The model that has been made is an abstract representation of reality. However, all assumptions made in the model about the environment and the behaviour of the home owners are based on real data about the housing and energy market. The data underlying the model can be divided in two: information about the building stock in The Netherlands and information about the heat supply to the built environment. In general Dutch data are used but when they were not available, information from other countries is used of which it can be assumed that they also apply to the Netherlands.

Building stock in The Netherlands

In The Netherlands the building stock can be categorised in three kinds of houses, (semi) detached houses, row/terraced houses and flats/apartments. Some figures about these different types of houses are given in figure 2. These houses are in 59% of the cases privately owned by the home owner (CBS, 2012) . In the model it is assumed that every house owner can decide to invest in a technology for themselves. In practice, residents that cannot decide on their own will try to convince their landlord to change the heating system but this is out of the reach of the research.

	Share (%)	Number	Floor area (m^2)	People
(Semi) Detached houses	26.2	1985041	137	2.8
Row/terraced houses	41.7	3116424	103	2.4
Flats/apartments	32	2391500	74	1.45

Figure 2. Building stock in The Netherlands (KEMA, 2012)

Housing: renovation and relocation

Relocation

Dutch residents relocate an average of seven times during their lifetimes (Planbureau voor de Leefomgeving). In 2011, 1.46 million people relocated within the Netherlands, which corresponds to one in eleven people. (CBS, 2011). Younger people tend to relocate more often than the elderly, which means that people don't relocate strict periodical.

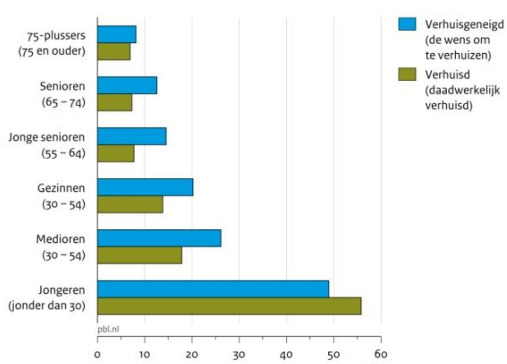
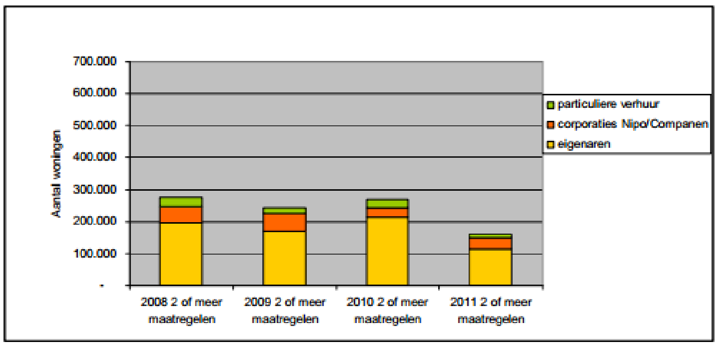
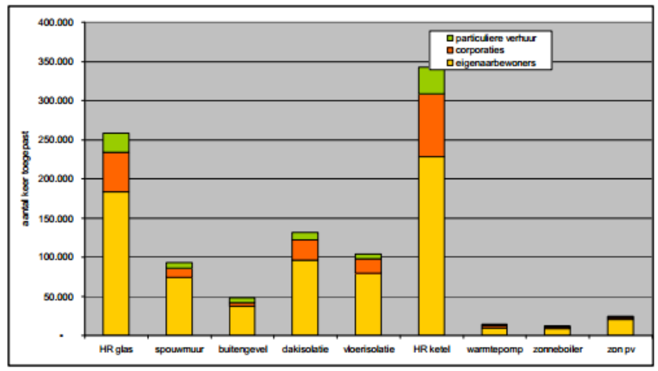


Figure 3. Relocation dynamics in 2008 (CBS, 2012).

Renovation

In the Netherlands between 2008 and 2012 each year around 200.000 out of the possible 7 million homes have been subject to substantial building specific energy saving refurbishment measures that are specific to a single building. This corresponds to around 5% of home and building owners that do substantial refurbishment each year. Changing the boiler is by far the most popular measure but because this is not a very substantial renovation, substantial refurbishment is defined as doing "more than one energy saving" measure. Home owner renovate mostly because something else in the house needed fixing or replacing (UK ERC, 2013) supporting this definition of "more then one energy saving" measure. During this period heat pumps were rarely installed. Substantial refurbishment of the building leads to an average energy bill reduction of 25%





(Agentschap NL, 2012).

Figure 4. Amount of energy saving measures taken 2012 (left) and different kinds of energy measures taken 2012 (right) (Agentschap NL, 2012)

In the last decade large efficiency gains have been reached in the last decade but because the floor area of an average home has increased, the total energy consumption has remained constant. Therefore efficiency gains have not caused energy use and CO_2 emissions to go down. This effect is called the rebound-effect. Therefore decarbonising the energy source by decarbonising electricity or using clean gas has high priority.

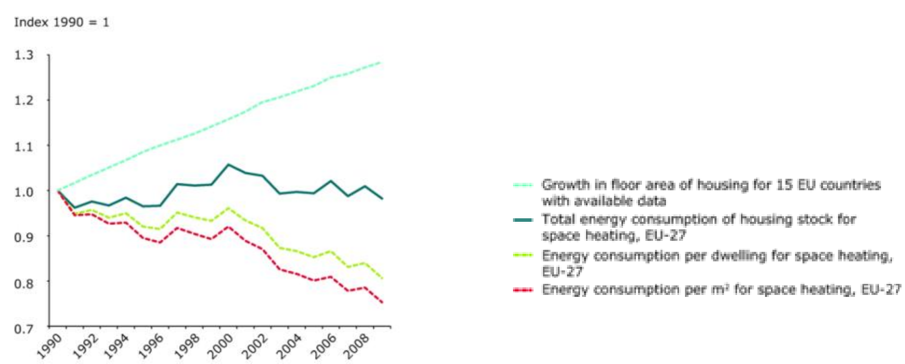


Figure 5. Trends in heating energy consumption and energy efficiency of housing (European Environmental Agency, 2012)

Heat supply in the built environment

If you look at the energy use of a house it not surprising that heating requires a lot of energy. Because energy is conserved and no energy is lost, all electric equipment uses energy in the form of electricity but disposes this energy to the environment as heat. Although this equipment uses a lot of energy and disposes this to the house as heat, this is by far not enough to warm the house. A heat system is required to produce warmth as efficient as possible.

There are several ways to heat a house. Existing buildings use predominantly a boiler that runs on natural gas for their heat supply and electricity for their appliances (Menkveld, 2009). An electric boiler is not often used because it is not very efficient, the heat lost with the production of the electricity is not disposed in the house but at the power plant. Although now a day's very rarely used (only 0,2% (Menkveld, 2009)) heat pumps are also a very effective way to heat a space.

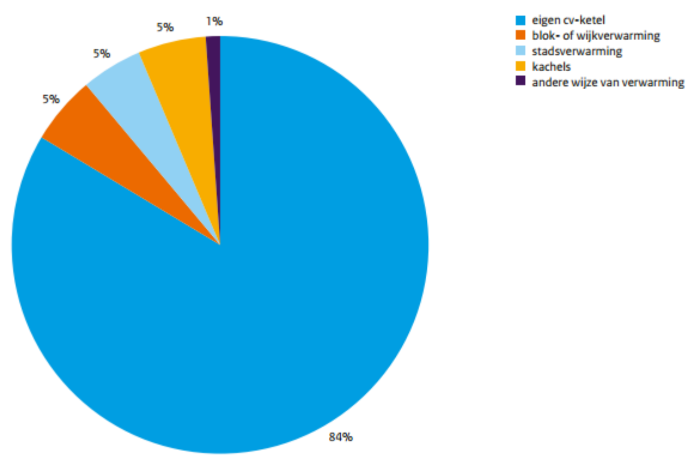


Figure 6. Share of heating technology 2009 (Ministerie van wonen wijken en integratie, 2009)

Heat pumps

Heat pumps are able to extract heat from a low temperature source to dispense it at a warm temperature source. A heat pump uses the same basic refrigeration-type cycle employed by an air conditioner or a refrigerator, but releasing heat into the conditioned-space rather than into the surrounding environment (Miles, 1993) According to the second law of thermodynamics, this transfer of heat cannot happen spontaneously and therefore heat pumps use electricity to drive this heat transfer cycle. In electrically powered heat pumps, the heat transferred can be three or four times larger than the electrical power consumed, giving the system a Coefficient of Performance (COP) of 3 or 4, as opposed to a COP of 1 of a conventional electrical resistance heater, in which all heat is produced from input electrical energy. Heat pumps can be used in all types of houses that are connected to an electricity network. They have the additional advantage that they can also be used reversely to cool a house when necessary.

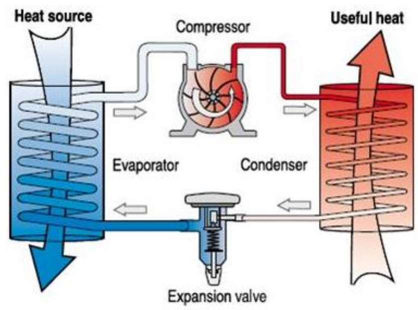


Figure 7. Heat pump (Hepisontheway, 2013)

Not investing

Home owners can have arguments why they would not invest in a new space heating technology. These arguments are given in figure 8 and are further explained in the conceptualisation of the model.

Technology	Issues found	Additional barriers to uptake
All	• disappointment in the level of fuel savings achieved • issues with the amount of disruption caused during installation	• high upfront capital costs and long payback periods and a risk of projected declines in cost not being achieved • hidden and missing costs • lack of awareness or understanding of different options • lack of suitability, particularly in terms of energy efficiency of housing • consumer confidence in new technologies • lack of credible installers and suppliers and other supply chain constraints • hassle factors associated with having work done, or for ongoing operation • concerns about ease and costs of maintenance
Heat pumps	• concerns over running costs, although this in part may reflect the switch to one heating fuel or heating the whole home • mixed views on their ease of use and ability to control • concern over noise for ASHPs • lower temperatures than desired	• uncertainty over improvements in COPs • poor installation standards • high levels of maintenance • the need for high levels of energy efficiency • the potential need for new heat distribution • the need to dig up gardens for GSHPs • failure to meet hot water demands

Figure 8. Barriers to invest in new space heating technology (Cabinet Office, 2011).

Natural and clean gas

There are several gaseous energy carriers. In Europe gas companies distribute natural gas (NG) to residential and commercial areas via an existing gas network. If natural gas is combusted it emits CO_2, the most important greenhouse gas, to the atmosphere. The network of gas pipes distributing the natural gas is able to also distribute another kind of gas (Liander, 2012).

In this study the term clean gas is used as overarching term that includes gas from biogas produced by the breakdown of organic matter, hydrogen (H_2) derived from biomass and hydrogen produced from fossil fuels with carbon capture and storage (CCS), or a mixture of these gasses. This clean gas is CO_2 neutral.

However the gas network cannot distribute both natural gas and clean gas at the same time, and therefore a gas company needs to make a choice to what gas they offer to their clients. When clean gas is offered, building owners only have to change the boiler to be able to use clean gas instead of natural gas.

Electricity

In Europe almost the entire build environment has a connection to the electricity grid. Electricity is not efficient storable in large amounts so supply and demand needs to be matched. As posed before, The European Commissioner for Energy concluded in the Energy Roadmap 2050 that electricity production needs to be fully decarbonizes in 2050 as this is assumed to be the easiest to realize (Comission, 2012). This can be done with renewable energy technologies but also with for example carbon capture and storage (CCS). When the electricity grid is fully decarbonised and the electricity demand is high, this will impose severe demands on the capacity of the grid as renewable resources are in time and space distributed differently around Europe.

Price development

The average price that consumers have to pay for their energy has risen quit dramatically in the last decades. As heat demand is a substantial part of this energy demand the energy use and which form of energy to use for heat in the built environment, are important. (CBS, 2011)

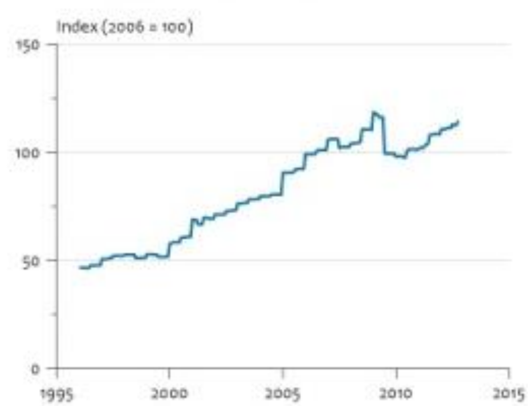


Figure 9. Consumer price index energy (CBS, 2011)

The difference between the individual choice for electricity and the collective choice for clean gas is a difference in price development. Both are assumed to be CO_2 neutral, electricity is assumed to be fully decarbonised. Regarding the price development of the overall system costs including fuel, technology and distribution investments, two pathways are distinguished, which will be used in this research

One scenario will lead to a situation where gas still has a role in the energy supply of the built environment and the other scenario ends in 2050 with all residential and commercial buildings relying on heat pumps and thus electricity for their energy supply. The development of the assumed overall system costs is shown below.

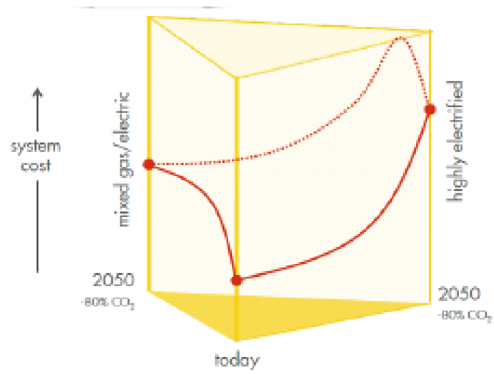


Figure 10. Overall system cost development (Prof Gert Jan Kramer, 2012)

It can be seen that the overall system costs for a mixed scenario will end up lower, although today the system cost grow faster than the scenario which is highly electrified, which ends up at higher overall system costs. As we move to a world where electricity is the main energy carrier the overall system costs will grow exponentially due to a higher electric load and subsequent investment in generation and grid capacity. The path towards a world where the system relies on electricity but where a gaseous energy carrier still distributes energy will be subject to economics of scale. The cost per unit of output generally decreases with increasing scale as fixed costs are spread out over more units of output. Often operational efficiency is also greater with increasing scale, also contributing to lower variable cost (Evans, Hunt, 2011).

Switching from a world that has developed towards a mixed energy demand mix to a highly electrified world will result in higher costs due to suboptimal grid enhancement (KEMA, 2012). Labour cost accounts for the main share of grid enhancement costs. The economic lifetime of the electricity grid is 40 years so the whole grid will be replaced by 2050. If the grid needs to be upgraded during its lifetime, the costs are higher. If there is a faster increase in preference for electricity than the replacement rate of the grid, then the situation would arise that the grid needs to be upgraded outside of its normal replacement periodicity with higher costs as result.

Collective versus individual

Psychological research in the last few decades has shown the tendency for people to adopt the opinions, judgments and behaviours of others. Social norms and the diffusion of behaviours through social networks effectively act as social vehicles to encourage the adoption of clean, green (or non-green) behaviours (Cabinet Office, 2011)

There exist several examples in the renewable industry of how a collective incentive can result in benefit for all individuals. Windvogel is one of these initiatives where members of the cooperation can give a loan (with interest) to the cooperation with which the cooperation will build windmills. Members can use this renewable energy to satisfy their energy demand (Windvogel). Other examples are Zeevogel and Energie Dongen (Dongen).

In the non-renewable industry we also see the same kind of problems. In The Netherlands a new network of high speed telecommunication made from glasfiber is unrolled. However, the distribution companies set threshold minimums on local support. Only with a minimum of interested future customers, the network will be put in place. Only with a collective incentive, the neighbourhood can enjoy high-speed telecommunication.

In the case of energy distribution for the heat supply in the built environment this is slightly different. The spatial distribution is important here as they deal with physical networks. In this case, neighbours are more important than acquaintances as neighbours can form a collective to change this physical network.

In this research it will be assumed that only when enough people in a certain area are interested in switching from natural gas to clean gas, this can be offered by a gas company. This means that only with a collective incentive people can reach an overall system cost in 2050 that is lower than when all of them make an individual choice for heat pumps and thus electricity for their energy and heat supply. This collective behaviour can arise because of agents that influence each other in the decision for an investment in a heat technology. With regards to electricity and refurbishment of their homes, this is an individual choice, which people can make for themselves.

ABM

The model has been written in a programming language called Netlogo and will be developed using the 10 steps proposed by Igor Nikolic in Agent-based modelling of socio-technical systems (Nikolic, Dam, Lukszo, 2013). The ten steps include

1. Problem formulation and actor identification
2. System identification and decomposition
3. Concept formulisation
4. Model formalisation
5. Software implementation
6. Model verification
7. Experimentation
8. Data Analysis
9. Model validation
10. Model use

The ten steps that have been described by Nikolic, will be used and at some point changed to accommodate the specifics of this agent based model.

Agent based modelling is a relatively new approach to model complex systems composed of interacting, autonomous “agents”. Besides elements of game theory it also consists of elements of complex systems, emergence, computational sociology and multi-agent systems. Agents have behaviours, described by simple rules and they have interactions with other agents, which in turn influence their behaviours. By modelling agents individually, the full effects of the diversity that exists among agents in their attributes and behaviours can be observed as it gives rise to the behaviour of the system as a whole (Macal, North, 2010). These emergent phenomena result from the interaction of individual agents. An emergent phenomenon can have properties that are decoupled from the properties of the consisting parts (Bonabeau, 2013).

By modelling systems from the ground up, agent by agent and interaction by interaction, self-organization can often be observed in these models. The emphasis on modelling the heterogeneity of agents across a population and the emergence of self-organization are two of the distinguishing features of agent based simulation as compared to other simulation techniques.

Netlogo

The model that has been created in Netlogo. NetLogo is a multi-agent programmable modelling environment. (Wilensky, 1999) It is a free program that allows easy implementation of agent based models (Nikolic et al., 2013). It is used by tens of thousands of students, teachers and researchers worldwide. It is authored by Uri Wilensky and developed at the The Center for Connected Learning (CCL) and Computer-Based Modeling of the Northwestern University in the United States of America.

R

For the analysis of the experiments the analysis software R is used. R is a language and environment for statistical computing and graphics. R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering) and graphical techniques. One of R's strengths is the ease with which well-designed publication-quality plots can be produced, including mathematical symbols and formulae where needed. R is available as free software on the website http://www.r-project.org/, more information is found there too.

3. Problem formulation and actor identification

Problem formulation

CO_2 emissions from space heating need to go down because of the emission reduction targets proposed by the European Commission. A study by KEMA (KEMA, 2012) commissioned by Shell shows two possible scenarios, a “mixed” scenario in which a gaseous energy carrier is still important and a “all electric scenario” in which decarbonised electricity will be predominantly used for space heating.

In comparison with a energy system where electricity is the dominant energy carrier in the energy demand mix for space heating, a energy system that depends on the distribution on clean gas for space heating has lower overall system cost, as proposed earlier. The assumption is that the development of clean gas will need a collective incentive to switch to clean gas as it is more expensive at first but less expensive if more home owners use it and the opposite holds for electricity as the grid will need a substantial upgrade to supply enough electricity which lead to higher cost at higher demand. Therefore this research will answer the following question:

What factors will be crucial and what influence do they have on the heat system technology choice of households in the decision between a collective incentive for clean gas or an individual choice for electricity as energy carrier for space heating.

And following this, the research will answer the question:

What consequence does this have on the sustainable usage of a gaseous energy carrier in the energy mix in 2050 under the assumption that CO_2 emissions will have to go down by 80% in 2050.

This problem will be modelled in an agent based model where residential citizens and commercial building owners will be modelled as home owners. These home owners will individually make decisions in which technology they invest for the heat supply in their buildings, depending on their behaviour, their neighbours and their restrictions outside of the agents behaviour. This will lead to different energy demand mixes over time and possibly emergent behaviour of the overall system.

By changing the home owners’ behaviour and their environment several experiments have been done to observe what factors are important in the different possible emergent behaviours following from technology choices made by home owners. This is reflected in the energy demand mix and overall system costs in 2050 for varying behavioural factors of the home owners and their environment.

Choice of technology

In this model, agents can choose between two main technologies, heat pumps on electricity or boilers using clean gas. Both scenarios in the study by KEMA (KEMA, 2012) supported an uptake of district heating in 2050 where it would make 20% of the energy demand mix. Therefore, in this research district heating is not taken into account as its share in the energy demand mix is very consistent over the different scenario's. This research will only look at the system behaviour in regards to the question whether to use clean gas or electricity as energy carrier for space heating.

Also the costs of the different technologies choices has been outside the scope of this research.

Why an agent based model?

In the introduction, ABM is been briefly discussed. Because the individual choice of heterogeneous agents that leads to individual or collective behaviour of the overall system is the main subject of this research ABM has been used as it has been proven to be particularly useful in these cases (Macal, Cm et al, 2010).

The application of different modelling methods regarding different problems and questions, have been investigated in several studies (Ligtvoet, 2013) (Chappin, 2011) (Yucel, 2010). One of the premises of ABM is that there is sufficient knowledge to model individual decision making. This is the case in this research, as research has been done on home owners behaviour with regards to space heating and home owners can decide between several distinct heating technology systems. (Ligtvoet, 2013). Other paradigms such as system dynamics, computational general equilibrium and dynamic system amongst others are not focused on decisions of individual agents which is the core of the transition this research wants to model. The fact that the problem involves physical components (the different networks), social components (social behaviour of mutual agents), interaction amongst agents, emergent system structure (an electrified world or a mixed world) makes ABM the ideal modelling method for this problem (Chappin, 2011). Besides that, the fact that in this research agents exhibit complex behaviour, including learning and adaptation (which will become clear later), suggests that ABM is the modelling method to use (Bonabeau, 2002).

Requirement	ABM	SD	DS	DES	CGE
Need to have					
Physical components	+	?	+	+	+
Social components	+	?	-	+	?
Interactions	+	?	+	+	?
Emergent system structure	+	-	-	-	-
Evaluation of policy design	?	?	-	?	?
Specific new insight	+	+	+	+	+
Nice to have					
Existing models	+	+	-	+	+
Modularity	+	-	-	?	+

Score on requirements for modelling paradigms (ABM=agent-based model, SD=system dynamics, DS=dynamic systems, DES=discreet event simulation, CGE=computational general equilibrium).

Figure 11. Different modelling paradigms and their requirements

From abstract model to reality

As Ligtvoet poses, one of the pitfalls of ABM is in thinking that detail leads to better insights. Often the model needs to remain somewhat abstract to render it tractable (Ligtvoet, 2013). Therefore the research problem has been addressed in an abstract model. This means that figures are normalized and real data are only rarely used. Only residential home owners are considered, which only have one type of house.

This research is based on the Dutch situation, but because of the abstraction and the adaptability of the model it can also be applied to other countries such as the UK and Germany with in general the same specifics such as the behaviour of consumers and price development. Of course the model uses a highly stylized abstraction of reality but by making the model this abstract it can show what factors can be crucial and what arguments can be produced in the analysis of realistic systems.

To make a clear playing field a few important concepts have to be discussed first.

Lack of insight

The lack of insight which has been addressed is what factors influence the decision by home owners for a particular space heating system which is more costly at the end but cheaper upfront and how this can be avoided by cooperating with other agents at an earlier stage.

Observed emergent pattern

The observed emergent pattern is that, starting from the situation where home owners in The Netherlands are now, using a boiler fuelled by NG and electricity from the net for their appliances, they will tend to invest in the cheapest option for their heat supply, while not looking ahead at price development. This option will be a refurbished house with heat pumps using electricity. Investing in heat pumps and to use electricity for their heat supply is relatively cheap at first and the decision to use clean gas is only possible with a critical density of home owners willing to invest in clean gas is reached. When many people make the transition to this all electric situation, the electricity price will rise as will be explained later. Because the home owners already made their decision and their investment they are stuck in this situation and have to accept this price development.

Desired emergent pattern

In the ideal situation home owners would like to spend as little money as possible on their heat supply. Following the assumptions made earlier, an energy system where home owners rely on a clean gas supply for their heat demand will have the lowest overall system cost. However, this is a difficult situation to attain because people need to form a collective incentive. Only with a large enough critical density of people willing to take clean gas, the gas company will actually supply this clean gas.

Hypothesis on how patterns emerge

As explained before, all agents together can only reach a system with the lowest overall system cost if they work together. Whether or not this will happen depends on their behaviour. The emergence of an overall system with a gaseous energy carrier will depend especially on how easily the agents are influenced by their neighbours to change their heating system to be fuelled by clean gas.

Problem owner

The addressed problem is owned by all home owners. All together they decide what the overall and thus average heat supply system will cost.

Other actors

Shell also plays a role in the force field of actors. With the obligation to reduce CO_2 emission by 80-95% in 2050 and large gas reserves, Shell's portfolio will possibly shift the coming years from oil to gas (Shell, 2013) The built environment is an important downstream gas market in Northwest Europe and the development of the gas sector in the built environment will therefore be of great interest to Shell as a gas supplier.

Governmental bodies such as the European Union will have its influence on the CO_2 price which will have its implications on the energy price of the different energy carriers. Gas and electricity companies will need to make choices for their customers, regarding capacity, production and distribution. The University of Utrecht will be interested in the results of this research and its implications for the development of the use of a gaseous energy carrier in the built environment for heating.

Role of modeller

The role of the modeller in this case will be developing a model that will give insight in the underlying factors that influence home owners' decisions in their technology choice and how these different emergent patterns emerge.

4. System identification and decomposition

Home owners and their behaviour

The agents that will be considered in the research are the home owners. Home owners own homes and have several different investing options regarding their heat supply, dependent their current situation. First the different technology decisions will be discussed, then the behaviour of the home owners and their environment. In the next chapter the choices and behaviour factors will be discussed in a more formalized way. The so called ontology of the model is a formalization of this conceptualization.

Technology decision

Looking at figure 12 it is assumed that home owners in 2012 are in Situation 1 which has been described in the introduction, a home with electricity supply for the appliances and natural gas supply for their heat demand. It is assumed that they can decide to invest in a technology for themselves. The figure shows the energy carrier used for the heat supply but all homes are connected to the gas and electricity network. Each year home owners can make a decision and make one step in the ladder of figure 12. If they are in Situation 1, home owners have five options.

- Go to situation 2. They will refurbish their homes and thereby reducing their CO_2 emissions. This is an intermediate situation.
- Go to situation 3. They will only change their boilers and start using clean gas in the gas company gives them this option.
- Go to Situation 4. They will refurbish their homes and at the same time change their heating system to heat pumps.
- Go to Situation 5. They will refurbish their homes and at the same time start using clean gas if the gas company gives them this option.
- Stay in Situation 1 and do nothing.

When they have chosen to invest in heat pumps or in clean gas, Situation 4 or 5, they are in an end position that remains the same till 2050, the end of the model run based on the fact that home owners inly invest one time in a new space heating technology. If they are in Situation 2 or 3, they can decide in another year to again invest in technology or stay in their own situation.

In figure 12 this technology choice has made visual. The different choices are displayed as well as which energy carrier the home owner will use in this situation. Each house will always have a connection with the electricity and gas network.

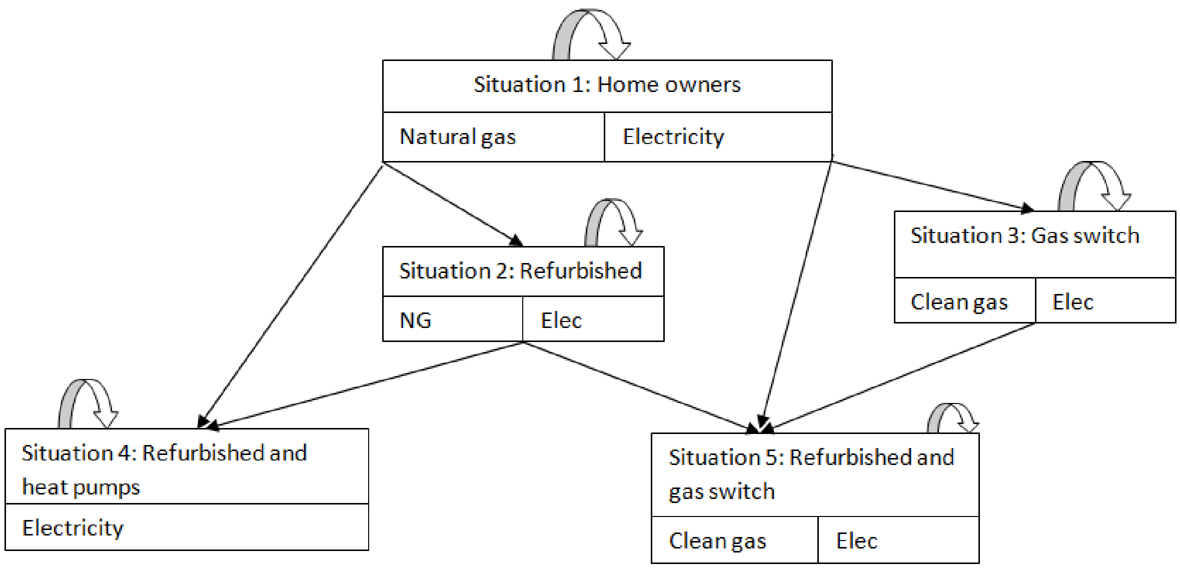


Figure 12. Schematic representation of the investment choice a home owner has in the model

The technology decision depends on the behaviour of the home owner and on the price offer the power and gas company have done to the home owner. This price offer depends on the energy demand mix of the whole system and thus on the behaviour of all the home owners together. The individual technology decision of all home owners then influences the power and gas company's offer the next year.

When home owners make an investment will be discussed in "Behaviour of home owners". *How* this technology choice is made depends on the behaviour of the home owners which is based on three elements and will also later discussed. in general all technology investments have two elements. They bring a certain inconvenience to the owner (whether or not the home owner thinks this is important) and they change their energy requirement for electricity and natural gas. These properties for the technology decision will be discussed in the ontology.

As can been seen in the schematic representation of the investment choices a home owner has in the model, choices have been made in which technology a home owner can invest. In the chapter 3, Problem formulation, it has been described why these choices were made.

Behaviour of home owners

In this model home owners have three reasons to change their heating system. The *when* of this decision influences *how* this decision is made so they will be discussed together. These abstractions of reality are modelling decisions but they are based on literature and reality.

Reasons for a home owner to change their heating technology

- ### Trigger point

When home owners decide to relocate, they are easily willing to change their heating system. The inconvenience this possibly brings is not important because this is for most people the moment where large renovation or refurbishment gives least inconvenience. Therefore people are willing to take all options to change their heating system in consideration. Which technology they chose in the end only depends on how much they can reduce their energy bill. These points in time are called trigger points (Hoggett et al., 2011). Other trigger points can be large renovation projects (UK ERC, 2013) but in this research this renovation factor is not considered and could be seen as reflected in the relocation factor. To keep the model from being complicated, the relocation factor is set to be stricty periodical for each home owner but, with a heterogeneous periodicity.

- ### Price reaction

When home owners think price is important because they are not as wealthy as others, price reduction can overcome the inertia of home owners to change their heating system. Some home owners will decide to change their heating system if they can reduce their energy bill by 10%, others only when they can reduce 50% or more. This is reflected in the price reduction level of the home owner. Home owners then look at what option gives them a certain price reduction but also reflect this to the inconvenience they allow. People may want to invest in changing their heating system but at the same time do not like the hassle of the renovation. How this is reflected in the price and inconvenience table will be discussed in the ontology.

  - #### *Price reduction level*

    The price reduction level of the home owner reflects the level of price reduction a technology investment must achieve for the home owner to consider it. Every home owner has a different price reduction level and each technology choice will have its own price reduction factor every year.

- ### Social pressure

Home owners can also be persuaded by their neighbours. When a certain percentage of their neighbours decide to change their heating system to any other heating system, the next year home owners are more likely to change their heating system themselves as a consequence of this social pressure. Which technology they choose in the end depends on how much they can reduce their energy bill and how much inconvenience they allow.

- ### Social pressure to switch to clean gas

When a certain percentage of the neighbours of the home owner considers going to Situation 3 or 5, using clean gas, the home owner himself will go for this option too.

To conclude, home owners can have three reasons to change their heating system

1. A home owner reaches a trigger point, they are relocating
2. A home owner wants to reduce their energy bill
3. A home owners is influenced by its neighbours

Inconvenience level

A home owner has another important behaviour factor, the inconvenience level. The inconvenience level of the home owner reflects the level of inconvenience a technology can exert on the home owner for the home owner to still consider it. Every home owner has a different inconvenience level and each technology choice has its own inconvenience factor.

Do nothing

Home owners can also have reasons not to change their heating system. Notwithstanding consumer concerns about the impact of high energy prices on households budgets as satisfaction surveys demonstrated (Hoggett et al., 2011), consumers appear generally content with the way that they currently meet their energy needs, particularly in the case of space heating using gas. Other surveys have also highlighted that most do not have any significant dislikes in relation to their current heating system and that its replacement is a low priority decision. People can also be opposed to large renovation works in their homes (Cabinet Office, 2011).

Discussion of system elements

Energy demand mix

The energy demand mix is defined as the overall energy demand for natural gas, clean gas and electricity of the whole system and depends on the technology decision all home owners have made that year.

The offer from the power and gas company

Each year the power and gas company makes an energy price offer to the home owner. This offer depends on the energy demand mix of the year before of the overall energy system. In general the power company will make an offer for the electricity price and the gas company will do an offer for the natural gas price and clean gas price. Consumers make a decision for their technology choice based on this offer, as they cannot look ahead. This is supported by the fact that consumers tend to discount the future, they may prefer a smaller reward today over a larger reward in the future (Cabinet Office, 2011). For that same year this offer is in essence a bill but consumers can see it as an offer for the next year. Based on this offer they make a decision in their technology choice. The power and gas company doing the offer are objects because they are not able to make independent decisions, the price and thus the offer they do by a certain demand is predetermined from outside of the system.

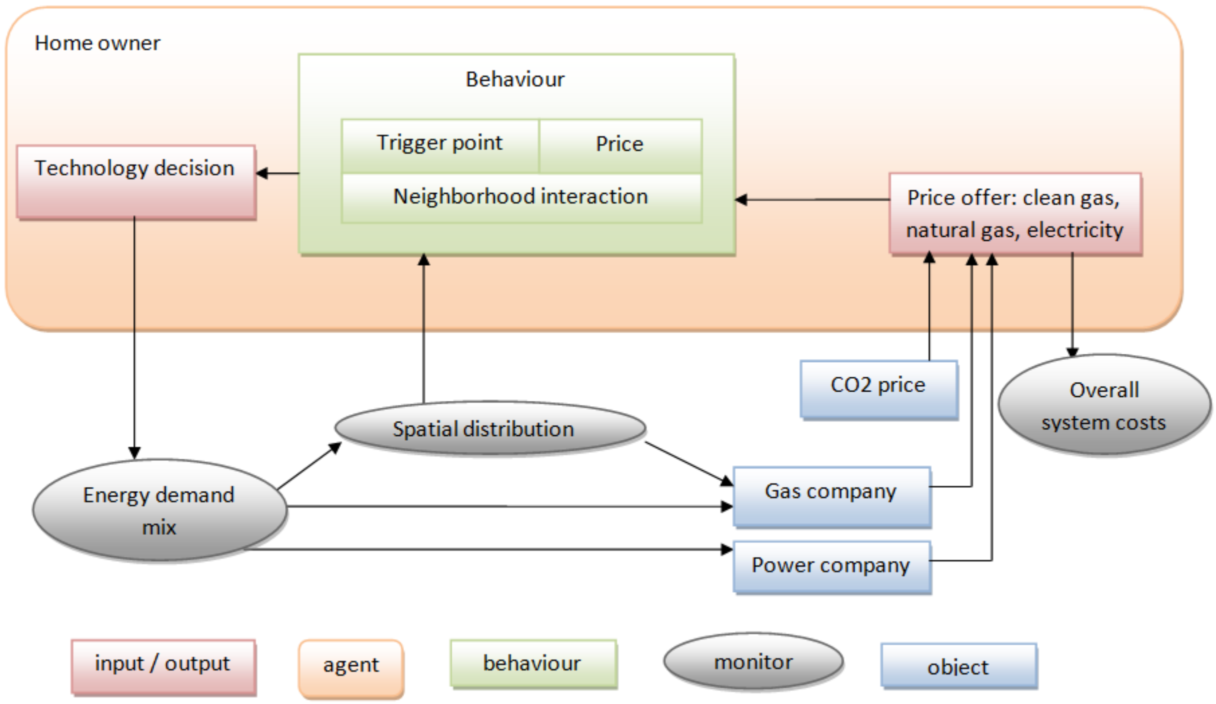


Figure 13. Schematic layout of system dynamics, the home owner and its environment

CO_2 price

The natural gas price that the gas company proposes is in essence a CO_2 price. Together with the clean gas price and the electricity price they form the offer given to the home owner. A virtual CO_2 price is determined every year and increases linearly over the years reflecting the ambition to cut CO_2 emission by 2050 with 80%.

The CO_2 price used to calculate the offer is based on this virtual CO_2 price. If the CO_2 emission goal of that year is not reached, the CO_2 price will be increased following the virtual CO_2 price with a penalty. In essence the system runs slow in respect to the time goal at that moment and the amount of time the system runs slow, is reflected in this penalty. If the system only reaches last year's goal (it runs 1 year slow), the CO_2 price is determined on the basis of next year instead of this year. How this is formalized will be treated in the ontology.

The CO_2 price determination is an object because the CO_2 price does influence the home owners, and the home owner's choice determines the CO_2 price, but this is done in a strict and fixed way. The electricity price is not multiplied with the CO_2 price although electricity possibly is generated using fossil fuels. The costs of the decarbonisation of electricity are however reflected in the electricity price as proposed in the introduction.

Spatial distribution

The spatial distribution of the different Situations of the home owners is important because they influence each other. As explained, home owners will take initiative if enough of their neighbours did this the last year. Changing this parameter that reflects the social pressure in the model, is a way to force home owners to make an investment decision.

When neighbours are considering the switch to clean gas, the next year the home owner will be more likely to be interested in this switch. Only when enough people in the area are considering the gas switch, the gas company will switch their distribution from natural gas to clean gas.

Overall system cost

All energy bills of all home owners together give us the overall system costs which are a measure on how efficient the system is.

Narrative of a model run

Some specifications of the model concept will now be discussed and some examples of model run are described.

Decision ladder of the agent

In general agents cannot decide to invest in a technology that predicts them a higher energy bill. If an agent encounters a trigger point, then inconvenience is not important. In all other situations, all options are open under the inconvenience level op the agent. The decision will be based on the price and the inconvenience level of the possible technology options. If an agent best option is to use clean gas, then it influences its neighbours to do the same.

Some special cases as example:

<u>Price is the decision driver: Case 1</u>

When a home owner decides to change their heating system caused by a trigger point or by a price reaction the technology choice will be based on the price reduction a home owner can achieve.

- Case 1.1. If the natural gas price is lower than the clean gas price the switch to clean gas is not an option and Situation 3 and 5 are no possible investing options because home owners will not include an investing option that raises its energy bill.
- Case 1.2. If the natural gas price is higher than the clean gas price, all options are considered
    - Case 1.2.1. If the home owner has a trigger point, inconvenience is not important.
    - Case 1.2.2. If the home owner has a price reaction, the inconvenience level an agent allows will determine which options are open. Then the decision is based on price and inconvenience.

<u>Price is not the decision driver: Case 2</u>

When price is not the direct driver because the neighbours of the home owner are changing their heating system there are several possible situations.

- Case 2.1. If the natural gas price is higher than the clean gas price, then the inconvenience level that the home owners allow will determine which options are open for investment.

- Case 2.1.1. When the home owner only allows a little inconvenience, only the gas switch will be considered as can be seen in the inconvenience table which will be discussed later. If enough people in the area consider the gas switch then the gas company will distribute clean gas instead of natural gas.
- Case 2.1.2. When the home owners allows a lot of inconvenience, then all options are open and the technology decision is based on the price and inconvenience

- Case 2.2. If the natural gas price is lower than the clean gas price the switch to clean gas is not an option and Situation 3 and 5 are no possible investing options because home owners will not include an investing option if it raises its energy bill.

When the decision is made, the energy demand mix is determined. If the agent's neighbours decided to invest, this positively influences the chance that the agent itself will change their heating system. If enough agents' best option was to apply for the gas switch, the gas company will accommodate this. Then a new price offer is made to the agent and the overall system costs are calculated.

5. Model formalisation

This model formalisation will consist of the ontology of the model in which the concept that has been created will be formalised. The *what* of the model will be formally encoded including objects, concepts, other entities, and their relationship between them within the system boundaries. (Nikolic et al., 2013). All variables that can be adjusted in the setup face of the model will be discussed and at the end a table is included in Appendix A that gives all standard parameter values before beginning to vary some of them for the experiments.

The agent that is modelled in the model is the home owner, represented as patches in the world. All patches together form an agent set. The "world" is two dimensional and is divided up into a grid of patches. Every patch has the same number of neighbour patches , if you're a patch on the edge of the world, some of your neighbours are on the opposite edge because the world is "wrapped". (Wilensky, 1999).

The model interface consists of two parts, the setup part and the result part. In the setup, all parameters can be set and the results of this setup are shown in some monitors. In the table in appendix A all factors that can be varied in the model are listed. They are categorised in agent behaviour factors, objects behaviour and model restriction.

Setup of the model: Agents and their behaviour

Trigger points

Whether or not an agent relocates in a specific tick (a year), is modelled by a normal distribution around the average relocation number as posed in the introduction. The standard deviation and averages of the normal distributions can be adjusted. A maximum and minimum value of the relocation factor can be given.

Price reaction

The different price reduction factors are reflected in the price reduction table. The factor reflects how concerned agents are with the bill they get from the energy company. If they think it is very high they are more eager to invest in technology that will lower their bill.

At what reduction percentage an agent will make a technology decision is normal distributed over all agents, is agent specific and does not change over time. The average and the standard deviation of the reduction percentage at which an agent will make a technology decision can be adjusted with a slider.

The price table

Every investment decision an agent can make has a certain effect on the energy bill of the agent. This is reflected in the price table. The price reduction factor for each technology is in case of refurbishment calculated by multiplying the natural gas (NG), clean gas (CG) or electricity (Elec) bill of the last tick with the refurbishment factor (R) that the refurbishment delivers. The refurbishment factor can be adjusted. The price of the last year energy carrier was calculated by the energy demand mix of the overall system.

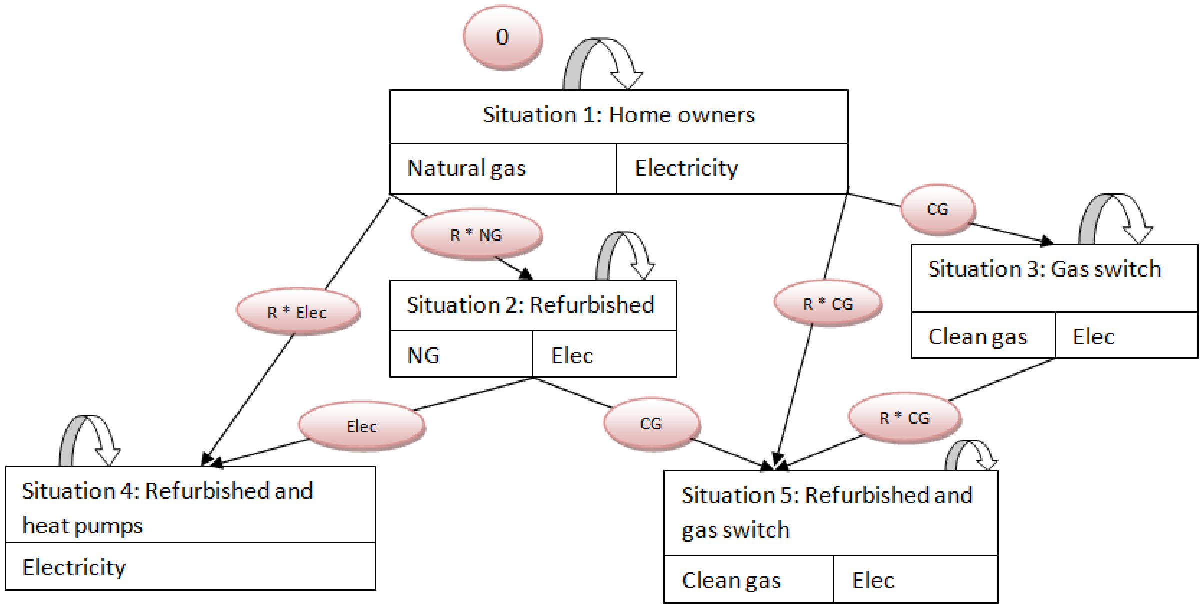


Figure14. Schematic representation of different technology choices with their related demand

Social pressure

If an adjustable percentage of neighbours in an adjustable radius around the agent have made an investment decision in the last tick, the agent itself will make an investment decision this tick.

Social pressure to switch to clean gas

When an adjustable percentage of neighbouring agents' best option in a certain adjustable radius around the agent, is to switch to clean gas, the gas company will provide clean gas to the agent. This can be seen in two ways. It can be seen as behaviour component of the agent, switching when they are convinced by their neighbours. But it can also be seen as obligation forced by the gas company. If a certain amount if neighbours are using clean gas, the agent itself is forced to use clean gas. The needed percentage within in a certain area can be seen as critical density to switch to clean gas.

Inconvenience level

The average inconvenience level an agent allows is normal distributed over all agents, this is agent specific. The standard deviation, maximum and minimum of the average inconvenience level can be adjusted with a slider.

The inconvenience table

The different inconvenience factors of the technologies are reflected in the inconvenience table. The factor reflects the inconvenience an agent experiences by refurbishing his house or making large changes to his heat system. It is assumed that both installing heat pumps as well as, a refurbishment requires major heat system changes to a home, while changing from natural to clean can only require changing the boiler.

The weight given to the different situations can be adjusted from preference for electricity to preference for the gas switch. The default inconvenience levels are given in figure 15.

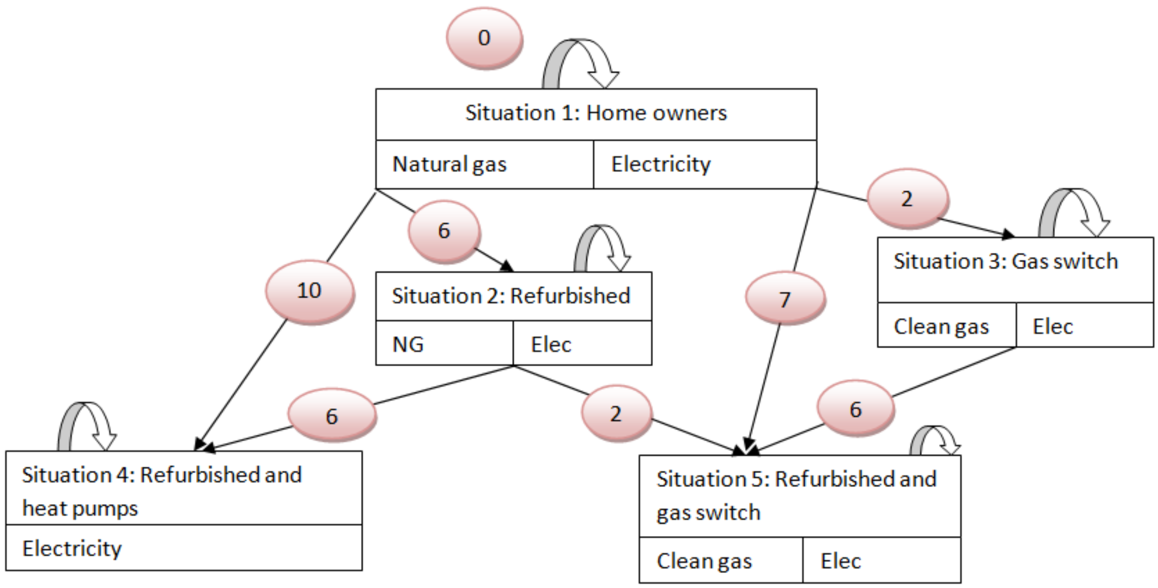


Figure15. Schematic representation of different technology choices with their related inconvenience levels

The different inconvenience factors of the different technologies can be adjusted. The numbers given in figure 15 are the default numbers, but preference can be given to electricity or clean gas technologies. The amount of preference can be adjusted with the chooser *mininconveniencebonus.*

As has been explained in the chapter 2, Important Backgound. Home owner renovate mostly because something else in the house needed fixing or replacing (UK ERC, 2013). This supports the assumption that less inconvenience is felt when a combination of things are done, like renovating and installing heat pumps.

Agents behaviour

During setup the different behaviour factors of the agents can be set on or off. If the agents responds to relocation, price, social reaction or social reaction for clean gas can be set.

Setup of the model: Objects

Electricity and gas company

The electricity, natural gas and clean gas demand is determined from the energy demand mix which includes all energy demands of all agents. From this energy demand, the electricity, natural gas and clean gas price are calculated. The price varies between 0 and 10. Demand is calculated by summing all agents demand (1 * refurbishment factor when the house is refurbished and 1 if it is not refurbished). The point where the electricity price and clean gas price are equal is called *intersection*. The price development can be adjusted by adjusting the beginning and end levels of both clean gas and electricity, and the curvature of both can be adjusted by changing the parameters *elecvar* and *cgvar*.

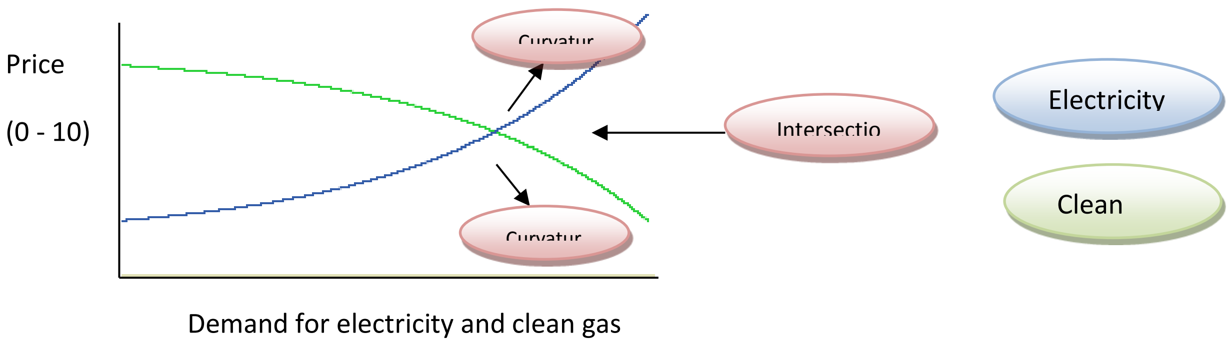


Figure 16. Price development of electricity and clean gas in the model

These price developments were calculated with the following equations. *Cgsum* reflects the total number of households using clean gas. *Elecsum* reflects the total demand of electricity which consists of the amount of home owners using electricity times the refurbishment factor.

$$cgprice =$$

$$\frac{cgendprice - cgbeginprice}{cgvar^{sizeofworld} - 1} * cgvar^{cgsum} + \left(cgbeginprice - \frac{cgendprice - cgbeginprice}{cgvar^{sizeofworld} - 1}\right)$$

$$elecprice =$$

$$\left(beginelecprice - \frac{beginelecprice - elecendprice}{-1 + elecvar^{sizeofworld}}\right) + \frac{cgendprice - cgbeginprice}{cgvar^{sizeofworld} - 1} * cgvar^{cgsum}$$

CO_2 price

The CO_2 price used to calculate the price offer for natural gas is based on the virtual CO_2 price. The virtual CO_2 price is a price that linearly increases every year. Every year, the emission goal and corresponding virtual CO_2 price is calculated. If the CO_2 emission goal of that year is not reached, the actual CO_2 price will be increased following the virtual CO_2 price with a penalty. In essence the system runs slow in respect to the time goal at that moment. The amount of time the system runs slow, is reflected in this penalty. If the system only reaches last year's goal (it runs 1 year slow) and the penalty is one, the CO_2 price is determined on the basis of next years' virtual CO_2 price instead of this year. The penalty and the starting level of the CO_2 price can be adjusted. The CO_2 price cannot be negative as this is not realistic.

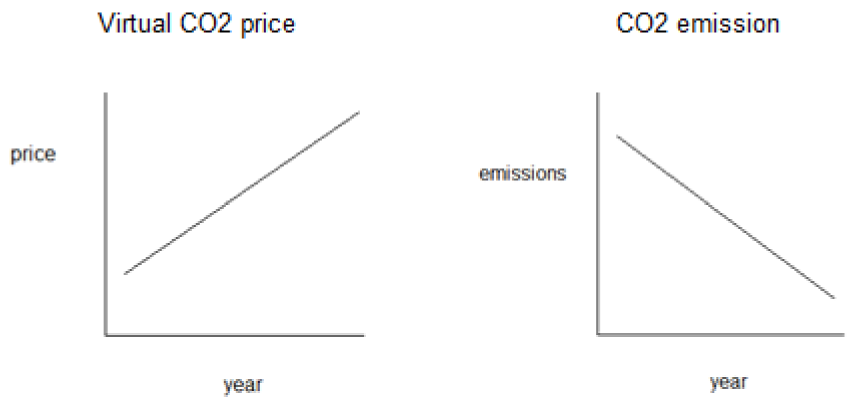


Figure 17. Virtual CO2 price and CO_2 emission target

Setup of the model: Model restrictions

CO_2 target emission reduction

Fifty target determines the CO_2 emission that is still allowed at *maxtime*, the year the target must have been reached. With the parameter fifty target the slope of the CO_2 price can be determined via the CO_2 emission target of that year. It is a percentage of the amount of patches in the world, which is the natural gas demand at tick zero.

Time frame

Each year is represented by a tick. Every tick the agent can make an investment decision and the overall system costs are calculated. The model runs an adjustable amount of ticks called *maxtime*, representing the years from 2012 onwards.

Size of the world

The number of patches world in our model cannot be adjusted easily; it has to be done via the settings in the Netlogo model. The number of patches in the world can be seen in the monitor *sizeofworld.* In the interface the size of the world can be adjusted by adjusting the size of the patches with the slider *patchsize.*

Seeds

A seed of a certain technology can be placed during or before the model setup. With this setting you force a patch to adjust its situation to a chosen situation. This can be done with *mousechoice* and *make choice for patch.* With the button *set seeds* seeds of 3 x 3 patches of clean gas are placed into the world by forcing these patches to go to Situation 3. How this is done will be explained in the experiments.

Time to set seeds

With this slider the time at which seeds of 3 x 3 patches of clean gas are placed into the world by forcing these patches to go to Situation 3 can be set.

Refurbishment factor

The refurbishment factor reflects the percentage of demand reduction when a house is refurbished. This factor can be adjusted.

Result and monitors of the model

Situation of patches

Shows the development the number of patches in a certain situation.

Amount of patches

Shows the exact number of patches in a certain situation.

Actual electricity, natural gas and clean gas price

Shows the price development of electricity, natural gas and clean gas.

The world

Shows the spatial distribution of the patches in the world. The colour of the patch reflects its situation, red = Situation 1, orange = Situation 2, light green = Situation 3, blue = Situation 4 and dark green = Situation 5.

Overall system cost

Shows the overall system cost, which is a summation of the bills of all agents at the end of the runtime of the model.

6. Software implementation

The model is written in the programming language called Netlogo. There are many agent based modelling platforms and modelling environments, each with strength and weaknesses. In this case Netlogo has been chosen because of its low barrier of entry, meaning that new users shouldn't find it hard to start using it from day one and because of it's extensive on-line community for support when questions inevitable arise (Nikolic et al., 2013). Besides that, NetLogo is particularly well suited for modelling complex systems developing over time. Modellers can give instructions to hundreds of thousands of "agents" all operating independently. This makes it possible to explore the connection between the micro-level behaviour of individuals and the macro-level patterns that emerge from their interaction (Wilensky, 1999).

A first introduction to the modelling language Netlogo was given by Dr. I. Nikolic in a course for the Master Systems Engineering, Policy Analysis and Management at the TU Delft called "Agent Based Modelling of complex energy and industrial networks". Further assistance was provided by Gerben Bas at the TU Delft.

The Netlogo model consists of three parts, the interface, the code and the info tab page.

Code

In the tab page called "code", the model code is written. The model code is composed of several modules that were created separately. The code is given in appendix C. The several modules are:

Globals

All global variables that will be used in the code are defined.

Setup

In the Setup module all agents individual behaviour parameters, all objects and all model restriction are set up.

- Set all variables to zero and clearing all plots.
- Set up the inconvenience table.
- Give all agents a relocation factor, an inconvenience level, a reduction level and a situation (Situation 1) based on the input parameters giving in the interface.
- Calculate and plot the input assumption on the electricity and clean gas price development over demand based on the parameter setting given in the interface.
- Set possible seeds into the world by setting the situation of certain patches to Situation 3.

Go procedure

After the model is setup, all agents will go trough the *Go procedure* that consists of all possible procedures an agent can call upon. This procedure was created last, after all other modules were created and tested. The modules were then combined in this Go procedure. It consists of:

- Set all variables correct to begin the procedure

- Calculate the demand for electricity, clean gas and natural gas
- Check if the patch will make an investment decisions and based on which reason (because it is relocating, the bill is to high, his neighbours have invested in the last tick etc.).
- Make the investment decisions and set all variables correct for this new situation the patch is in
- Update the plots and monitors
- Check if the maximum runtime of the model is reached. It this is the case, the model will stop.

Bill calculation

In the module *Bill calculation* the electricity, clean gas and natural gas price are determined. The electricity and natural gas price are based on the demand for electricity and natural gas, incorporating the effect of decreasing demand because of refurbishment. The clean gas price is based on the number of patches with clean gas. The bill calculation module consists of:

- Determine the electricity, natural gas and clean gas demand.
- Calculate the natural gas price based on the CO_2 price.
- Calculate clean gas price.
- Calculate the electricity price.
- Set all bills for all the agents correct.

Offer calculation

Offer calculation is a small module to summarize the different offers an agent has. It consists of:

- Based on the electricity, clean gas and natural price that have been calculated in the module *Bill calculation,* calculate the several offers (for each technology) for an agent.
- Calculate the difference between the different offers and the old bill.
- Check whether the offers are lower than their old bill, otherwise the offer is rejected. If all offers are rejected, the agent will not make a decision to invest.

Inconvenience

In this module all offers are checked for their inconvenience. If the inconvenience factor of the investment decisions are higher then the inconvenience level of the agent, the offer are rejected. When the agent will make a decision based on relocation this module is not called.

- Check the offers inconvenience with the inconvenience level of the agent

Technology decision

In this module the process of the investment decision is brought together. It consists of:

- Check on which bases an investment decisions is made. A decision can be based on:
    - Relocation
    - Price
    - Social reaction
    - Social reaction to switch to clean gas

- If an agent has several reasons to make an investment decision the one with the least restriction is chosen. For example if an agent has a price reaction and relocates, the investment decision is based on the relocation because when an agent relocates the inconvenience is neglected.

Relocation

The module checks whether the agent is relocating the current tick and based on this then makes an investment decision.

- The relocation factor of the agent is divided by the tick the model is in. If this is zero, the agent will make an investment decision based on the relocation procedure making sure the agent has a periodic trigger point.
- Chose the offer with the largest difference to their old bill.
- Set all variables correct for the new situation.

Price

First this module checks if the agent has a price reaction the current tick and makes an investment decision based on the reduction factor and inconvenience factor.

- Check if there are one or several offers that are lower than the reduction level of the agent requires. Otherwise reject these offers.
- If there are offers left, check if these offer's inconvenience factor's are lower then the inconvenience level of the agent. Otherwise reject these offers.
- From the offers that are left, chose the offer with the largest difference to their old bill.
- Set all variables correct for the new situation

Social pressure

First the module checks if enough neighbours in a certain radius around the agent made an investment decision the previous tick. If this is the case, the agent will make an investment decision based on the price module.

- Check if the required percentage of neighbours in the predetermined radius of the agent has invested during the previous tick.
- If this is the case, the agent will go to the price module.

Clean gas bonus

This module checks if enough neighbours in a certain radius around the agent made the investment to switch to clean gas. If there are enough neighbours that did this, the agent itself will make this decision

- Check if the required percentage of neighbours in the predetermined radius of the agent have invested in the switch to clean gas the previous tick.
- If this is the case, the agent will make the investment decisions to switch to clean gas.
- Set all variables correct for the new situation.

Interface

The setup of the model is represented in the interface by all monitors, sliders and buttons on the left side of the interface. In the right side of the model all outputs of the model, monitors and plots are presented, also the world is shown there.

See a picture of the interface in appendix D.

7. Model verification

Before experiments were carried out, the model has been verified. This process is put in place to ensure that the model implementation corresponds to the model design. Verification checks that all relevant entities and relationships from the conceptual model have been translated into the computational model correctly (Nikolic et al., 2013).

The verification has been done in several different ways.

- By doing input-output tests for isolated modules of the model and for the whole model together.

  Input-output tests have been done for all modules. Especially *Setup, Bill calculation, Offer calculation, Inconvenience, Relocation, Price reaction, Social reaction* and *Clean gas switch* could be tested individually. In the modules *Go* and *Technology decisions* the different modules came together and their function has been tested by adding one module at a time. After that all modules where put together and input-output tests have been done by monitoring outputs with given inputs. Setup outputs monitors are *Relocation distribution*, *Inconvenience distribution, Reduction factor distribution*, *amountofneighborsinradius* and *amountofneighborsinradius-cleangas*, *sizeofworld*. *Bill and offer calculation* outputs monitors are *Electricity and clean development assumption* and *intersection CGprice and Elecprice.* With these monitors the different setup parameters could be tested for the right setup for the model.

  By monitoring the right side of the interface and running the model with the different behaviour settings calculated in the modules *Relocation*, *Price reaction*, *Social reaction* and *Cleangasswitch*, these modules could be tested individually and together.

  In this verification process different errors where corrected. For example the electricity demand should be calculated by summing the demand for electricity (incorporating the effect of possible refurbishment). However for the demand for clean gas the amount of agents with clean gas should be summed.
- By doing an extreme value test.

  Different behaviour modules could be setup with an extreme parameter setting in a way that should not have influence on the behaviour of the model even though, the module is still run. For example, the module relocation could be turned on, but in a way that agents never relocate. This could be compared by a model setup where the relocation module was turned off. This could be done for the other behaviour components. Likewise, the price reaction parameters could be setup in an extreme way so that the price reaction module worked the same as the relocation module. Extreme value test have also be done for the Setup modules of the model, especially regarding the price development of electricity and clean gas.

8. Experimental design aspects

Working with an agent based model, two types of hypotheses for an experiment are possible. As I. Nikolic describes the two types are characterized by these two questions:

- Does the macroscopic regularity of interest emerge from the designed agent based model? Under which conditions does this happen?

  This question relates to an attempt to model expected real world regularity and will attempt to provide an explanation about the conditions needed to produce the regularity. As explained in chapter 3, Problem formulation, the desired emergent pattern is an emergent system with the lowest overall system costs, which relates to a world where clean gas has a large part of the heating energy demand mix. In the experiments this is a point of focus and the question is asked: under which conditions will the overall system costs be the lowest and how robust are these findings with varying parameters?
- Given the agent based model of a system, what is the range of behaviours, results and system level regularities that emerge with the available parameters?
  In some cases experiments have been carried out that answer the question in which kind of system we can end up under specific range of behaviours. This has been done explicitly in experiments around the agent behaviour.

In the experiments that have been done, these two hypotheses were combined. First, experiments have been done with parameters settings that came from literature, or are assumed at values with intuitive logic. Then variables have been changed to see what kind of different emergent systems could be created. Secondly it has been observed with which parameter settings the desired emergent would emerge and how robust these results were for differences in the parameter setting.

Experimental setup

Normally when a model is created and verified, a full factorial or reduced parameter sweep will be carried out to look at all possible variable and parameter space combinations. Because a full factorial parameter sweep often takes to much computer run time (in this model with 35 variables), parameter space reduction techniques that use statistical sampling of the multidimensional parameter space such as Latin Hypercube Sampling have been created. This is a statistical technique that guarantees uniform sampling with the desired granularity of the scenario space given a Y dimensional parameter space and with a limit of X experiments (Nikolic et al., 2013).

However, in this research a different method proposed by Dr. G. J. Kramer is chosen, which only looks at variables and parameter spaces that are reasonable within the scope of the behaviour of agents, objects and their environment in real world. In this way computer run time is saved for realistic and interesting parameter sweeps and points in the multidimensional parameter space that are not of interest can be neglected.

Randomness

In computer models there is no such thing as random as computer cannot generate random numbers. Only the decay of radioactive atoms is known to be truly random (Nikolic et al., 2013). In this computer model pseudo randomness is used to generate the world of agents and their associated pseudo random assigned behaviour. This behaviour is assigned in three factors, the relocation, inconvenience and reduction levels.

In the model the members of an agent set are not stored in any particular order. This means that every time an agent set (in this case formed of patches) is called upon, the order of agents in the agent set will be different. This helps to keep the model from treating any particular agent differently from any other (Wilensky, 1999).

Repetitions

Reliable statements about the experimental results of an agent based model demand multiple runs because every single run could be a unrepresentative outlier of the outcome space. Agent based models can be chaotic because of their iterative nature (Nikolic et al., 2013). In order to find a good balance between reliably large samples and reasonable long experimental computer run time, in the representation of the experiments that have been carried out not everywhere multiple runs are visible. However in all cases, several runs have been carried out and special experiments are carried out to defend the conclusions drawn from these results.

9. Experiments and data analysis

Using the model four different groups of experiments were carried out. First the influence of the price development of clean gas and electricity on the emergent behaviour of the system has been evaluated. Secondly the different behaviour factors of the agents were evaluated. The neighbourhood interaction of the agents was investigated in the third group of experiments. Finally seeds of clean gas were placed into the agent world in fourth group of experiments. The experiments were evaluated by the overall system cost and the energy demand mix of the system.

At first experiments were done in a world of 81 by 81 patches. Because of limited computer run time it was decided to switch to a world of 41 by 41 patches, all described experiments were done in 41 by 41 patches world. Other parameters were set as discussed in the ontology of the model.

Each run of a set of particular parameter settings took between a few seconds and a few minutes resulting in a wide variety of CPU time for the different experiment. Figure 22 later on shows nine parameters settings each one run for 1000 times. This was performed with almost two weeks of fulltime running of the computer. Because Shell provided a virtual machine that could be accessed by the network, the model could run fulltime.

The model output was a .csv (comma separated values) fine, which could be opened and analysed using the analysis software R. with the code given in Appendix E.

Experiment group 1: Influence of price

Introduction

In the first group of experiments the effect of the price development of electricity and clean gas on the energy demand mix and overall system costs has been explored. This has been done over several parameters such as the curvature of the price of electricity and clean gas, the begin price of electricity and clean gas and over time.

Results

Energy demand mix

First the energy demand mix over time with different begin prices for electricity and clean gas have been

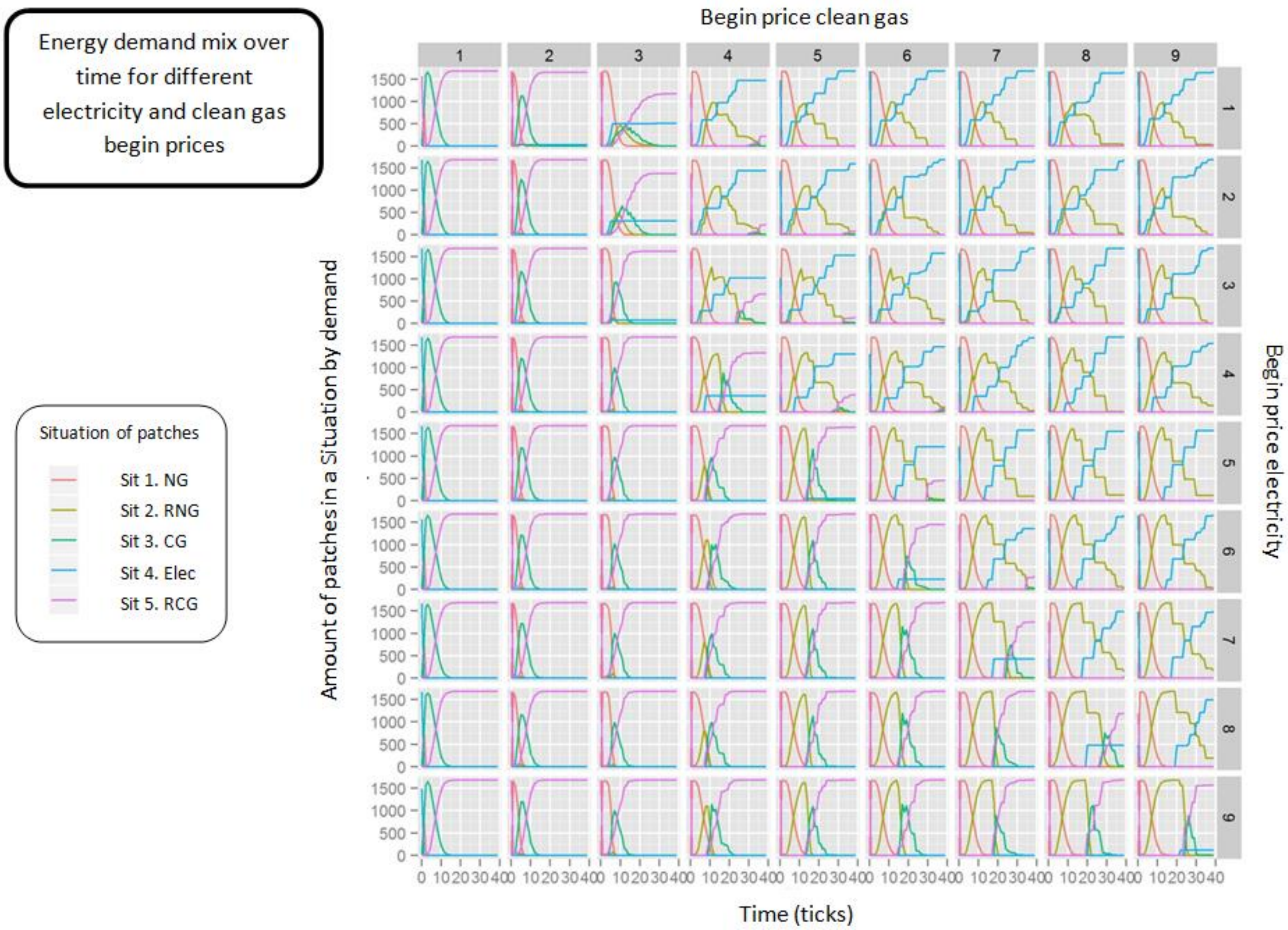


Figure 18. Energy demand mix over time for different electricity and clean gas begin price. Begin electricity and clean gas price varied between [1 – 10] with 1 increment. Number of patches in a situation was measured every tick.

investigated in figure 18 and figure 37 enclosed in appendix B.

With regards to the situation at the end of the runtime several conclusions can be drawn

- If the clean gas price is lower than the electricity price at the beginning, clean gas will dominant in the end of the runtime.
- In the parameter setting that clean gas is more expensive than electricity, only with the parameter setting (begin clean gas price, begin electricity price) = (3, 1), clean gas can be dominant in the end of the runtime. In all other cases, clean gas will only be dominant if their begin level is equal.
- In the areas (x, x - (x + 3))) a switch of emergent behaviour between clean gas and electricity is expected and mixed scenarios are observed. These mixed scenarios are expected not to be emergent but it can be concluded that the system does not reach to an emergent behaviour at the end of the runtime.
- If the begin level of clean gas and electricity is above 4, all agents will first refurbish their homes before they will make a decision between electricity or clean gas.
- Some special cases
    - (2,1). Because of the inconvenience factor of heat pumps and the fact that price is very low, the system will emerge very fast to a clean gas scenario although the electricity price is lower at first.
    - (8,2). The most realistic scenario as seen as the described assumption on price development as posed in the chapter2, Important background, would be a (8, 2) scenario. In this setting electricity is clearly dominant at the end of the runtime of the model.

In figure 41 in appendix B the related development of the different prices can be seen as actually experienced by the model.

Looking at the development of the different Situations over time the rise and fall of Situations 3 (clean gas) and Situations 2 (refurbished natural gas) is interesting.

- When prices are low (< 4), agents will not all use the intermediate step between Situation 1 and 3, Situation 2.
- Natural gas can stay in the mix for various parameter setting such as (9, 4).

Figure 37 and 39 in appendix B show the same price development but then zoomed in and for several runs.

Overall system costs

If we look at the overall system cost of the system figure 19 (and figure 38 in appendix B) two things attract attention.

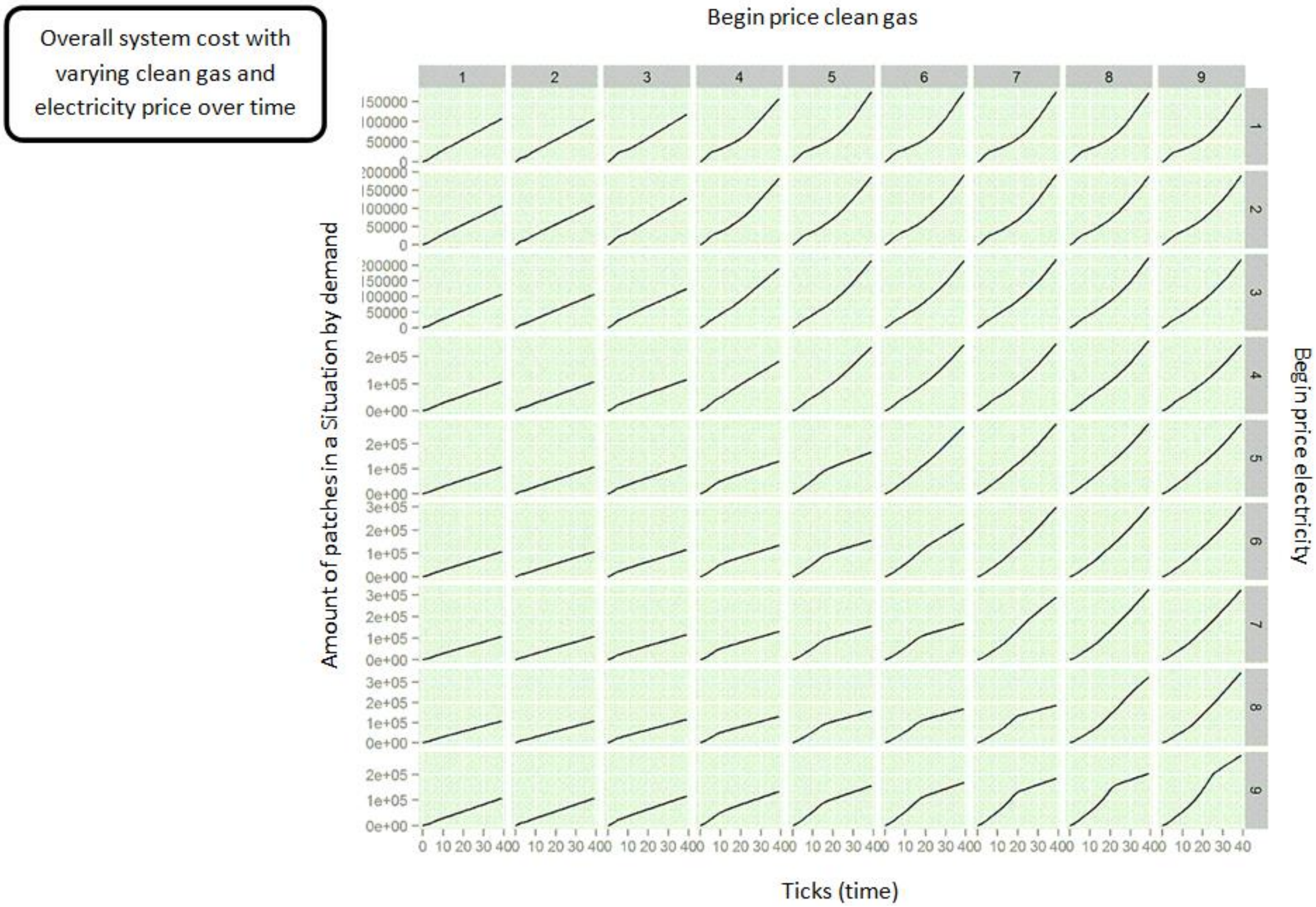


Figure 19. Overall system cost development over time with different clean gas and electricity begin price levels. Overall system cost was measured every tick.

- It can be seen that the overall system cost of the system is higher when electricity is dominant in the energy demand mix. This is what we would expect with regards to the price development of electricity and clean gas as described in the ontology.
- In the development over time of the overall system cost the small kink around tick (t) = 20 can be explained by a fast switch of large amount of patches from Situation 2 to Situation 3 and 5 in the energy demand mix.

Curvature

Besides varying the begin price of clean gas and electricity also the curvature of the two developments has been investigated. The results are shown in figure 20. The figure shows the end energy demand mixes and the intersection at what amount of patches clean gas and electricity became the same price with varying curvatures.

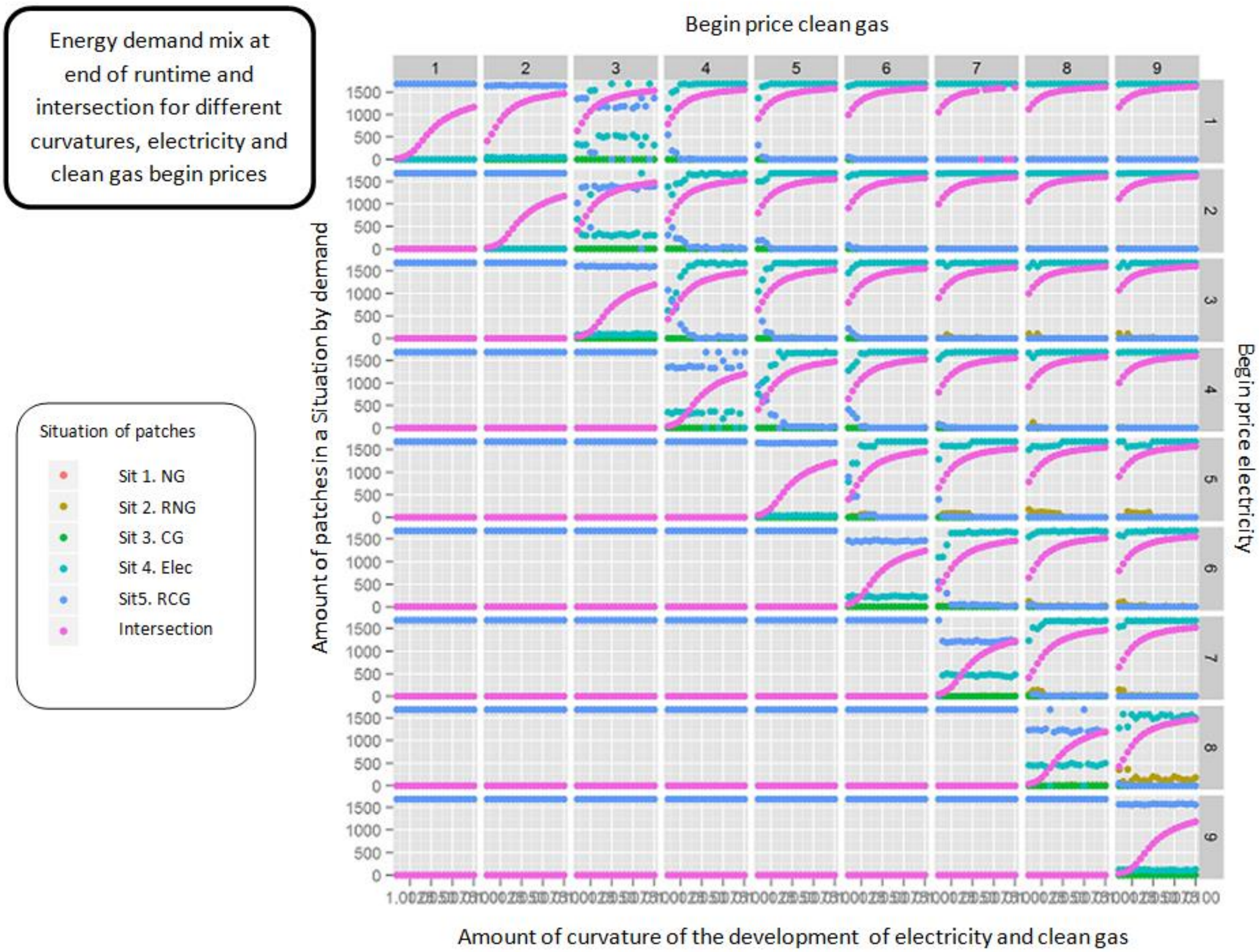


Figure 20. Energy demand mix at the end of the runtime with varying curvature. Every curvature value was run 10 times, identified by 10 dots. The intersection is also plotted.

The figure shows that

- (4,3). When the clean gas price matches the electricity price early on, it can be seen that clean gas will win easier.
- The same variable space that will result in switching between clean gas and electricity can be observed. In the areas where a switch of emergent behaviour between clean gas and electricity

is expected (x, x - (x + 3))) the curvature of the price development of electricity and clean gas can be decisive in the switch between clean gas and electricity.

- (3,1) It has been observed that this parameter setting looked quite chaotic and therefore this parameter setting has been done in repetition. Figure 21.

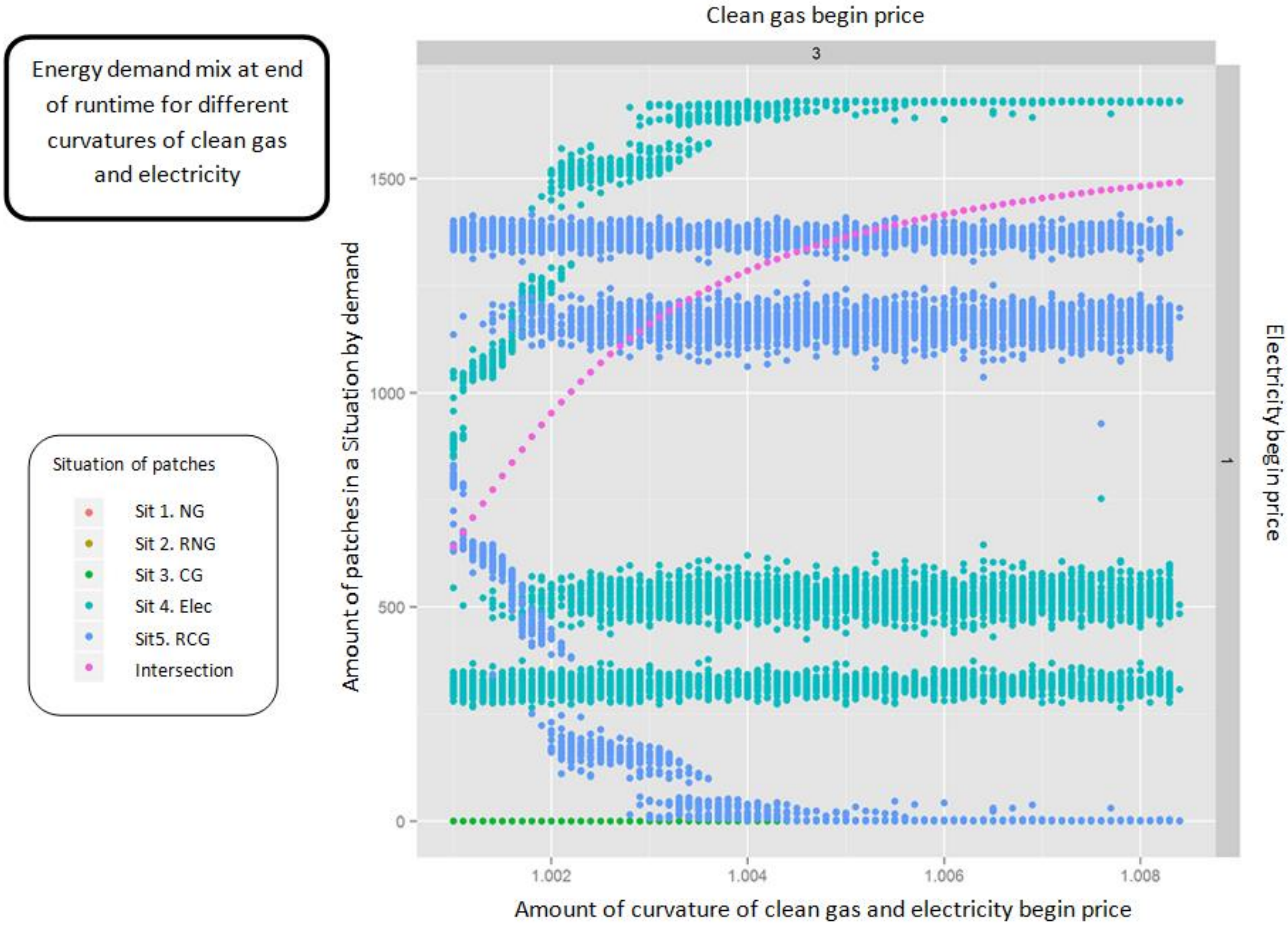


Figure 21. Energy demand mix at the end of the runtime with (begin clean gas price , begin electricity price) = (3, 1) with varying curvature. Every curvature value was run 100 times, identified by 100 dots. The intersection is also plotted.

Figure 21 shows chaotic behaviour because it displays that the system is very sensitive to the initial conditions, in this case the distribution of behaviour factors over the agents.

- Different spreadings of the behaviour factors gives rise to different emergent energy demand mixes at the end of the runtime.

- Six branches can identified, that are connected in couples because 0% demand for electricity is connected with 100% demand for clean gas etc. Therefore three different kinds of behaviours can be identified.

Discussion

In figure 22 and figure 23 the degree of chaotic behaviour is shown. The selection of parameter settings was used of figure 18 and figure 19 and it was run 1000 times.

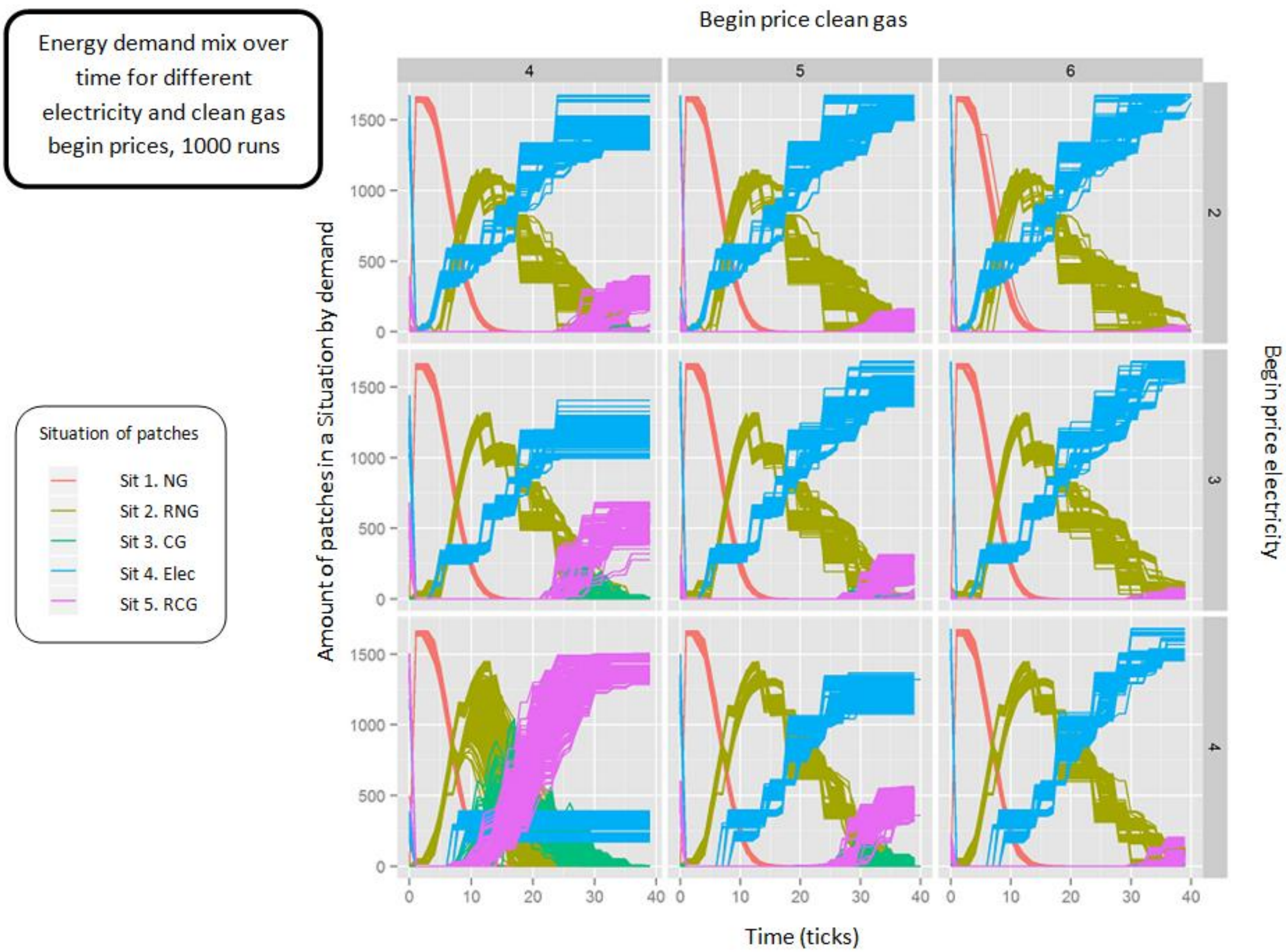


Figure 22. Energy demand mix over time for clean gas and different clean gas begin prices. Begin clean gas price varied between [4 – 6] with 1 increment, electricity begin price between [2 – 4]. Amount of patches in a situation was measured every tick. Every parameter setting was run 1000 times.

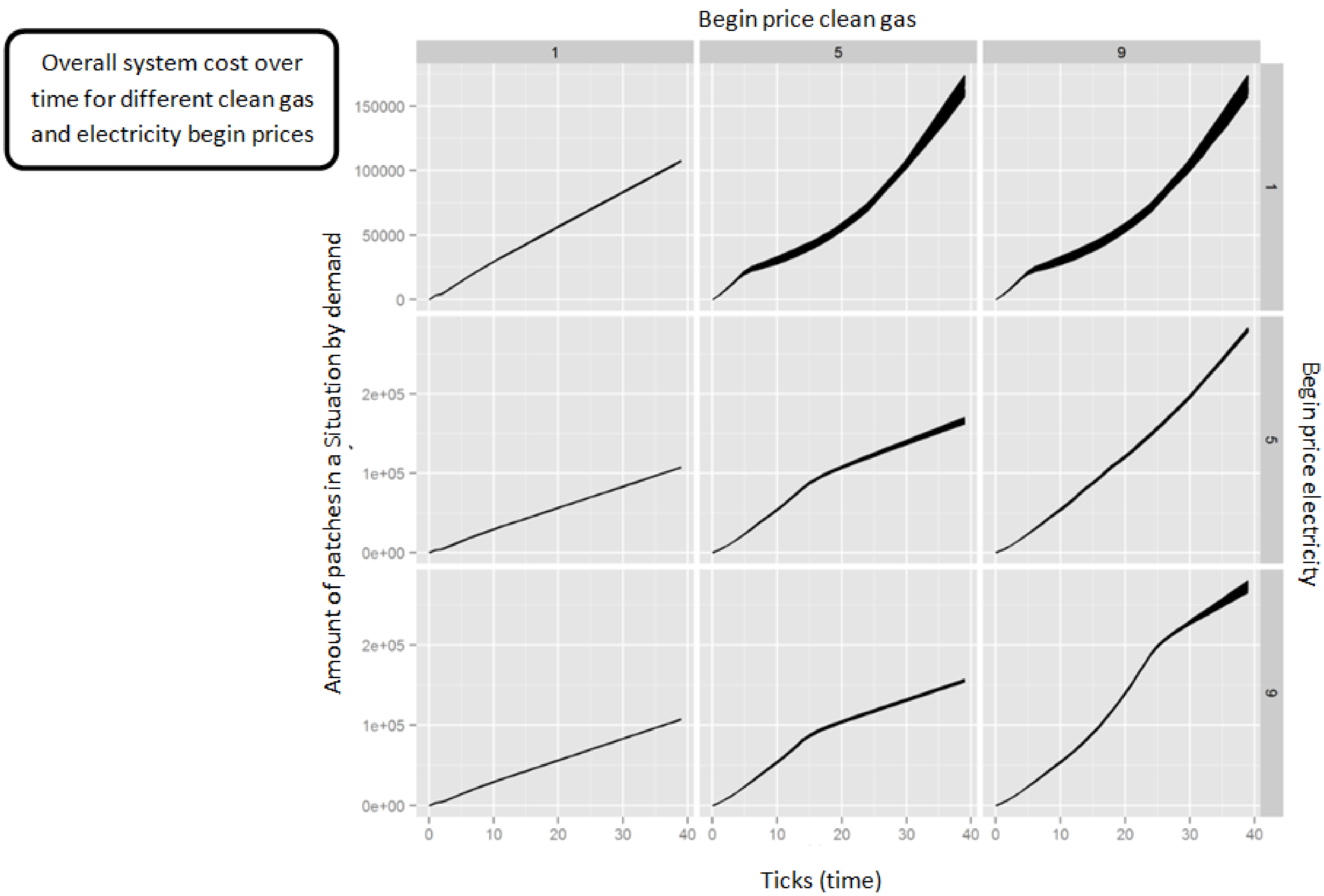


Figure 38. Overall system cost development over time with different clean gas and electricity begin price levels, zoomed in. Begin electricity and clean gas price varied between [1 - 9] with 4 increment. Overall system cost was measured every tick. Every parameter setting was run 1000 times.

Conclusions are:

- The difference between the two most extreme scenarios within the same parameter setting will result in a +- 1/8 (which is 40.000) difference in overall system cost.
- The development over time shows difference between the different runs, but the overall behaviour has the same characteristics.
- The difference between the two most extreme scenarios within the same parameter setting of the energy demand mix is a difference of +- 350 patches of a total of 1681 patches.

Robustness of results:

With these experiments it has come clear that the begin level of electricity and clean gas is of major influence of the emergent behaviour at the end of the run time. This is expected behaviour but the size of the difference between the begin level of electricity and clean gas at which a different emergent behaviour can be expected has been shown. Also it has been shown that the degree of curvature of the price development will be important in these areas where a switch of emergent behaviour is expected. Outside of these areas, the curvature is not important as the same emergent behaviour will develop over a wide range of different curvatures.

Conclusion

To conclude on this part of the experiments, if the model can be seen as realistic representation of the problem addressed as has been argued in previous sections, the model shows that:

If clean gas will be much more expensive then electricity now, as is the assumption on the price development as explained in the introduction, heat pumps will be the dominant space heating technology in houses in 2050. This will result in relatively high overall system costs.

Only when clean gas is subsidized or extra taxes are charged on the use of electricity, the use of clean gas will get a chance to develop. The model shows that they do not need to be at the same level, a small difference will be overwon by other behaviour aspects of home owners. When clean gas will be the dominant energy carrier, the overall system costs will be the lowest.

The assumed on the curvature of the price development of electricity and clean gas can be important, but only when policies are in place to reduce the difference between clean gas and electricity.

In the development over time, it can be concluded that when clean gas and electricity are both at high begin levels, home owners will try to postpone investment decisions that are irreversible and invest in renovation of their homes still using natural gas, instead.

In some cases the system can be very sensitivity to the distribution of behaviour factors. As policy makers want to have a maximum influence on their policies, these situations should be avoided. The outcome of the policy is very uncertain and can depend on the distribution of home owners and their behaviour in space.

Experiment 2: Influence of neighbours

In this group of experiments the influence of the neighbourhood interaction is explored. In this setting, neighbours will encourage each other to make the investment decision to switch to clean gas. The influence of the area and the percentage of neighbours needed in that area have been explored. The needed percentage within a certain area can be seen as the critical density to switch to clean gas. It is expected that this critical density will be crucial in areas where a switch between clean gas and electricity as dominant energy carrier is expected.

First the height of the clean gas price was investigated at which switches between electricity and clean gas as emergent energy demand mix were observed. The results are shown in figure 24.

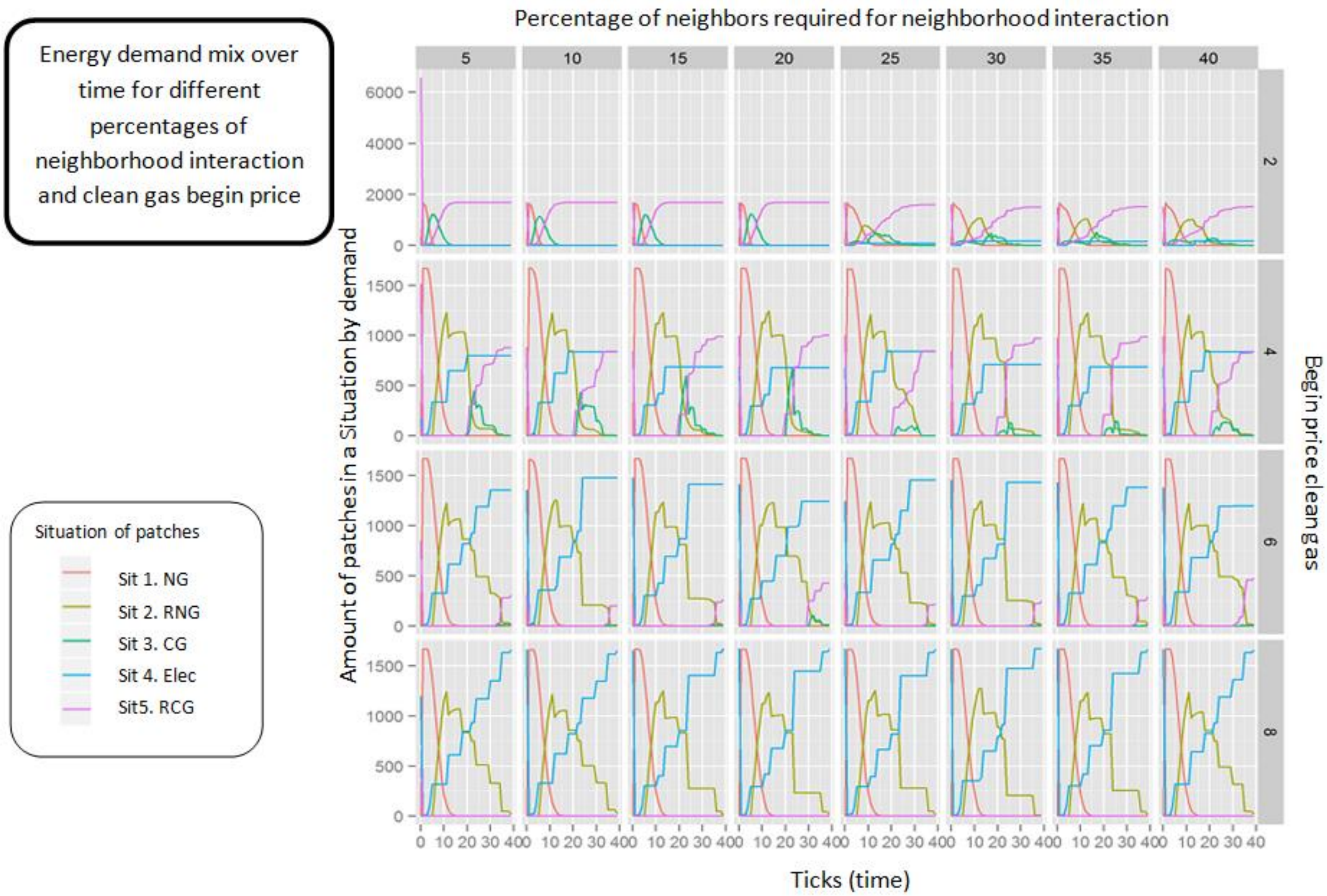


Figure 24. Energy demand mix over time for different percentages of neighbours that invested in clean gas and different clean gas begin prices. . Begin clean gas price varied between [2 – 8] with increment of 2. Amount of patches in a situation was measured every tick.

From figure 24 it was concluded that

- A clean gas begin price between 2 and 4 would result in behaviour that would be very sensitive to the begin conditions, which was expected from the experiments in group 1.
- The influence of the neighbourhood interaction changes when the required percentage is more than 20%.

To investigate the dependence of distance, the parameter setting (begin clean gas price, begin electricity price) was set (3, 2). Figure 25 shows the result

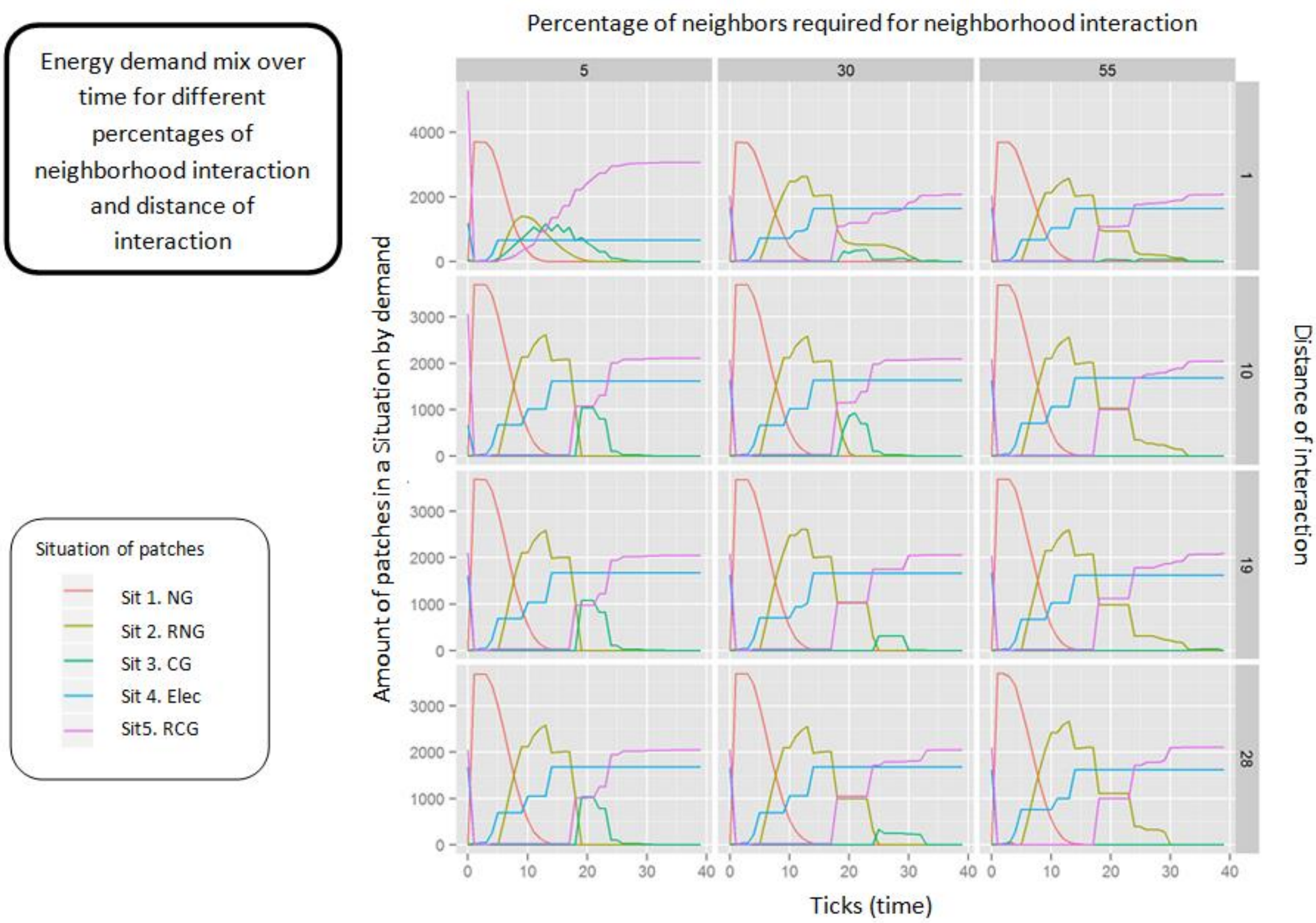


Figure 2.5 Energy demand mix over time for different critical densities. . (begin clean gas price , begin electricity price) = (3, 2). Amount of patches in a situation was measured every tick.

From figure 25 it can seen that

- The influence of the neighbourhood interaction does not exist anymore when the required when the radius is 10 or more.
- Again it can be seen that the influence of the neighbourhood interaction changes when the required percentage is more than 20%.

A smaller parameter space was set for the distance, the results are in figure 26.

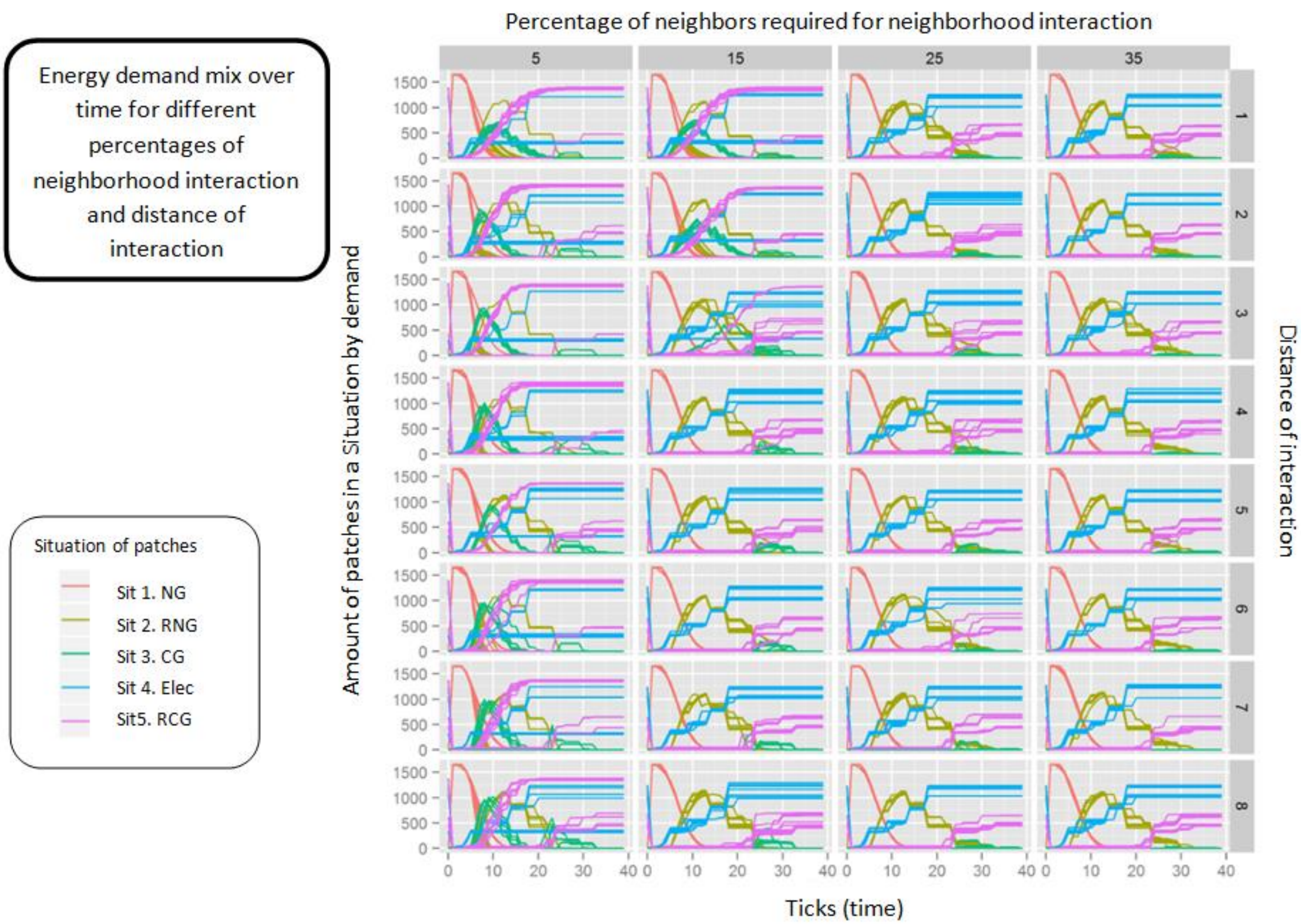


Figure 26. Energy demand mix over time for different critical densities.. (begin clean gas price , begin electricity price) = (3, 2). Distance to agent varied [1-8] with increment 1 and percentage of neighbours with clean gas varied [5-35] with increment 10. Amount of patches in a situation was measured every tick.

Figure 26 shows:

- The system is very sensitive to the distance between the agent and its neighbours. Several runs were carried out, which show that in the area where a switch between clean gas and electricity as dominant energy carrier is observed, chaotic behaviour is expected. The system is very sensitive to the percentage of neighbours needed for clean gas and the distance between the agents.

Discussion

This experiment shows that the development of clean gas and electricity is dependent on the amount of neighbourhood interaction. For a percentage of more than 20% required to switch to clean gas, the system is robust because no difference can be observed beyond this threshold. The same holds for a distance of more than four agents. As has been shown before in the first group of experiments, the system is very dependent on the begin price of clean gas. Figure 26 shows also that there are different possible outcomes in the area where a switch is expected with regards to the price development. In this field, the amount of neighbourhood interaction can be decisive.

In figure 24 an unexpected peak was observed. This results must be a calculation error in the model, and does not give rise to uncertainty in the rest of the experimental results as it has not been seen in other parts of the experimental results.

Conclusion

From this second group of experiment it can be concluded that the critical density necessary to make the switch to clean gas is important in the overall emergent behaviour of the system. A strong suggestion has been shown that the percentage and distance between home owners to influence each other is important.

This can be important for policy makers. Policies that are aimed at encouraging the dialog between neighbours will influence the evolution of the use of clean gas. This can be done by for example organizing neighbourhood meetings. Home owners that are not close neighbours can be broad in contact with each other.

Another way to stimulate the self-organisation and form a collective incentive has been used by the fiberglass industry as has been explained in chapter 1, the Introduction. This method to stimulate self-organisation has been backed-up by the results of this research.

As has been posed before, the critical density required to switch to clean gas can be seen in two ways. It can be seen as behaviour component of the agent, switching when there are convinced by their neighbours. But it can also be seen as obligation forced by the gas company. If a certain amount of neighbours are using clean gas, the agent itself is forced to use clean gas. The fact that the critical density required to switch to clean gas is important makes tools to stimulate gas companies to use a smaller required critical density to distribute clean gas more important. This can be done by subsidising gas companies to use a lower required critical density.

Experiment 3: Influence of the relocation and inconvenience factor

To investigate the influence of the relocation periodicity of home owners and how important the inconvenience is they experience when they install new technology or refurbish their homes, several experiments have been done.

Relocation

First the possibility for agents to invest when they relocate thereby not experiencing any (extra) inconvenience for the technology, is made impossible. It is expected that without the relocation factor, agents will choose technologies with low inconvenience.

If figure 27 is compared with figure 18 the influence of the relocation module can be seen. The same settings have been used, only the relocation module has been excluded.

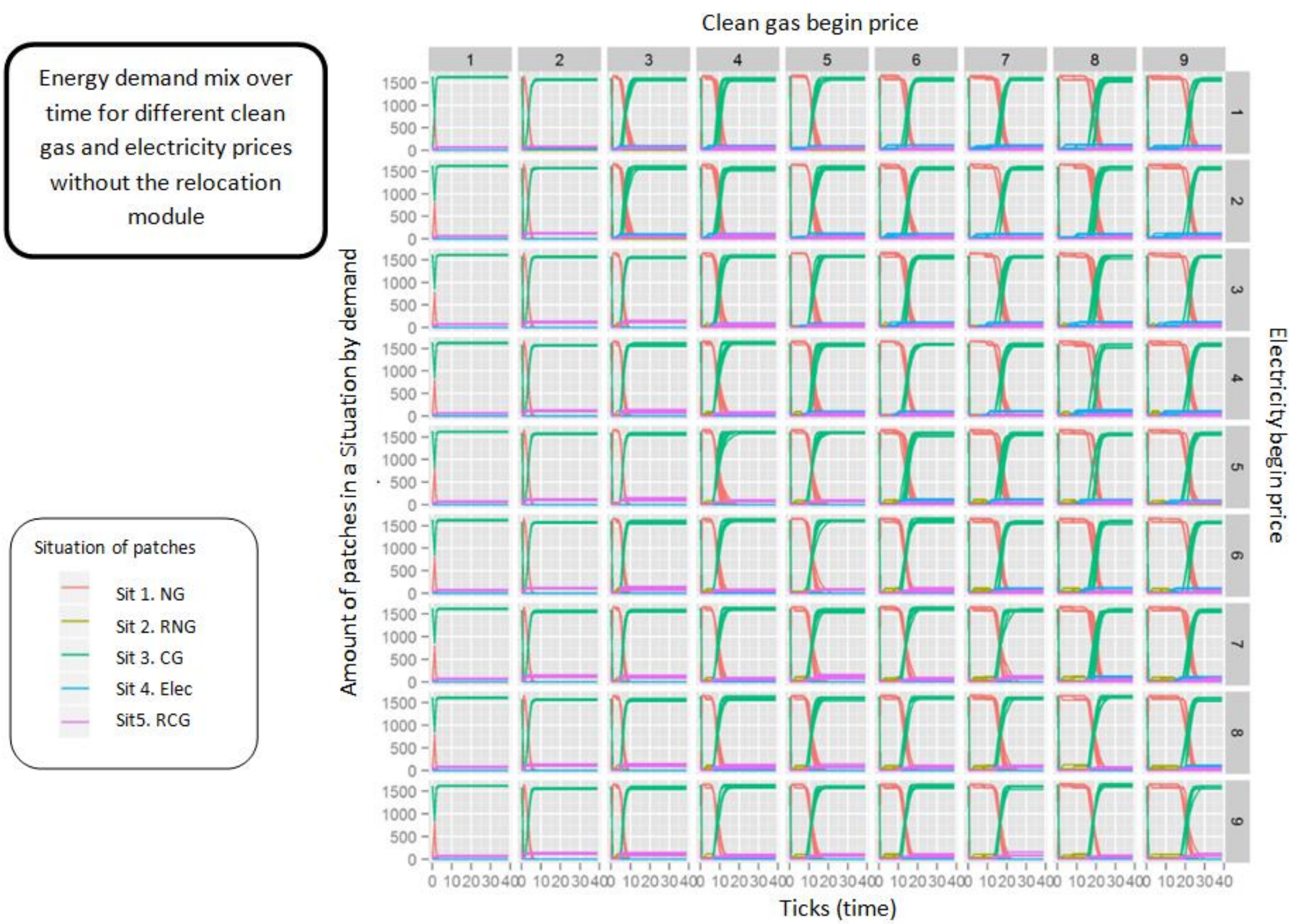


Figure 27. Energy demand mix over time for different electricity and clean gas begin price with the relocation module off. . Begin electricity and clean gas price varied between [1 – 10] with 1 increment. Amount of patches in a situation was measured every tick. 10 repetitions.

Figure 27 shows:

- The relocation and inconvenience of the different technologies has a big influence. Without the ability to invest when agents relocate, the inconvenience factor is critically important as all agents choose Situation 3, the situation with lowest inconvenience. With relocation, the inconvenience factor is excluded, so without relocation, the inconvenience module gets greater importance.

Inconvenience factor within the price behaviour module

In this experiment, all behaviour modules were available for the agents, but the distribution of the inconvenience factor assigned to the agents was changed to investigate the importance of the agents' factor on the overall emergent behaviour.

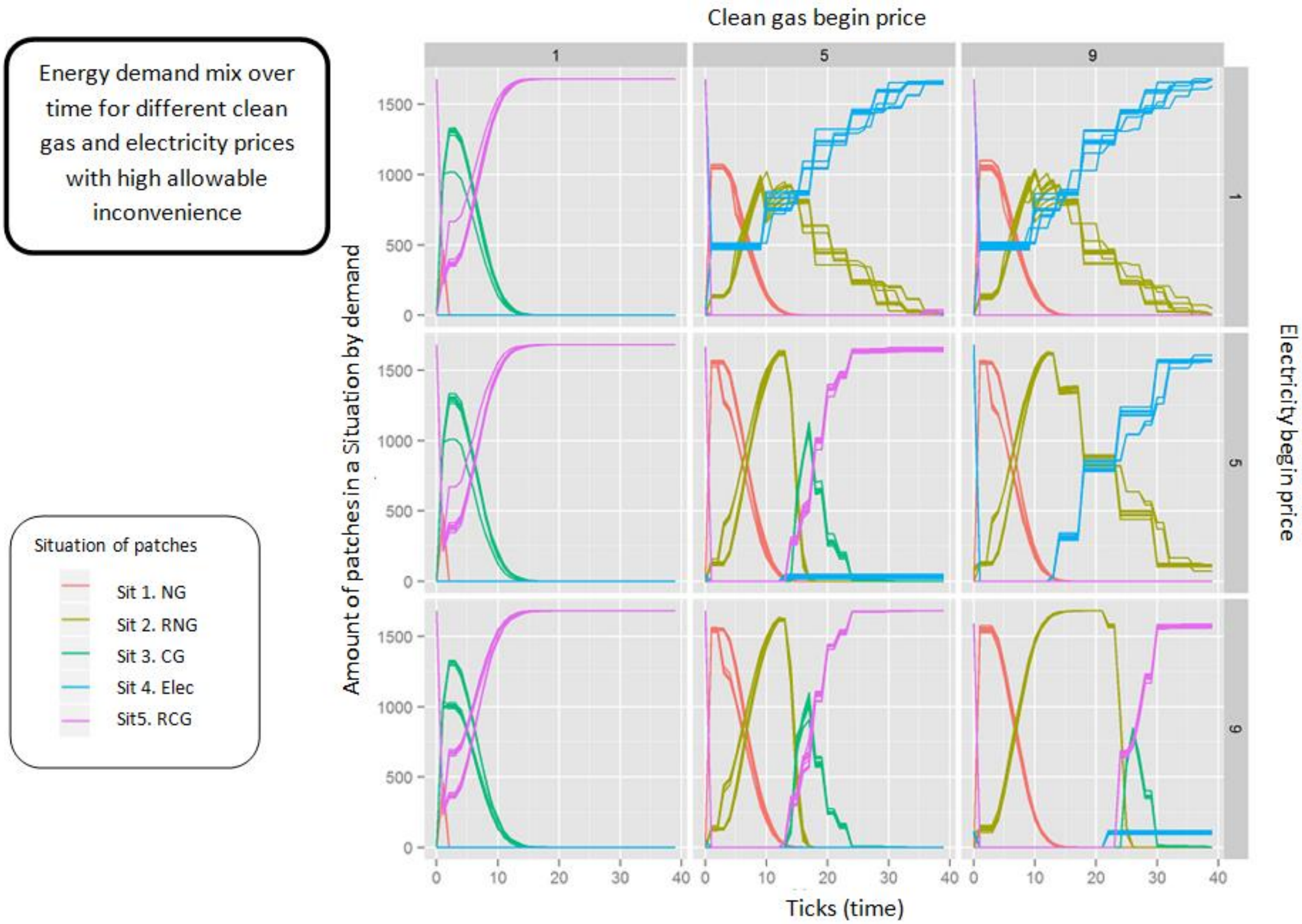


Figure 28. Energy demand mix over time for different electricity and clean gas begin price with low allowable inconvenience. Inconvenience mean = 10, inconvenience min = 11, inconvenience max = 10, inconvenience standard deviation = 1. . Begin electricity and clean gas price varied between [1 – 9] with 4 increment. Amount of patches in a situation was measured every tick. 10 repetitions.

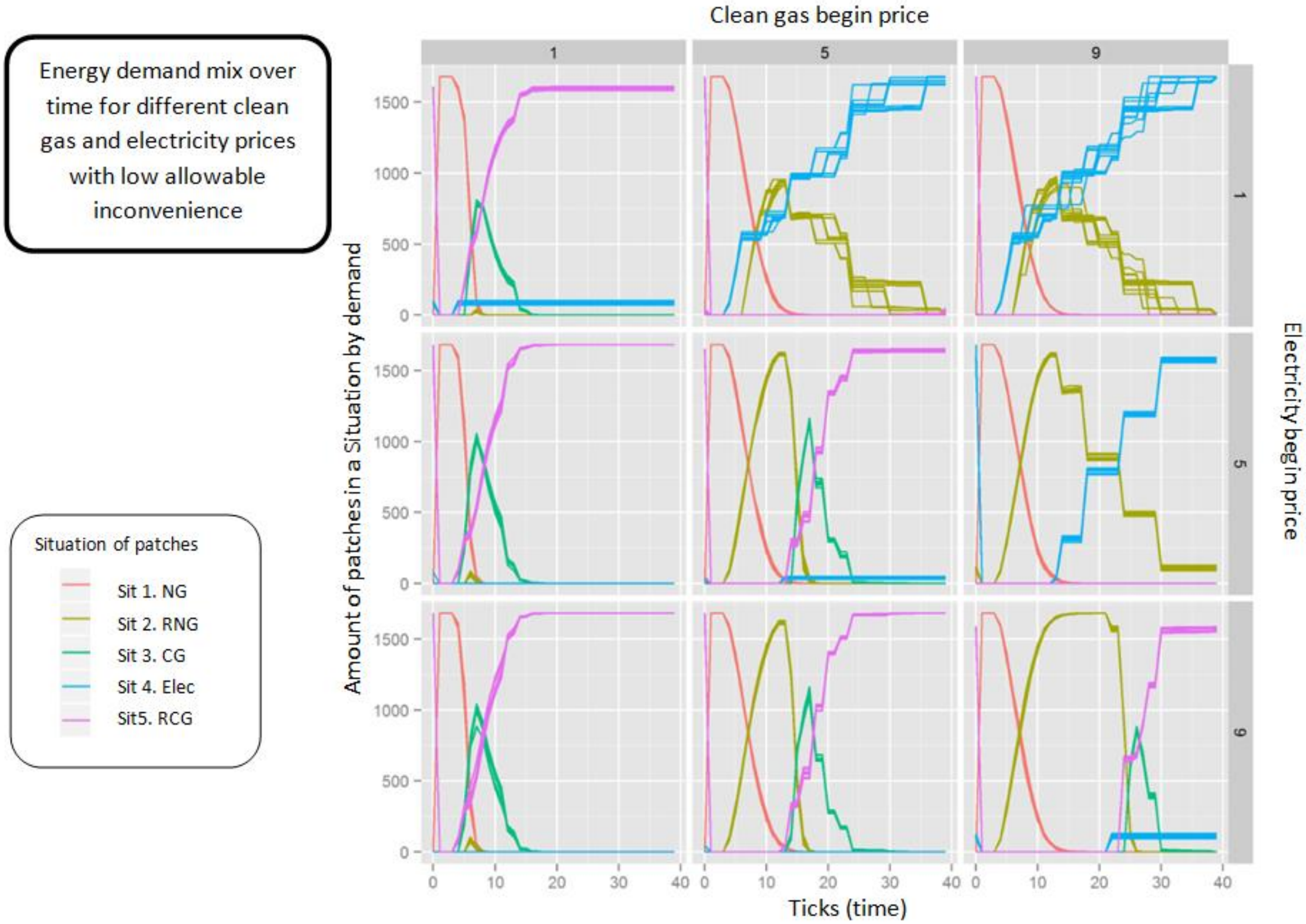


Figure 29. Energy demand mix over time for different electricity and clean gas begin price with low allowable inconvenience. Inconvenience mean = 2, inconvenience min = 1.5, inconvenience max = 2, inconvenience standard deviation = 1. . Begin electricity and clean gas price varied between [1 – 9] with 4 increment. Amount of patches in a situation was measured every tick. 10 repetitions

Figure 29 shows the development of the different situation if the agents allow only for very low inconvenience. This figure can be compared with figure 45 with a very high allowable inconvenience. In these experiment agents were still able to choose technologies with higher inconvenience than they normally allow because when they relocate they don't experience this inconvenience. It can be seen that

- With a low inconvenience factor, agents will postpone their investment decision a few years. Something you would expect to happen as less investment options will be considered as these investment options will have an inconvenience factor that is too high.

- The development of the energy demand mix is still quite similar because of the fact that when agents relocate, they are still able to choose technologies with higher inconvenience then they normally allow.

In appendix B the figure for the overall system costs of the associated parameter settings can be found, figure 42, 43.

Discussion

From the robustness of the result it can be concluded that the assumptions on the behaviour of home owners with regards to their inconvenience they allow do not affect the end energy demand mix. Besides that the general development of the different technologies is also very familiar.

In the relocation experiment it has been shown that relocating is a big chance for home owners to change their heating system. The relocation periodicity of home owners and the assumptions that they experience less inconvenience when they relocate are very strong which makes this conclusion robust.

Conclusion

The conclusion of this part of the experiments is twofold. On the one hand it shows that different policies with regards to the inconvenience of switching technology can influence the adoption rate at which agents make technology decisions. In this way they can obtain an overall system cost that is lower over the whole runtime. These policies could include better communication about the inconvenience home owners will experience overcoming unnecessary anxiety. Besides that, installation practices could be changed to minimize the inconvenience home owners will experience. On the other hand it has been shown that the general development of the different technologies is robust on the assumption of the behaviour of home owners in regards to the range of inconveniences they allow and possibly experience.

On the relocation aspect it has been concluded that inconvenience is very important as the development of the energy demand mix is very different if home owners always experience inconvenience. On the other hand policies aimed at encouraging people to invest in a different heating technology when they relocate are backed up by the results of this experiment. The presumption that relocating is a big chance for home owners to change their heating system is supported by the results of this research.

Experiment 4: Placing clean gas seeds

In the fourth group of experiments, two areas in the world of patches were forced to switch to clean gas at a certain tick. In a world of 41 by 41 patches (1681 total), two neighbourhoods of three by three (18 patches in total) patches were set on Situation 3 at a certain tick as shown on tick 1 in figure…

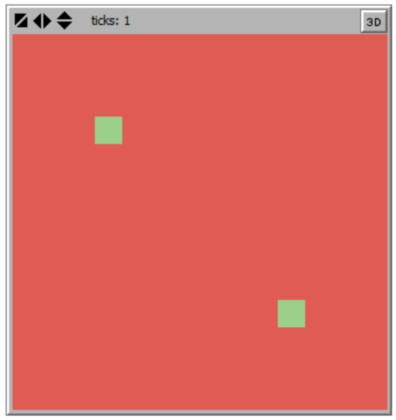


Figure 30. Picture of the world (41 by 41 patches) at the first tick with two seeds (3 by 3 patches) put in place.

At first the place and the size of the seeds were determined on the intuitive logic. The seeds needed to be small enough to get interesting behaviour (behaviour that shows sensitivity to initial condition to the model outcome). If they were too large, the system would immediately switch to clean gas, if they were to small, the system would go to electricity as been explained in the first group of experiments.

An example of a development over time of the energy demand mix with seeds is shown in figure.. Red means a patch that uses natural gas (Sit 1.), orange a patch that has renovated but still uses natural gas (Sit. 2), bleu means a patch that uses heat pumps and thus electricity (Sit. 4), light green patches have switched to clean gas (Sit. 3.) and darker green patches switched to clean gas and also renovated their homes (Sit. 5).

In the first "world" it can be seen that already many patches made an investment, but still there is a large potential for clean gas. When times goes on, more patches choose for heat pumps and at the end, because so many patches already have electricity, the neighbourhood interaction to switch to clean gas is to weak too break through all the blue patches.

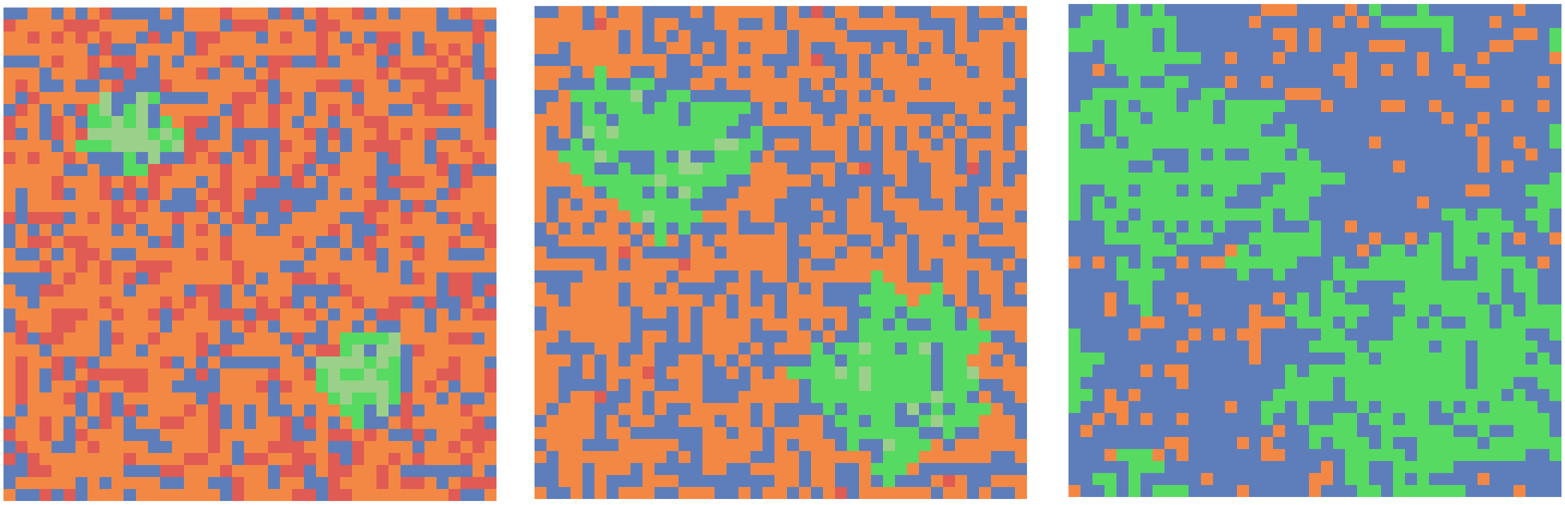


Figure 31. Development over time (tick 6, 15, 23) of the world of patches representing home owners using different space heating technology. Seeds were placed at tick 4. Red: natural gas (Sit 1.), Orange: renovated natural gas (Sit. 2), Bleu: heat pumps, electricity (Sit. 4), Light green: clean gas (Sit. 3.) and Darker green renovated clean gas(Sit. 5).

In the first experiment, the time at which the seed was placed was investigated in relation to the percentage of neighbours that were needed to switch to clean gas. It was observed looking at the development of the world of patches that because of the price assumption on electricity and clean gas, electricity will start to gain share in the energy demand mix from the first tick. Because the patches that choose electricity are randomly distributed it will get harder for the neighbourhood interaction to break through these patches when the electricity density is too high in a specific region.

The results are shown in figure 32.

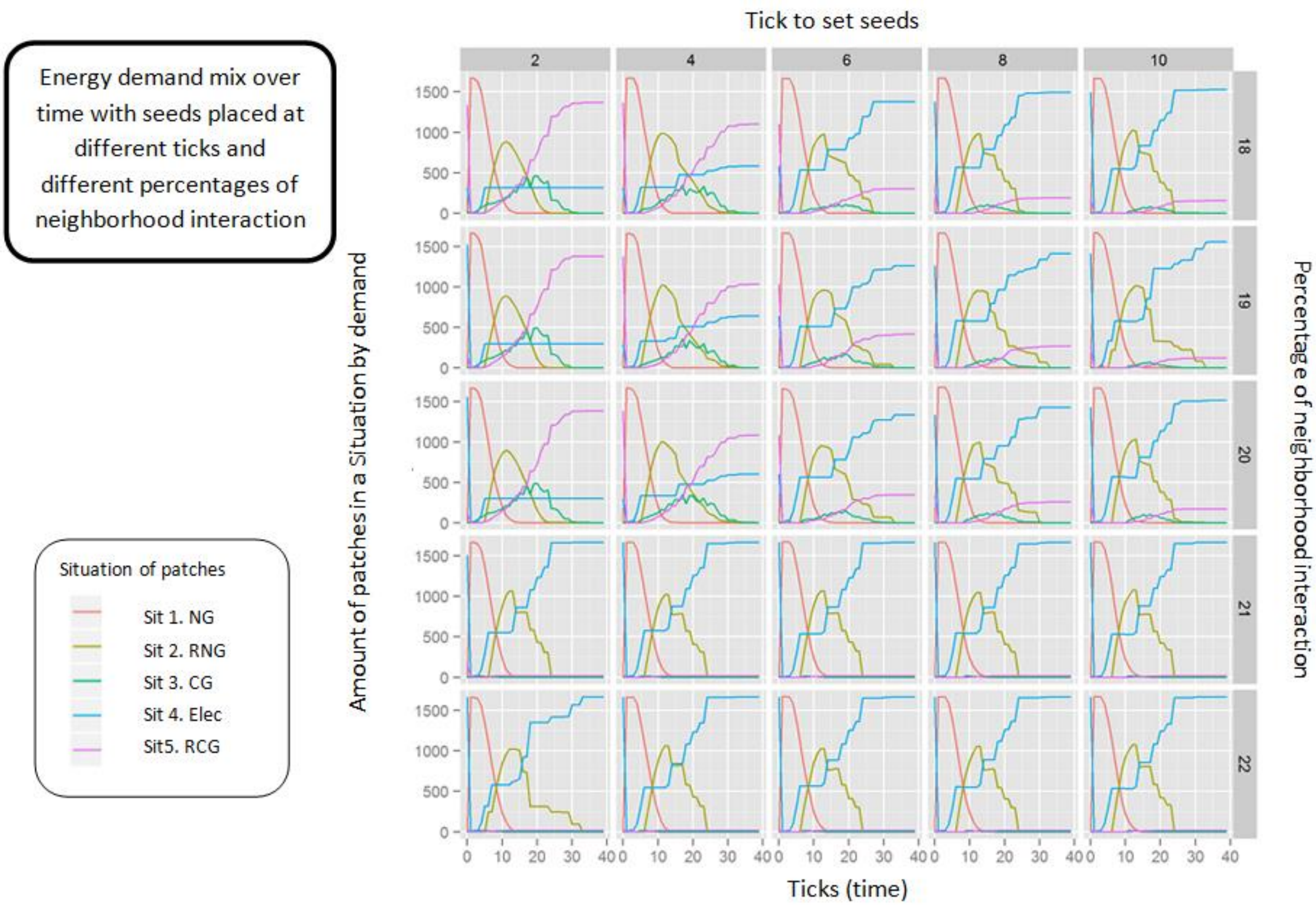


Figure 32. Energy demand mix over time with two seeds (3 by 3 patches) of clean gas placed at different ticks evaluated over different percentage of neighbours needed to switch to clean gas. Size of world is 1681. Amount of patches in a situation was measured every tick.

The experiment shows that

- The model is sensitive to what tick the seeds are placed. If the seed is placed before tick 4, clean gas will be the dominant energy carrier. If the seeds are placed too late, they will not influence the evolution of the energy demand mix anymore and electricity will be the dominant energy carrier.
- As has been shown before, the model shows clear neighbourhood interaction when the percentage needed for clean gas is 20% of lower.

To investigate the area where a switch is expected based on the price development of electricity and clean gas on the overall energy demand mix, an experiment was carried out at (begin clean gas price , begin electricity price) = (6, 4) shown in figure 33.

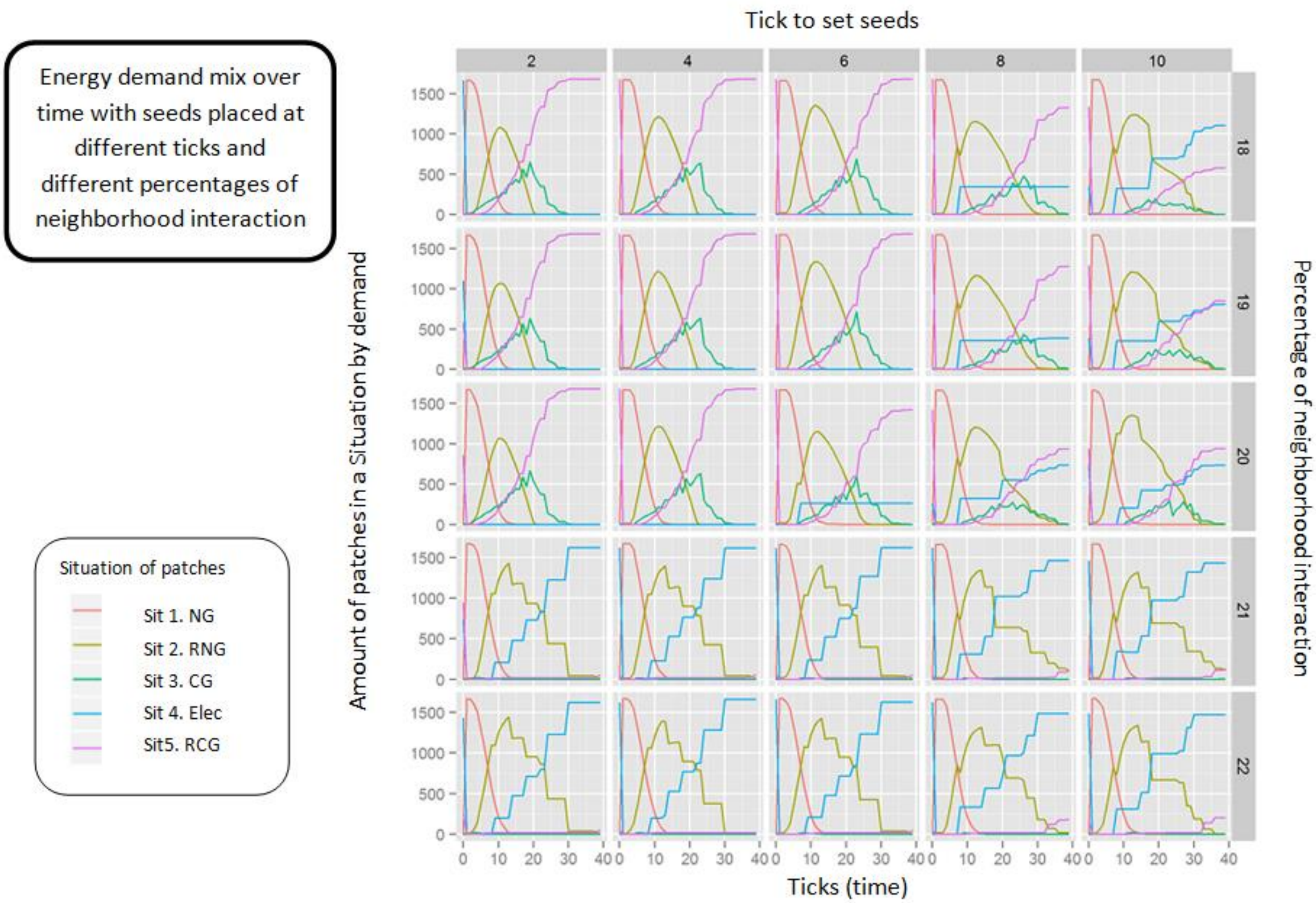


Figure 33. Energy demand mix over time with two seeds (3 by 3 patches) of clean gas placed at different ticks evaluated over different percentage of neighbours needed to switch to clean gas. Size of world = 1681. Clean gas price and begin electricity price and was set on (6,4) .Amount of patches in a situation was measured every tick.

The figure shows that:

- Again, the model is sensitive to what tick the seeds are placed. If the seed is placed before tick 10, clean gas will become the dominant energy carrier. If the seeds are placed to late, they will not influence the evolution of the energy demand mix any more and electricity will be the dominant energy carrier.
- Again, has been shown before, the model shows clear neighbourhood interaction when the percentage needed for clean gas is 20% of lower.

The associated overall system costs are shown in figure 34 and develop as expected.

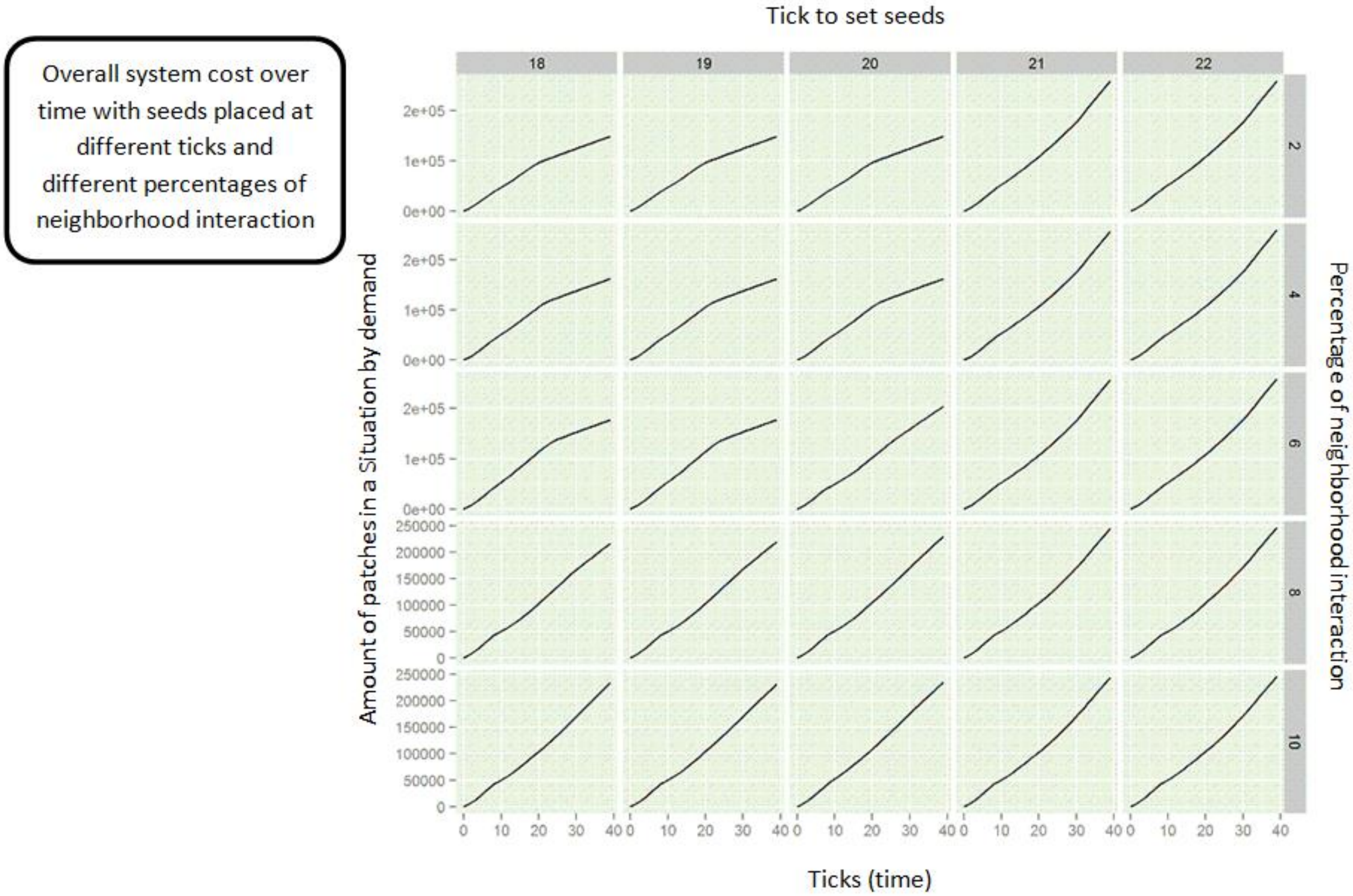


Figure 34. Overall system cost over time with two seeds (3 by 3 patches) of clean gas placed at different ticks evaluated over different percentage of neighbours needed to switch to clean gas. Size of world = 1681. Clean gas price and begin electricity price and was set on (6,4). Overall system costs were measured every tick.

Discussion

In the two experiments, different time constraints for the seeds placement were observed showing that there is dependence on the initial conditions (price of clean gas and electricity predominantly) on the time the seeds are placed that initiate a switch in emergent behaviour of the system. The model does not show at which tick the seeds needs to be placed but shows that, at which tick the seeds are placed can be very important. This result is very robust as it is shown with several different initial conditions. The experiment show also that a percentage of more than 20% already shown in experiment group two is again confirmed also under these different conditions making this a robust result for the model.

It’s difficult to predict how strong the connection between neighboring home owners exactly is. However, Literature shows that neighbourhood interaction is very strong (Cabinet Office, 2011). Therefore conclusion can be drawn for this group experiments.

Conclusion

This group of experiments show that the time at which a neighbourhood is forced to switch to clean gas is very important for the further development of clean gas in the region. Placing seeds will have a large influence on the development on clean gas in the region, and if placed early enough, the larger this region will become making a large impact on the overall system cost.

At which time this should be done is not shown by the model, but it does show that a careful time planning is important. The time at which a switch occurred on the emergent system behaviour was dependent on the price development of clean gas and electricity. Placing the seeds too late, at a time that a lot of home owners already made a decision to use heat pumps, will not have the same effect on the overall energy demand mix and overall system cost as when the seeds are placed early. In general it has been shown that, the earlier, the better.

10. Conclusion

To investigate the development of the energy demand mix for space heating using different heating technologies, an agent based model has been created that captures the essence of the behaviour of home owners and their environment. Assumptions of this behaviour and the world around them were made based on literature and reality. The model can be seen as realistic but abstract representation of the problem addressed as has been argued in chapter 4, System identification and decomposition.

The following questions can now been answered based on these model experiments that have been carried out:

What factors will be crucial and what influence do they have on the heat system technology choice of households in the decision between a collective incentive for clean gas or an individual choice for electricity as energy carrier for space heating.

What consequence does this have on the sustainable usage of a gaseous energy carrier in the energy mix in 2050 under the assumption that CO_2 emissions will have to go down by 80% in 2050.

The main conclusions of the experiments are:

- The begin level of clean gas and electricity has a large influence on the emergent system behaviour. Clean gas can be the dominant energy carrier in 2050 but only if the price difference between clean gas and electricity is small. In this area the development of the price of clean gas and electricity can be a decisive factor in which one will be dominant.
- The critical density needed to switch to clean gas and the distance of neighbourhood interaction is important. If a too large critical density is chosen, the switch to clean gas because of the critical density will not have an effect on the system.
- The inconvenience or the lack of inconvenience associated with the installations of a new space heating technology is important as low inconvenience supports early adoption of new technology. The difference in inconvenience between electricity and clean gas is less important. The influence of the difference in inconvenience level between electricity and clean gas cannot be distinguished in this model as the development of the energy demand mix has the same characteristics.
- When neighbourhoods are forced or strongly stimulated to switch to clean gas, the time at which this policy is put in place is very important. Placing these clean gas seeds to late, at a time that a lot of home owners already made a decision to use heat pumps, will lead to an electricity dominated energy demand mix and associated overall system costs which are different from the energy demand mix when the seeds are placed early where clean gas can be the dominant energy carrier.

The energy demand mix development and the associated emergent system behaviour are robust under different large variable ranges showing that these variables are less important in the overall system behaviour.

- Assumptions on the price development are only important when the difference between clean gas and electricity is small.
- The level of inconvenience of the technologies and the inconvenience allowance of the home owner are less important because there are several ways to get around this inconvenience, for example by investing when people relocate.

However, in places where a switch between clean gas and electricity as emergent behaviour is expected these variables can be decisive.

To answer the second research question,

The development of the energy demand mix and its associated overall system cost depends on a lot of factors. This research has identified several factors that are important to keep a sustainable share of a gaseous energy carrier in the energy demand mix in 2050 under strict European CO_2 emission regulation. The results of the research show that clean gas can take a significant share of the energy demand mix for space heating but only with policies or stimulation activities in place to support the collective incentive of the development of clean gas.

11. Recommendations for policy makers

A world where clean gas is dominant over electricity is associated with the lowest overall system costs because of the price development of electricity and clean gas. Under business as usual conditions however, electricity will be the dominant energy carrier in 2050. Therefore policies that stimulate clean gas over electricity are necessary. There are different ways to do this that are supported by the model experimental outcome.

First of all the externalities of CO_2 emissions from fossil fuels need to be included in the price of these fuels. The model has made assumptions on how this CO_2 could develop and following this assumption, this research can make several recommendations for other policies.

Because of the importance of the price of clean gas and electricity in the energy demand mix development, taxes or subsidies that level of the difference between clean gas and electricity are backed up by this research. The model shows that they do not need to be at the same level, a small difference will be overcome by other behaviour aspects of home owners.

Policies that are aimed at encouraging the dialog between neighbours will influence the evolution of the use of clean gas. This can be done by for example organizing neighbourhood meetings in which neighbours can be brought in contact with each other. Lessons can be learned from the fiberglass industry, which sets threshold minimums on local support before they unfold their fiberglass network.

When the inconvenience hurdle of some of the technologies that home owners experience can be reduced, this will stimulate early investments but it has less effect on clean gas development.

Stimulation of a particular neighbourhood to switch to clean gas can be very effective in the adoption of clean gas in the region around it. However, time management in this case is very important. When these neighbourhoods come too late, home owners have already made a decision to switch to heat pumps and the group of home owners that could be interested in clean gas is too small.

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Appendix A. Parameter setting of variables

Variables		Based on	Standard value	Rationale
Agents behaviour factors				
Relocation factor	mean	literature	7	See introduction
	standard deviation	assumption	3	only very few people move more then once in 5 year
	maximum	literature	15	
	minimum	assumption	2	
Reduction factor	mean	assumption	3	People will make an investment if they can reduce 20% on their energy bill.
	standard deviation	assumption	3	
	maximum	assumption	10	some people will never change their heating system, because they don't care about the bill
	minimum	assumption	1	some people try reduce where ever they can
inconvenience factor	mean	assumption	4	people generally don't care about a boiler replacement
	standard deviation	assumption	3	
	maximum	assumption	11	
	minimum	assumption	1.5	
percentage of neighbours needed for cleangasbonus		assumption	5	very easy to convince your neighbours
neighbouring distance clean gas bonus		assumption	1	only look at close neighbours
percentage of neighbours needed for social reaction		assumption	5	very easy to convince your neighbours
neighborindistance social reaction		assumption	1	only look at close neighbours
Procedures	relocation	assumption	aan	
	price	assumption	aan	
	social reaction	assumption	aan	
	clean gas switch	assumption	aan	
Inconveniencebonus		assumption	no bonus	assumption

Objects behaviour

natural gas price	minimum	assumption	0.01	assumption CO2 price can not be zero or lower
	begin level	literature	2	is the same as elecbegin price level as CO2 emission of heatpump is the same as CO2 emission of boiler
	punishment	assumption	1	
electricity price	variable	assumption	1.0004	At 81 x 81 patches
			1.002	At 41 x 41 patches
	begin level	literature	2	is the same as NG begin price level
	end level	assumption	10	
clean gas price	variable	assumption	1.0004	At 81 x 81 patches
			1.002	At 41 x 41 patches
	begin level	assumption	8	
	end level	assumption	2	is the same as NG begin price level, begin NG price level has no CO2 taxation

Model restricitions

Fifty target			20	
maxtime			40	Assumption of model, 2050.
seed				
size of world			6561	81x81
refurbishment factor		literature	0.8	

Table 36. Parameter setting for all variables in the model

Appendix B. Results of experiments

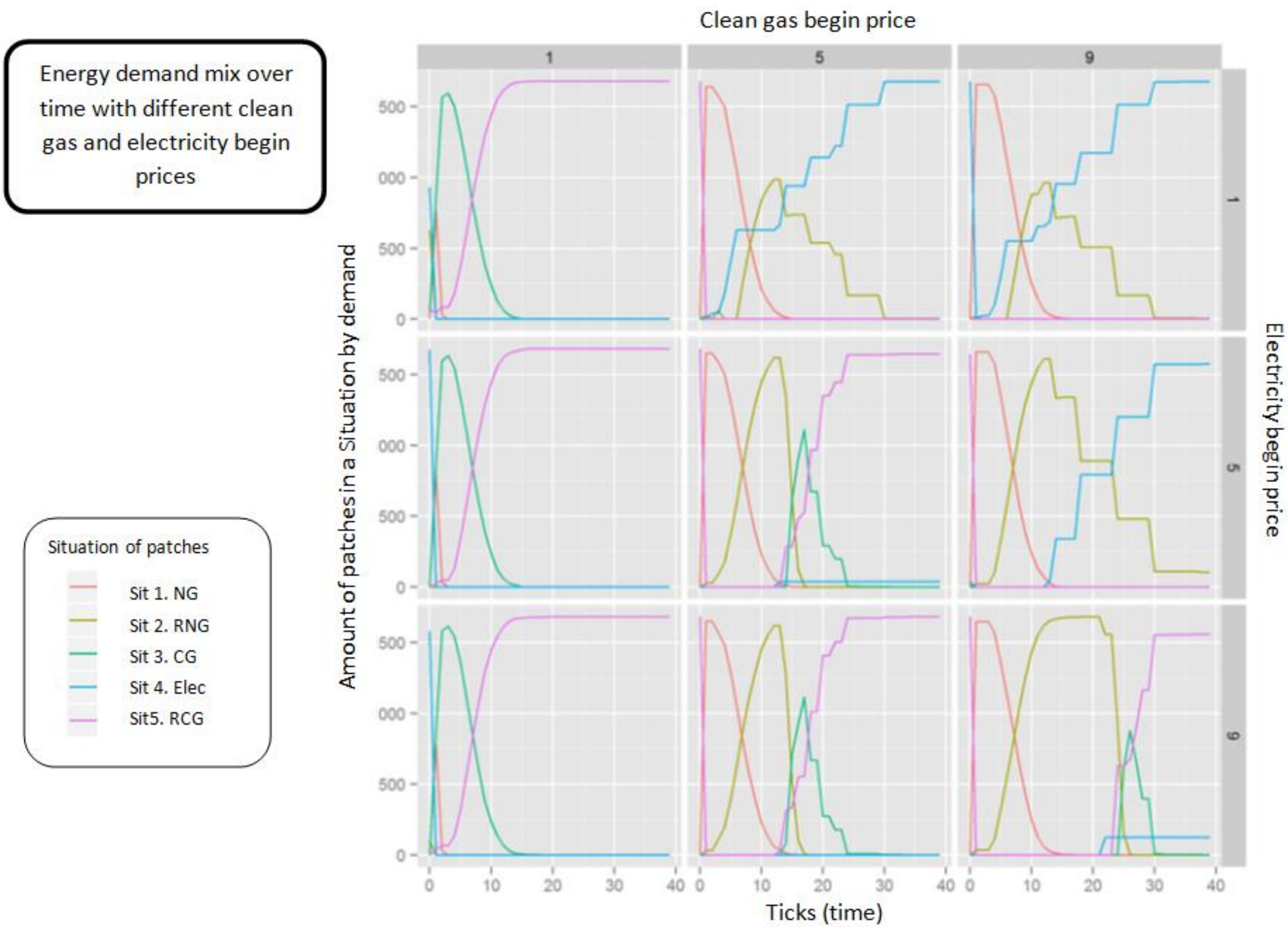

Figure 37. Energy demand mix over time for different electricity and clean gas begin price, zoomed in. . Begin electricity and clean gas price varied between [1 – 10] with 4 increment. Amount of patches in a situation was measured every tick.

Overall system cost over time with different clean gas and electricity begin prices

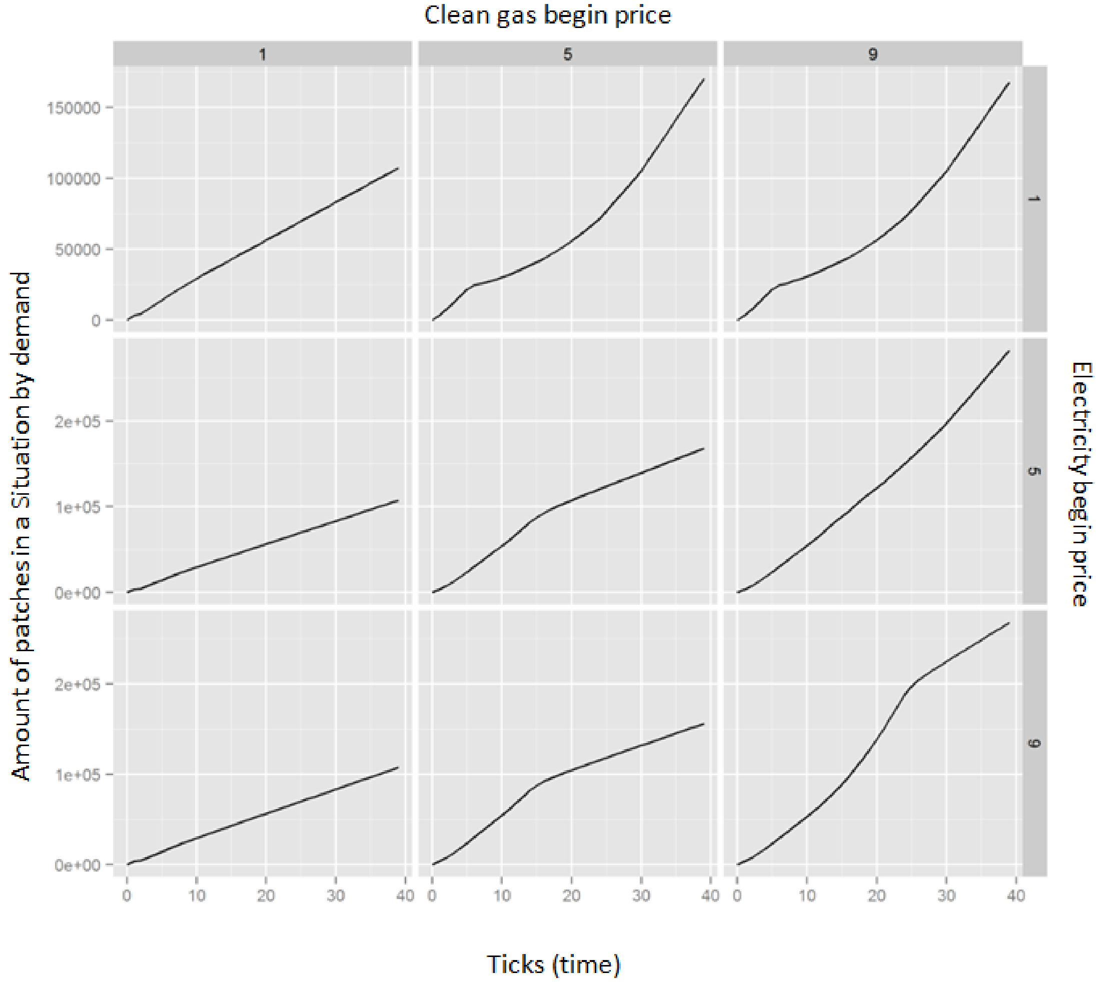

Figure 38. Overall system cost development over time with different clean gas and electricity begin price levels, zoomed in. Begin electricity and clean gas price varied between [1 - 9] with 4 increment. Overall system cost was measured every tick.

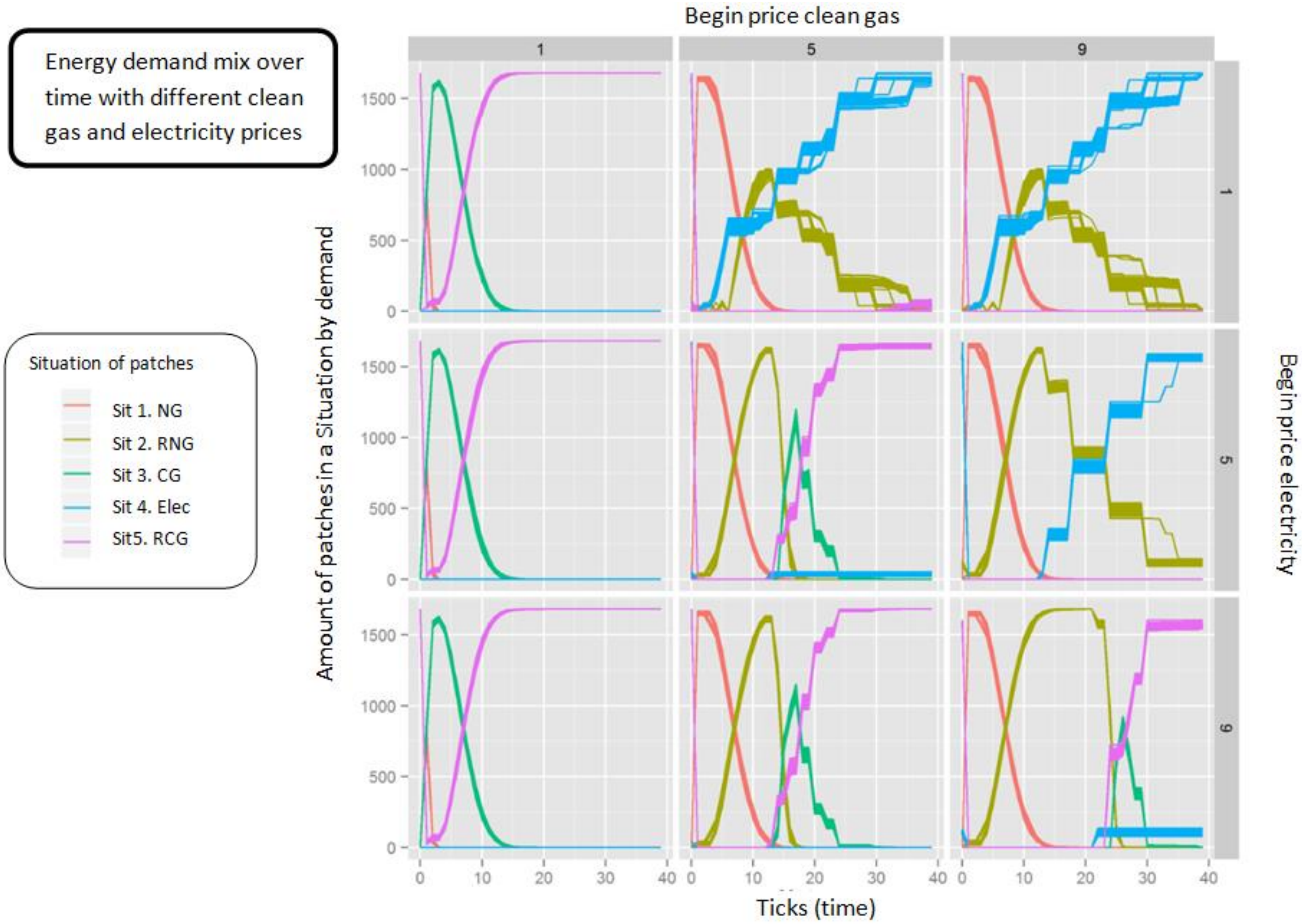

Figure 39. Energy demand mix over time for different electricity and clean gas begin price, zoomed in. . Begin electricity and clean gas price varied between [1 – 10] with 4 increment. Amount of patches in a situation was measured every tick. Every parameter setting was run 10 times.

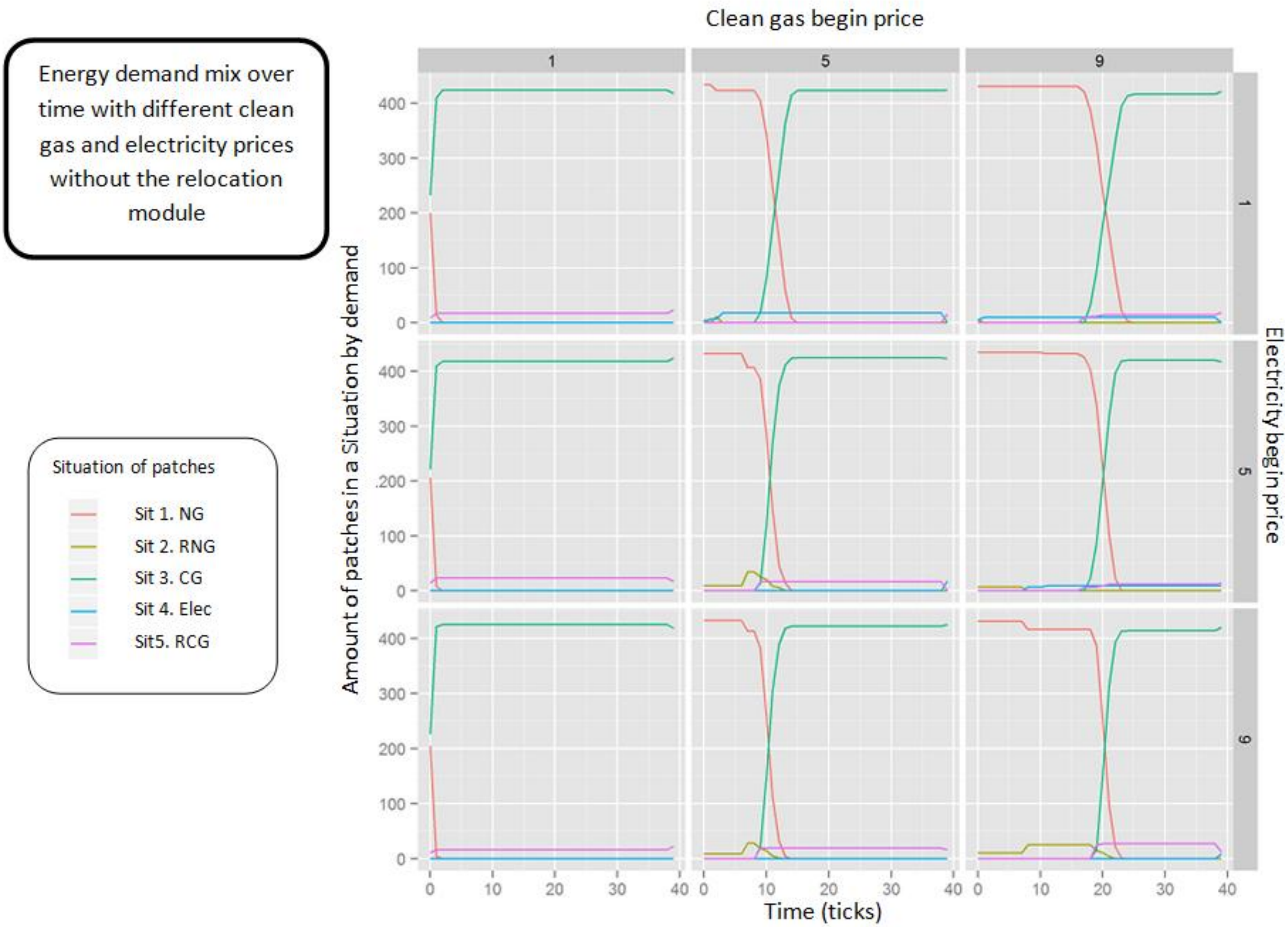

Figure 41. Energy demand mix over time for different electricity and clean gas begin price with the relocation module off, zoomed in. . Begin electricity and clean gas price varied between [1 – 9] with 4 increment. Amount of patches in a situation was measured every tick.

Overall system costs over time for different clean gas and electricity prices with low allowable inconvenience

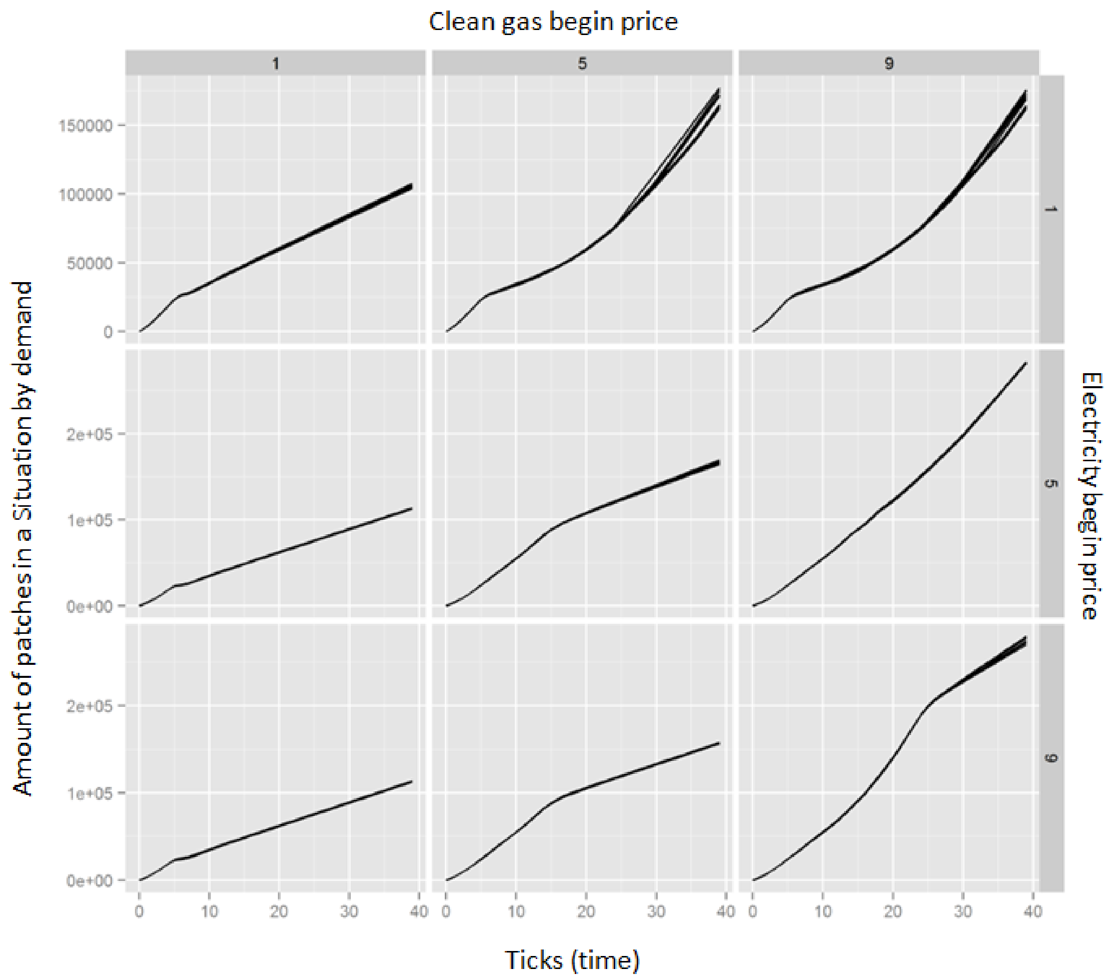

Figure 42. Overall system cost over time for different electricity and clean gas begin price with low allowable inconvenience. Inconvenience mean = 2, inconvenience min = 1.5, inconvenience max = 2, inconvenience standard deviation = 1. . Begin electricity and clean gas price varied between [1 – 9] with 4 increment. Amount of patches in a situation was measured every tick. 10 repetitions

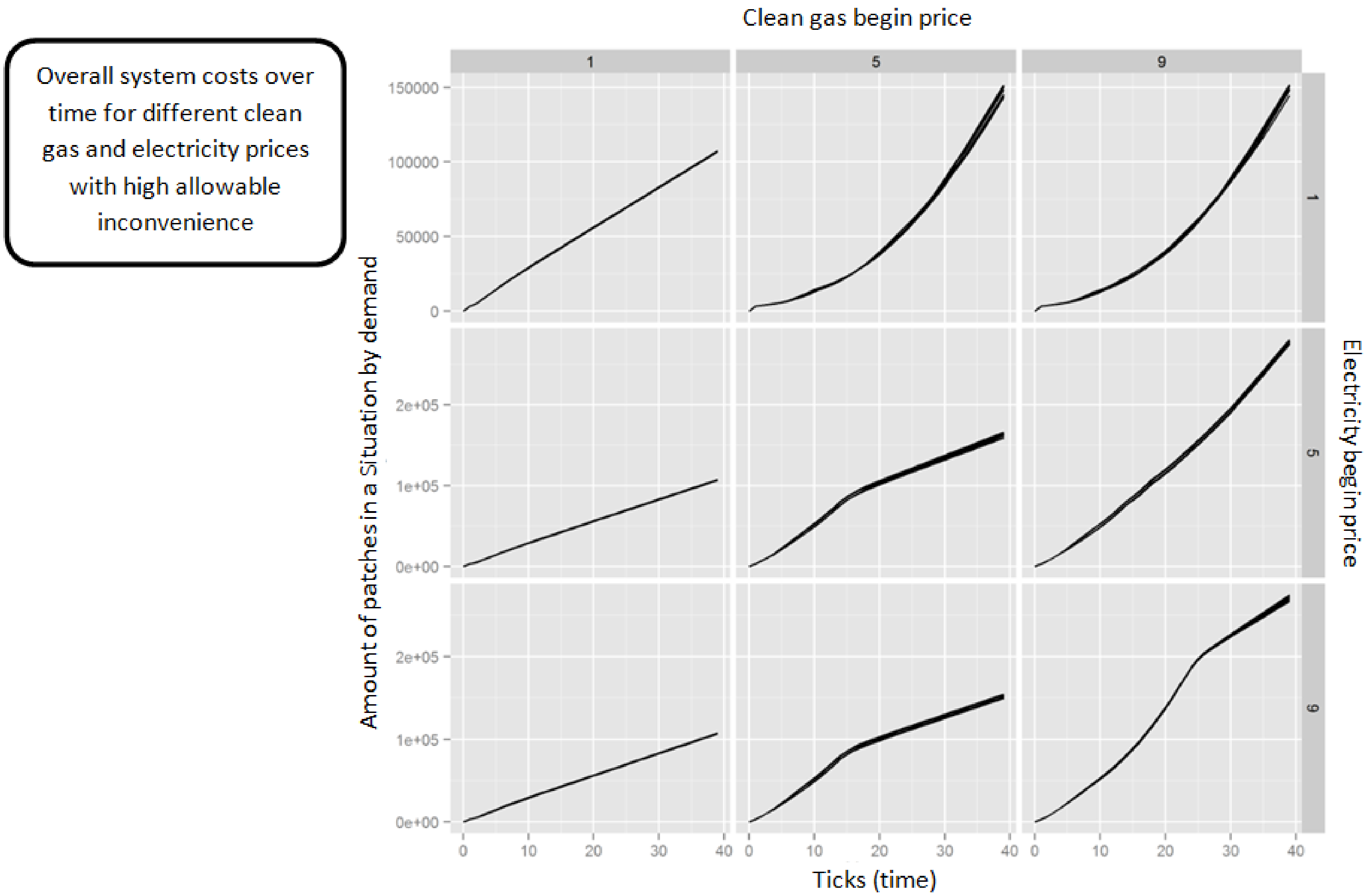

Figure 43. Overall system cost over time for different electricity and clean gas begin price with low allowable inconvenience. Inconvenience mean = 10, inconvenience min = 11, inconvenience max = 10, inconvenience standard deviation = 1. . Begin electricity and clean gas price varied between [1 – 9] with 4 increment. Amount of patches in a situation was measured every tick. 10 repetitions.

Appendix C. Source code of model

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;    GLOBALS  ;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

patches-own [relocationfactor reductionfactor inconveniencefactor bill oneprocentofbill
oneprocentofbill2 situation  socialpressure pricereaction relocationreaction socialreaction
situationdummy socialpressuredummy

  elec ng cg refurb listincon1 listincon2 listincon3 differencelistoffer cleangasbonus]
  ; situation discripment

globals [
  ;setup interfaceknoppen

  elecrun cgrun co2run showelecprice showcgprice showemissiontarget

  ;bill calculation globals
ngsum cgsum elecsum overallsystemcost ngprice elecprice cgprice virtualticks virtualngprice realngprice
real-virtualdifference emissiontarget sizeofworld percentageemissiontarget

  ;bill calculation interfaceknoppen

offer calculation globals
 offer1 offer2 offer3 offer4 offer5 listoffer

 ;inconvenience globals
 inconsit12 inconsit14 inconsit13 inconsit15 inconsit24 inconsit25 inconsit35

 ; make-tech-choice globals

 ; price globals
 differencelistoffercheck1 differencelistoffercheck2 differencelistoffercheck3
 sit10choice sit20choice sit30choice

 ; relocation globals
 sumlistoffer sit1choice sumoflist1 sumoflist2 sumoflist3

 ; social pressure globals
  amountofneighborsinradius amountofneighboringpatchesinvested amountofneighborswithcleangas
amountofneighborsinradius-cleangas cleangasbonusdummy

 ; social pressure interfaceknoppen

 choice
```

```
 reductionfactorcheck
 differencelistoffercheck

 sumoflist1.1.
 sumoflist2.2.
 sumoflist3.3.

 intersection
 fiftytargetdemand
 NGdemand
 setseed

 direct
 bonusonpricereaction

 amountofpatchesinsit1
 amountofpatchesinsit2
amountofpatchesinsit3
amountofpatchesinsit4
amountofpatchesinsit5
thisistick

]

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;   SETUP PROCEDURES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;

;geef alle huiseigenaren een relocation, reduction and inconvenience factor en geef ze eerste rekening, een gasrekening
;relocation,reduction en inconvenience is normaal verdeeld over de patches met een gemiddelde, een standaard deviatie en een max en min
;reloaction geeft periodische investeringsbereidheid
;reduction geeft minimale besparing aan
;inconvenience geeft maximaal toelaatbare puinhoop aan

to setup
  reset-ticks
  clear-all-plots
  createworld
  give-relocation-reducation-inconveniencefactor
    give-bill
  give-situation
  set-inconveniencetable
  setvariablescorrecttobegin
```

```
 showeleccgngprice
 calculateamountneighbors
 calculateamountneighbors-cleangas
 ask patches [set pcolor 16 set socialpressure false]

 end

to makechoiceforpatch

   if mouse-down?    ;; reports true or false to indicate whether mouse button is down
   [
     ;; mouse-xcor and mouse-ycor report the position of the mouse --
     ;; note that they report the precise position of the mouse,
     ;; so you might get a decimal number like 12.3, but "patch"
     ;; automatically rounds to the nearest patch
     ask patch mouse-xcor mouse-ycor
       [
     set situation mousechoice
    ]
   ]

setallvariablescorrect
update-color
end

to createworld

 set-patch-size patchsize
 set overallsystemcost 0
 set NGdemand 0
 set fiftytargetdemand 0
 set showemissiontarget sizeofworld
 set intersection 0

; EXTRA
set sizeofworld (count patches)

end

 to showeleccgngprice
  set showemissiontarget sizeofworld
  set elecrun 0   set cgrun 0
  set co2run 0
  set showelecprice beginelecprice
  set showcgprice cleangasbeginpricelevel
  set overallsystemcost 0
  set NGdemand 0
  set fiftytargetdemand 0
```

```
  update-plots

while [elecrun < sizeofworld and cgrun < sizeofworld] [

set elecrun (elecrun + 1)
set showelecprice (beginelecprice - ((elecendpricelevel - beginelecprice) / (-1 + elecvar ^ (sizeofworld))))
+ (((elecendpricelevel - beginelecprice) / (-1 + elecvar ^ (sizeofworld)) * elecvar ^ elecrun))
set cgrun (cgrun + 1)
set showcgprice ((((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1)) * cgvar ^ cgrun) +
(cleangasbeginpricelevel - ((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1))))

update-plots
if (precision showelecprice 2  = precision showcgprice 2) [set intersection elecrun]
]
while [co2run < maxtime][
set co2run (co2run + 1)
set showemissiontarget ((((((sizeofworld) / 100) * fiftytarget) - (sizeofworld)) / maxtime) * co2run) +
sizeofworld)

 update-plots
 ]
end

; grafieken lopen tot maxtime


to give-relocation-reducation-inconveniencefactor
  ask patches [set-relocationfactor-for-a-single-patch set-reductionfactor-for-a-single-patch set-
inconveniencefactor-for-a-single-patch]
end

to set-relocationfactor-for-a-single-patch
  set relocationfactor (random-normal relocationfactor-mean relocationfactor-std-dev)
  while [(relocationfactor > maxrelocationfactor) or (relocationfactor < minrelocationfactor)] [ set
relocationfactor (random-normal relocationfactor-mean relocationfactor-std-dev) ]
   set relocationfactor (round relocationfactor)
end

to set-reductionfactor-for-a-single-patch
  set reductionfactor (random-normal reductionfactor-mean reductionfactor-std-dev)
   while [(reductionfactor > maxreductionfactor) or (reductionfactor < minreductionfactor)]  [ set
reductionfactor (random-normal reductionfactor-mean reductionfactor-std-dev) ]
   set reductionfactor (round reductionfactor)
end

to set-inconveniencefactor-for-a-single-patch
```

```
  set inconveniencefactor (random-normal inconveniencefactor-mean inconveniencefactor-std-dev)
  while [(inconveniencefactor > maxinconveniencefactor) or (inconveniencefactor <
mininconveniencefactor)] [set inconveniencefactor (random-normal inconveniencefactor-mean
inconveniencefactor-std-dev)]
  set inconveniencefactor (round inconveniencefactor)

end

to give-bill
 ask patches [ set bill initial-bill ]
end

to give-situation
 ask patches [
   set situation 1
   set elec 0
   set ng 1
   set cg 0
   set refurb 0
   set choice 0

  set pricereaction false
  set relocationreaction false
  set socialreaction false
  set socialpressure false
  set cleangasbonus false
  set socialpressuredummy false
  set situationdummy 1
   ]
end

to set-inconveniencetable

  set inconsit12 6
  set inconsit14 10
  set inconsit13 2
  set inconsit15 7
  set inconsit24 6
  set inconsit25 2
  set inconsit35 6

;  inconveniencebonussen
;INCLUDE veel te ingewikkeld, moet er uit.

simpleinconveniencebonussen
end

to simpleinconveniencebonussen
```

```
if (inconveniencebonus = "refurbbonus") [
  set inconsit12 mininconveniencebonus
  set inconsit14 (6 + mininconveniencebonus)
  set inconsit13 2
  set inconsit15 (2 + mininconveniencebonus)
  set inconsit24 6
  set inconsit25 2
  set inconsit35 mininconveniencebonus
;  refurb geeft mininconveniencebonus inconvenience
  ]
if(inconveniencebonus = "elecbonus") [
  set inconsit12 6
  set inconsit14 (6 + mininconveniencebonus)
  set inconsit13 2
  set inconsit15 7
  set inconsit24 mininconveniencebonus
  set inconsit25 2
  set inconsit35 6
  ; elec geeft mininconveniencebonus inconvenience
  ]
if (inconveniencebonus = "cleangasbonusincon")[
  set inconsit12 (6 + extrapunnishment)
  set inconsit14 (10 + extrapunnishment)
  set inconsit13 mininconveniencebonus
  set inconsit15 (6 + mininconveniencebonus)
  set inconsit24 (6 + extrapunnishment)
  set inconsit25 mininconveniencebonus
  set inconsit35 (6 + extrapunnishment)
  ;cleangas geeft 1 inconvenience
  ]

end

; de bonus moet laag zijn,
; bij refurbbonus is het normaal 6
; bij elecbonus is het normaal 6
; bij cleangasbonus is het normaal 2
;
to setvariablescorrecttobegin
 set ngsum 0
  set cgsum 0
  set elecsum 0
  set elecprice 0
  set ngprice 0
  set cgprice 0
end

to setseeds
```

```
 set setseed true
end

to seed
ask patches with [(pxcor >= -11 and pxcor <= -9 and pycor <= 11 and pycor >= 9)] [set socialreaction true
set cleangasbonus true set situation 3 set pcolor green set situationdummy 3 ]
ask patches with [(pxcor <= 11 and pxcor >= 9 and pycor >= -11 and pycor <= -9)] [set cleangasbonus
true set socialreaction true set situation 3 set pcolor green set situationdummy 3 ]

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;    GO PROCEDURE
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to go

  if ((ticks = timetosetseeds) and (setseed = true)) [seed]

  readyfornexttick
  ask patches [
   give-patch-inconlist
   calculatedemand
   ]

   makeprices

   ask patches
  [ set amountofneighborswithcleangas 0
   makebills

   calculateoffer ]

  ask patches [check-make-tech-choice]
  ask patches [ socialreactiononchoices]
  ask patches [set socialpressure socialpressuredummy]
  ask patches [if (situationdummy != situation)[set situation situationdummy]]

  ;als ik geen price of relocation ga doen, check ik of ik misschien wel social ga doen

  ask patches [cleangasswitchprocedure]
  ask patches [cleangasatonce]

  ;nu heb ik of social gedaan of niks. als ik niks heb gedaan kan socialpressure false worden
```

```
  ask patches [setvariablescorrect]

  ;nu ga ik price of relocation doen.
  ask patches [make-tech-choice]

  ; dit zorgt voor de juiste volgorde:
  ; eerst kijken we wat de patches willen gaan doen, price, relocation, social
  ; ga ik ook social doen als in de vorige tick mensen hebben geinvesteerd (hun socialpressure variable
staat nog true als ze hebben geinvesteerd) en deze tick geen price of relocation gaan doen
  ; en ditzelfde doe ik voor de cleangas-check
  ; dan zet ik de socialpressure false en cleangasvariable false voor alle patches
  ; ik laat de patches investeren op basis van price en relocation, waarbij als ze investeren socialpressure
weer true wordt, wat bewaard wordt naar de volgende tick

  ask patches [
    update-color
    set overallsystemcost (overallsystemcost + bill)
     set amountofpatchesinsit1 (count patches with [situation = 1])
     set amountofpatchesinsit2 (count patches with [situation = 2])
     set amountofpatchesinsit3 (count patches with [situation = 3])
     set amountofpatchesinsit4 (count patches with [situation = 4])
     set amountofpatchesinsit5 (count patches with [situation = 5])     ]

  update-plots

 set thisistick ticks
 export-interface (word "frame" but-first (word (100000 + ticks)) ".png")

  tick

  if (ticks = maxtime)[
     ask patches [
     makebills
     set overallsystemcost (overallsystemcost + bill) ]

     set fiftytargetdemand (fiftytarget / 100 * sizeofworld)
     ask patches [set NGdemand (NGdemand + (ng * refurb * refurbishmentfactor) + ((1 - refurb) * ng))]

     stop]

end

to readyfornexttick
set ngsum 0
set cgsum 0
set elecsum 0
set virtualticks 0
set amountofneighboringpatchesinvested 0
```

```
set amountofneighborswithcleangas 0
set fiftytargetdemand 0
set NGdemand 0

end

to update-color

  if situation = 1 [set pcolor 16]
  if situation = 2 [set pcolor 26]
  if situation = 3 [set pcolor 57]
  if situation = 4 [set pcolor 106]
  if situation = 5 [set pcolor 66]
  if situation = 7 [set pcolor 127]

end

to makeplots
end

to calculate-overall-systemcost
  if (ticks = maxtime) [
    makebills
    ask patches [
    set overallsystemcost (overallsystemcost + bill)]
    set fiftytargetdemand (fiftytarget / 100 * sizeofworld)
    set fiftytargetdemand 10

 ask patches [set NGdemand (NGdemand + (ng * refurb))]
  ]


  end
;overall system cost wordt berekent

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;; Bill calculation
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to calculatedemand

; INCLUDE zitten we niet al in een patch?

set ngsum (ngsum + ((ng * refurb * refurbishmentfactor) + ((1 - refurb) * ng)))
```

```
;set cgsum (cgsum + ((cg * refurb * refurbishmentfactor) + ((1 - refurb) * cg)))
;alternatief
;als je denkt dat CG prijs afhangt van demand of van het aantal huishoudens
; cgsum hangt af van het aantal huishoudens, elecsum hangt af van demand!

set cgsum (cgsum + cg)



set elecsum (elecsum + ((elec * refurb * refurbishmentfactor) + ((1 - refurb) * elec)))

;als refurb = 1 --> ngsum wordt som van ng*refurbishmentfactor
;als refurb = 0 --> ngsum telt gewoon 1 erbij op
;ngsum, clsum, elecsum is totale demand waarmee straks prijs voor individuele agent wordt bepaald.
; x(x*y) + (1-x)y

end
; demand van het systeem aan gas, elek en clean wordt bepaald

to makeprices

  ;;;;;;;;;;;;;;;
NGPRICE;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;

set realngprice 0
set percentageemissiontarget 100

set virtualticks ((( maxtime / ((( (sizeofworld) / 100) * fiftytarget) - (sizeofworld))) * ngsum) - (( maxtime /
((( (sizeofworld) / 100) * fiftytarget) - (sizeofworld))) * (sizeofworld)))
set virtualngprice ((( 9 / maxtime) * virtualticks))


 set realngprice (((9 / maxtime) * ticks))
 set real-virtualdifference (realngprice - virtualngprice)

 set ngprice (realngprice + (real-virtualdifference * punishment)) + beginnglevel
 if (ngprice < minNGgasprice) [set ngprice minNGgasprice]

if (not CO2taxswitch) [set ngprice beginnglevel]

    ; punnishment op 1 geeft de lineaire stijging van de CO2 prijs

; voor de plots:
   set emissiontarget ((((((sizeofworld) / 100) * fiftytarget) - (sizeofworld)) / maxtime) * ticks) +
sizeofworld)
```

```
  set percentageemissiontarget (((fiftytarget - 100) / maxtime) * ticks + 100)


  ; HELP waarom begint emissiontarget niet bij 0? berekening gaat goed, maar plot wil ook 1.2 tick
showen
  ; HELP er gaat iets nog goed mis met sizeofworld
  ; HELP dit werkt niet???

; fiftytarget = heoveelemissie die in 2050 nog over mag zijn van nu... normaal gesproken dus 20%
; INCLUDE plot ngprice plot realngprice
; ngprice = CO2 price

; virtual ticks: (0 ; sizeofworld ^2) ( maxtime ; sizeofworld ^2 / 100 * fiftytarget) --> y= ax+b --> x= y-b / a

;CO2 price procedure
; we beginnen met emissies: ngsum. daar bepalen we uit welk virtuele jaar we leven wat betreft ons
emissidoel. met dat virtuele jaar bepalen we de virtuele prijs.
; het verschil tussen de virtuele prijs met de virtuele jaar en de echte prijs met het echte jaar wordt de
straf verdubbelt (of aanpasbaar).


;   y= ax + b (0;1) (40;10). Y = 0.225x + 1
; (0;sizeofworld^2) (maxtime;sizeofworld /100*20)


 ;;;;;;;;;;  CG price
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
set cgprice cleangasbeginpricelevel

 ; set cgprice (((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1)) * cgvar ^ cgsum +
((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1)))
  set cgprice ((((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1)) * cgvar ^ cgsum) +
(cleangasbeginpricelevel - ((cgendlevel - cleangasbeginpricelevel) / ((cgvar ^ sizeofworld) - 1))))

  ;sizeofworld
  ;cgsum
  ;cgvar

  ;  plot cgrice

  ;;;;;;;;;; elecprice
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

  set elecprice (beginelecprice - ((elecendpricelevel - beginelecprice) / (-1 + elecvar ^ (sizeofworld)))) +
(((elecendpricelevel - beginelecprice) / (-1 + elecvar ^ (sizeofworld)) * elecvar ^ elecsum))

; elecsum aantal gebruikers van electriciteit
; sizeofworld aantal gebruikers uberhaupt
```

```
; elecvar variabele waarmee de grafiek lineair / extreem exponentieel kan worden getrokken

  ; plot elecprice

  ;y=a+b*g^x
  ;twee punten (amountofpatches ; 10) en (0 ; 0)
  ;De formule voor gegeven N is dus y=-10/(-1+g^(N^2)) + 10/(-1+g^(N^2))*g^x. Als je g variëert, blijft de grafiek door (0;0) en (N^2;10) gaan




end

to makebills

  set bill ((refurb * refurbishmentfactor) * (ng * ngprice + cg * cgprice + elec * elecprice) + ((1 - refurb) * (ng * ngprice + cg * cgprice + elec * elecprice)))

end

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;;;;;;;;;;;;;;;;  Offer calculation
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;INCLUDE refurbishmentfactor wordt in interface bepaald
;EXTRA bill geset

to calculateoffer

  set offer2 (refurbishmentfactor * ngprice)
    set offer3 (cgprice)
   set offer4 (elecprice * refurbishmentfactor)
  set offer5 (refurbishmentfactor * cgprice)
   set listoffer (list 0 0 offer2 offer3 offer4 offer5)

  ; list eerste positie is 0, 1e is offer 1, offer1 etc)
  ;ik heb nu voor elke patch een lijst gemaakt met welke prijsoffers er worden geboden. Nu ga ik differenceenergyprice, het verschil berekenen met de prijs die ze nu betalen. Als de nieuwe prijs hoger is dan de oude prijs, dan wordt het offer 0.

   if (situation = 3) [ set differencelistoffer ( list 0 0 0 0 (bill - offer4) (bill - offer5))]

if (situation = 1) [set differencelistoffer (list 0 0 (bill - offer2) (bill - offer3) (bill - offer4) (bill - offer5))]
```

```
if (situation = 2) [set differencelistoffer (list 0 0 0 0 (bill - offer4) (bill - offer5))]
if (situation = 3) [set differencelistoffer (list 0 0 0 0 0 (bill - offer5))]
set differencelistoffer map [max ( list 0 ?)] differencelistoffer

; INCLUDE is dit nu netjes opgelost? zijn alle wegen nu afgesneden?

  end

; dit werkt, hiep hoi!
; bereken verschil tussen offer en bill, zet de offers die kleiner zijn dan 0  op 0
;je gaat niet naar duurdere energierekening




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;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;  INCONVENIENCE
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;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;inconveniencetable is naar setup verhuist

to give-patch-inconlist

  make-inconlist
;
;  set listincon1 map [max ( list inconveniencefactor ?)] listincon1
;  set listincon2 map [max ( list inconveniencefactor ?)] listincon2
;  set listincon3 map [max ( list inconveniencefactor ?)] listincon3
;
;
; let replacelistincon1 filter [? = inconveniencefactor] listincon1
; foreach replacelistincon1 [
;   set listincon1 replace-item (position inconveniencefactor listincon1) listincon1 -10000]
;
; let replacelistincon2 filter [? = inconveniencefactor] listincon2
; foreach replacelistincon2 [
;   set listincon2 replace-item (position inconveniencefactor listincon2) listincon2 -10000]
;
; let replacelistincon3 filter [? = inconveniencefactor] listincon3
; foreach replacelistincon3 [
;   set listincon3 replace-item (position inconveniencefactor listincon3) listincon3 -10000]
;

; De truc van Gerben:
```

```
;  to processList
; let testList (list 8 6 2 7 5 2 9)
;  let replaceList filter [? = 2] testList
;  print testList
 ;  foreach replaceList [
;    set testList replace-item (position 2 testList) testList 100
;  ]
;  print testList
;end
;De truc is om een extra lijst aan te maken met daarin de items die je wilt vervangen. Het gaat er hierbij vooral om dat ze er even vaak in zitten als dat ze daadwerkelijk in de lijst voorkomen.
;Als we dan over de nieuwe lijst heen itereren, vervangen we steeds in de echte lijst de eerste keer dat de waarde voorkomt. Doordat we dit het aantal keer herhalen dat de te vervangen waarde in de lijst voorkomt hebben we uiteindelijk alle te vervangen waarden vervangen.


;elke patch heeft drie inconveniencelijsten

  end
; maak eerst lijst met alle inconveniencelevels in make-inconlist daarna
; maak lijst met inconveniencelevels die beschikbaar zijn omdat inconvenience van situatie
; onder de inconveniencefactor is die de patch aanvaardbaar vindt

to make-inconlist

if (situation = 1) [set listincon1 (list 0 0 inconsit12 inconsit13 inconsit14 inconsit15)]
if (situation = 2) [set listincon2 (list 0 0 0 0 inconsit24 inconsit25 )]
if (situation = 3) [set listincon3 (list 0 0 0 0 0 inconsit35)]

end
; dit kan elke patch maken, maakt niet uit in welke situatie hij is

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to check-make-tech-choice
  set pricereaction false
  set relocationreaction false

  if (situation = 4 or situation = 5 or situation = 7) [ stop ]
  ;als je in all electric of cleangas zit kan je niet meer terug


  if (pricereactionbutton) [pricereactionq]
```

```
  if (relocationbutton) [relocationreactionq]

  ;procedures in de verschillende parts die checken of er pricereaction, relocationreaction of
socialreaction is

end
;nu weten alle patches wat ze gaan doen


to socialreactiononchoices
 if (socialreactionbutton) [ socialreactionq]
 ifelse (socialreaction and (not relocationreaction) and (not pricereaction)) [social][set
socialpressuredummy false]
end
; we moeten eerst op socialpressure checken want in make-tech-choice worden deze variabele alweer
verandert

 to setvariablescorrect

  set socialreaction false
  set cleangasbonus false

end

to make-tech-choice

  if (situation = 4 or situation = 5 or situation = 7) [ stop ]

  if (pricereaction and (not relocationreaction) and (not socialreaction)) [price ]
  if (relocationreaction and (not pricereaction) and (not socialreaction)) [relocation ]
   if (pricereaction and relocationreaction and (not socialreaction)) [relocation ]        ;inconvenience niet
belangrijk
  if (relocationreaction and socialreaction and (not pricereaction)) [relocation ]      ;inconvenience niet
belangrijk
  if (pricereaction and socialreaction and (relocationreaction = false)) [price ]     ;inconvenience belangrijk

  if (pricereaction and relocationreaction and socialreaction) [relocation  ]   ;set socialpressure true als
men investeert heeft agent 1 jaar invloed op buur-agenten
  if (not pricereaction and (not relocationreaction) and (not socialreaction)) [ ]

  end
;wat is de reden voor investering
; set socialpressure true wordt gedaan als er ook investering wordt gedaan in de verschillende delen

to cleangasswitchprocedure

  if (situation = 4 or situation = 5 or situation = 7) [stop ]
```

```
  if (cleangasswitch) [cleangasbonusq]
  ;zet de functie cleangasswitch aan of uit

end

to cleangasatonce

   if (cleangasbonus) [makecleangasbonus ]
 end




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to relocationreactionq


 ifelse (((ticks + 1) mod relocationfactor) = 0) [set relocationreaction true] [set relocationreaction false]

; ticks + 1 omdat anders in tick 0 iedereen gelijk relocation gaat doen
end
; ticks mod relocationfactor >> (ticks/relocationfactor) geeft true als er geen rest is (als ik het goed
begrijp) dus dan wordt het periodisch
;INCLUDE mogelijkheid het totaal random te laten lopen, niet periodisch

to relocation

    set sumlistoffer (sum differencelistoffer)
    ifelse (sumlistoffer = 0) [set socialpressure false ] [       ;; als alle waardes 0 zijn, dan doen we niks, er is
geen investering de moeite waard


    set sit1choice position (max differencelistoffer) differencelistoffer  ; we pakken de grootste
differencelistoffer!
    set situation sit1choice

      ]
      setallvariablescorrect

    end
```

```
  ; zet eerst de offers die hoger zijn dan de oude rekening op 0 (al gedaan in " price"
; als alle items 0 zijn --> do nothing
; als er item niet 0 is, zet alle nullen op 100.
; bewaar de positie van de minimale waarde
; bewaar deze minimale waarde
; laat situation de nieuwe situatie zijn
; zet nieuwe situatie om in situatie-variable
; differencelistoffer: hoe groter hoe beter!



   to setallvariablescorrect
   if (situation = 1) [ set refurb 0 set ng 1 set cg 0 set elec 0 set socialpressure false set situationdummy
situation]                          ;afhankelijk welke nieuwe situatie er gekozen is, veranderen de variabele van
de patch nu mee.
   if (situation = 2) [ set refurb 1 set ng 1 set cg 0 set elec 0 set socialpressure true set situationdummy
situation]
   if (situation = 3) [ set refurb 0 set ng 0 set cg 1 set elec 0 set socialpressure true  set situationdummy
situation]
   if (situation = 4) [ set refurb 1 set ng 0 set cg 0 set elec 1 set socialpressure true set situationdummy
situation]
   if (situation = 5) [ set refurb 1 set ng 0 set cg 1 set elec 0 set socialpressure true set situationdummy
situation]
   if (situation = 7) [set refurb 1 set ng 0 set cg 1 set elec 0 set socialpressure true  set situationdummy
situation]
      end

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to pricereactionq

set oneprocentofbill (bill / 100)
set reductionfactorcheck (reductionfactor * 10)
set differencelistoffercheck differencelistoffer
set differencelistoffercheck map [? / oneprocentofbill] differencelistoffercheck

 ;reductionfactor is getal tussen 0 en 100, bijvoorbeeld 25, een offer wordt alleen in bekeken als het
meer dan 25% reduceert ten opzicht van de oude bill. 7/10 = 0.7 1-0.7 = 0.3 dus dit offer is goed

 set differencelistoffercheck map [max (list reductionfactorcheck ?)] differencelistoffercheck
 set differencelistoffercheck (remove reductionfactorcheck differencelistoffercheck)
```

;we checken eerst of er een offer is dat beter is dan de reducationfactor, alle offers die kleiner zijn worden gelijk gemaakt met
;de reductionfactor. Daarna worden alle waardes die gelijk zijn aan de reductionfactor eruit gehaald. als er dus alleen
;waardes waren met de reductionfactor (er waren geen offers beter dan de reductionfactor) dan is de lijst nu leeg.

  ifelse (empty? differencelistoffercheck) [set pricereaction false] [set pricereaction true]

; Om een investering te doen met de reden dat er pricereaction is wordt in "pricereaction" vervolgens de offers verwijderd die hoger dan de gewenste reductionfactor (het minimale prijsverschil om investering te doen). Als nu de lijst leeg is, dan is er geen pricereactie
;als er een waarde overblijft dan is er een prijsreactie
;remove item dat minder reduceert dat reductionfactor, als de lijst niet leeg is dan pricereaction = true, anders pricereaction = false)
;behoudt de differencelistoffer

set reductionfactorcheck 0
set differencelistoffercheck 0

end
;compare bill with investing options, if there is an option reducing more then reductionfactor, pricereaction = true

to price

 set oneprocentofbill2 (bill / 100)

 let reductionfactorcheck2 (reductionfactor * 10)

;Reductionfactor check: compare bill with offers. only options that reduce more then reductionfactor are considered.
;set reductionfactor (reductionfactor / 100)
set differencelistoffer map [? / oneprocentofbill2] differencelistoffer
set differencelistoffer map [max (list reductionfactorcheck2 ?)] differencelistoffer

;let replacedifferencelistoffer (remove reductionfactor differencelistoffer)

;let positionvalue position reductionfactor differencelistoffer
;ifelse (positionvalue != false) [foreach replacedifferencelistoffer[set differencelistoffer (replace-item (position reductionfactor differencelistoffer) differencelistoffer -10000)]] []

let replacedifferencelistoffer filter [? = reductionfactorcheck2] differencelistoffer

```
let positionvalue position reductionfactorcheck2 differencelistoffer

ifelse (positionvalue != false) [ foreach replacedifferencelistoffer[ set differencelistoffer (replace-item
(position reductionfactorcheck2 differencelistoffer) differencelistoffer -100000) ]] []

; De truc van Gerben:
;  to processList
; let testList (list 8 6 2 7 5 2 9)
;  let replaceList filter [? = 2] testList
;  print testList
 ;  foreach replaceList [
;    set testList replace-item (position 2 testList) testList 100
;  ]
;  print testList
;end
;De truc is om een extra lijst aan te maken met daarin de items die je wilt vervangen. Het gaat er hierbij
vooral om dat ze er even vaak in zitten als dat ze daadwerkelijk in de lijst voorkomen.
;Als we dan over de nieuwe lijst heen itereren, vervangen we steeds in de echte lijst de eerste keer dat
de waarde voorkomt. Doordat we dit het aantal keer herhalen dat de te vervangen waarde in de lijst
voorkomt hebben we uiteindelijk alle te vervangen waarden vervangen.

set differencelistoffer map [? / 10] differencelistoffer

; nu hebben we lijst met offers die groter zijn dan reducationfactor en offers die gelijk gestelt zijn met
reductionfactor

; Inconveniencefactor check: check if remaining investingoptions are allowed by inconveniencefactor

if (situation = 1) [

  set listincon1 map [min (list inconveniencefactor ?)] listincon1

  let replacelistincon1 filter [? = inconveniencefactor] listincon1

    foreach replacelistincon1 [ set listincon1 replace-item (position inconveniencefactor listincon1)
listincon1 10000 ]


  set listincon1 map [10 - ?] listincon1

  set sumoflist1 (map + listincon1 differencelistoffer)
set sumoflist1.1. sumoflist1
set sumoflist1.1. sort-by < sumoflist1.1.


while [(not (empty? sumoflist1.1.)) and (item 0 sumoflist1.1. < 0)] [if (item 0 sumoflist1.1. < 0) [set
sumoflist1.1. remove (item 0 sumoflist1.1.) sumoflist1.1.]]
```

```
 ; check of lijst bestaat uit positieve getallen, als lijst leeg is, donothing


ifelse (not (empty? sumoflist1.1.)) [set sit10choice position (max sumoflist1) sumoflist1 ; we pakken de
grootste differencelistoffer!
  set situation sit10choice
  setallvariablescorrect
  set reductionfactorcheck2 0
set replacedifferencelistoffer 0
set positionvalue 0
  stop
] [set socialpressure false]
]

if (situation = 2) [
  set listincon2 map [min (list inconveniencefactor ?)] listincon2
  let replacelistincon2 filter [? = inconveniencefactor] listincon2
foreach replacelistincon2 [ set listincon2 replace-item (position inconveniencefactor listincon2)
listincon2 10000 ]
  set listincon2 map [10 - ?] listincon2
  set sumoflist2 (map + listincon2 differencelistoffer)
  set sumoflist2.2. sumoflist2
  set sumoflist2.2. sort-by < sumoflist2.2.
while [(not (empty? sumoflist2.2.)) and (item 0 sumoflist2.2. < 0)] [if (item 0 sumoflist2.2. < 0) [set
sumoflist2.2. remove (item 0 sumoflist2.2.) sumoflist2.2.]]
ifelse (not (empty? sumoflist2.2.))[ set sit20choice position (max sumoflist2) sumoflist2 ; we pakken de
grootste differencelistoffer!

  set situation sit20choice
  setallvariablescorrect
  set reductionfactorcheck2 0
set replacedifferencelistoffer 0
set positionvalue 0

  stop
] [set socialpressure false]
]

if (situation = 3) [
  set listincon3 map [min (list inconveniencefactor ?)] listincon3
  let replacelistincon3 filter [? = inconveniencefactor] listincon3
foreach replacelistincon3 [ set listincon3 replace-item (position inconveniencefactor listincon3)
listincon3 10000 ]
  set listincon3 map [10 - ?] listincon3

  set sumoflist3 (map + listincon3 differencelistoffer)
  set sumoflist3.3. sumoflist3
```

```
  set sumoflist3.3. sort-by < sumoflist3.3.
while [(not (empty? sumoflist3.3.)) and (item 0 sumoflist3.3. < 0)] [if (item 0 sumoflist3.3. < 0) [set
sumoflist3.3. remove (item 0 sumoflist3.3.) sumoflist3.3.
    ]]
ifelse (not (empty? sumoflist3.3.)) [set sit30choice position (max sumoflist3) sumoflist3 ; we pakken de
grootste differencelistoffer!


  set situation sit30choice
  setallvariablescorrect
  set reductionfactorcheck2 0
set replacedifferencelistoffer 0
set positionvalue 0

  stop
][set socialpressure false]
]

; nu hebben we lijst met offers die kleiner zijn dan de inconveniencefactor die toelaatbaar is

; dit worden de lijsten met price en inconveniencefactor gecombineerd


;iets met + inconvenience in nieuwe list opslaan. min of max van die list nemeen en je hebt de tech
choice

end

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;;;;;;;;;;;;;;;;  SOCIAL PRESSURE
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 to socialreactionq

; vraag een patch eerst om het aantal buren die hebben geinvesteerd in bepaalde radius
; dan bereken of aantal buren genoeg is voor de vooringestelde eis (percentageminamountofneighbors)
; door deze truc gaan alle patches nu in een keer in plaats van dat ze elkaar beinvloeden

   ask other patches in-radius neighboringdistance [
   checksocialpressure ]
   ask self [ setsocialreaction ]

   set amountofneighboringpatchesinvested 0
```
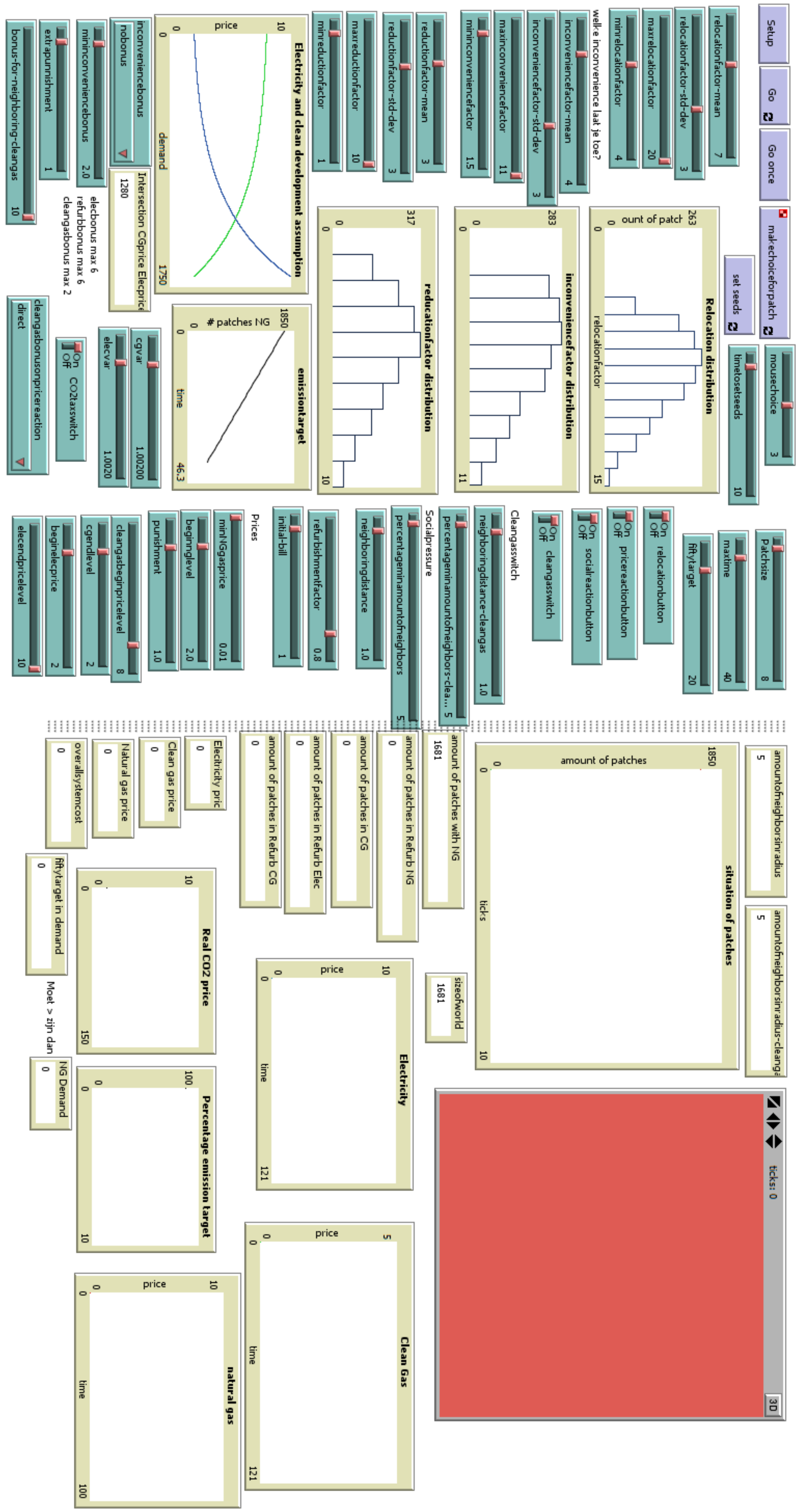

```
 end

to checksocialpressure
      if (socialpressure ) [counting]
end

to counting

  set amountofneighboringpatchesinvested (amountofneighboringpatchesinvested + 1)

end

to calculateamountneighbors
 ask patch  0 0 [
   set amountofneighborsinradius (count patches in-radius neighboringdistance)
 ]
  if (amountofneighborsinradius > sizeofworld) [set amountofneighborsinradius sizeofworld]

  end

to setsocialreaction

 ifelse (amountofneighboringpatchesinvested >= (amountofneighborsinradius *
(percentageminamountofneighbors / 100)))[
  set socialreaction true ] [ set socialreaction false]
end
  ;als er genoeg buren zijn die vorig jaar investering hebben genomen, dan wordt socialreaction true

to social

price

;setallvariablescorrect

end
;als ik socialpressure mij dwingt om keuze te maken, dan ga ik gewoon de price procedure voeren

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;; CLEANGASBONUS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

to cleangasbonusq

ask other patches in-radius neighboringdistance-cleangas [
```

```
checkcleangas ]
ask self [ setcleangasbonus ]

set amountofneighborswithcleangas 0

end

to checkcleangas

  if (situation = 3 or situation = 5 or situation = 7) [counting2]

end

to counting2
set amountofneighborswithcleangas (amountofneighborswithcleangas + 1)

end

to calculateamountneighbors-cleangas
 ask patch  0 0 [
   set amountofneighborsinradius-cleangas (count patches in-radius neighboringdistance-cleangas)
 ]
 if (amountofneighborsinradius-cleangas > sizeofworld) [set amountofneighborsinradius-cleangas
sizeofworld]
end

to setcleangasbonus

ifelse (amountofneighborswithcleangas >= (amountofneighborsinradius-cleangas *
(percentageminamountofneighbors-cleangas / 100)))[
 set cleangasbonus true  ] [set cleangasbonus false]
end

to makecleangasbonus

 if (cleangasbonusonpricereaction = "direct")[
set situation 3
]
 if (cleangasbonusonpricereaction = bonusonpricereaction) [if (pricereaction = true) [ set situation 3]]

if (situation = 3) [ set refurb 0 set ng 0 set cg 1 set elec 0 set socialpressure true  set situationdummy
situation set listincon3 (list 0 0 0 0 0 inconsit35) set differencelistoffer (list 0 0 0 0 0 (bill - offer5))]

end
```

Appendix D. Interface of the Model



Appendix E. Source code for analyzing software R.

```
getwd()
setwd("C:/Users/Administrator/Documents")

#inladen data
myDataFrame = read.table("38.csv", skip = 6, sep= ",", head=TRUE)

4#just give me a quick scatterplot
scatterplot = ggplot(myDataFrame,
            geom_line(aes(x=thisistick , y=amountofpatchesinsit1, colour = "sit1")) +
            geom_line(aes(x=thisistick , y=amountofpatchesinsit2, colour = "sit2")) +
            geom_line(aes(x=thisistick , y=amountofpatchesinsit3, colour = "sit3")) +
            geom_line(aes(x=thisistick , y=amountofpatchesinsit4, colour = "sit4")) +
            geom_line(aes(x=thisistick , y=amountofpatchesinsit5, colour = "sit5")) +
print(scatterplot )
ggsave(scatterplot , file="scatter.png")

#setting the scale with coord_cartesian
scatterplot2 = ggplot(myDataFrame,aes(x = beginelecprice, y = overallsystemcost)) + geom_line(size = 2)
+ coord_cartesian(xlim = c(0, 10)) + coord_cartesian(ylim = c(0,50000))
print(scatterplot2)

#samenvatting
head(myDataFrame)

#facetgrid
facetGridScatterPlot = ggplot(data=myDataFrame, aes(x=X.step., y=overallsystemcost, group =
X.run.number. )) +
  geom_line() +
  facet_grid(beginelecprice  ~ cleangasbeginpricelevel , scales="free")

            print(facetGridScatterPlot)

ggsave(facetGridScatterPlot, file="exp70.1.png")

head(myDataFrame)
```

```
#facetgrid met meerdere lijnen
facetGridScatterPlot = ggplot(data=myDataFrame) +
  geom_line(aes(x=X.step., y=ngprice, colour = "a: NG"))+
  geom_line(aes(x=X.step., y=cgprice, colour = "b: CG"))+
  geom_line(aes(x=X.step., y=elecprice, colour = "c: elec"))+



  facet_grid(beginelecprice ~ cleangasbeginpricelevel , scales ="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="60.1.jpg")
```

```
#facetgrid met meerdere lijnen
facetGridScatterPlot = ggplot(data=myDataFrame) +
  geom_line(aes(x=elecvar , y=elecprice, colour = "elecprice")) +
 geom_line(aes(x=elecvar , y=cgprice, colour = "cgprice")) +


  facet_grid(beginelecprice ~ cgvar, scales ="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="exp1.2.6.jpg")
```

```
#facetgrid met meerdere lijnen
df <- rbind(df, data.frame(X.step. = i, X.run.number = j, value = v))
ymin <- min(df[df$X.step.==i,]$value)
ymax <- max(df[df$X.step.==i,]$value)
df2 <- rbind(df2, data.frame(X.step.=i, ymin=ymin, ymax=ymax))


facetGridScatterPlot = ggplot(data=myDataFrame) +
  geom_line(aes(x=X.step., y=amountofpatchesinsit1, group = X.run.number., colour =
"sit1")) +
  geom_line(aes(x=X.step., y=amountofpatchesinsit2, group = X.run.number., colour =
"sit2")) +
  geom_line(aes(x=X.step., y=amountofpatchesinsit3, group = X.run.number., colour =
"sit3")) +
  geom_line(aes(x=X.step., y=amountofpatchesinsit4, group = X.run.number., colour =
"sit4")) +
```

```
  geom_line(aes(x=X.step., y=amountofpatchesinsit5, group = X.run.number., colour =
"sit5")) +

  facet_grid(begineleprice ~ cleangasbeginpricelevel, scales ="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="exp49.jpg")

#facetgrid met meerdere lijnen
hist_cut = ggplot(data=myDataFrame) +

  geom_bar(position="fill", aes(x=cgvar, y=amountofpatchesinsit4, colour = "sit4")) +

  facet_grid(beginelecprice ~ cleangasbeginpricelevel, scales ="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="exp53.jpg")

df2 <- NULL
for(i in unique(df$tick)) {
  ymin <- min(df[df$tick==i,]$value)
  ymax <- max(df[df$tick==i,]$value)
  df2 <- rbind(df2, data.frame(tick=i, ymin=ymin, ymax=ymax))
}

# I create a new map that also contains the error bars
 + geom_errorbar(data=df2, aes(x=tick, ymin=ymin, ymax=ymax))
print (map2)
ggsave(map2, file="map2.jpg")


#facetgrid met meerdere lijnen
facetGridScatterPlot = ggplot(data=myDataFrame) +
  geom_line(aes(x=elecprice , y=overallsystemcost, colour = "elecprice")) +
  geom_line(aes(x=cgprice , y=overallsystemcost, colour = "cgprice")) +


  facet_grid(beginelecprice ~ cgvar, scales ="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="exp1.2.8.jpg")


facetGridScatterPlot = ggplot(data=myDataFrame) +
geom_line(aes(x=X.step., y=amountofpatchesinsit1, group=X.run.number., colour = "sit1")) +
```

```
geom_line(aes(x=X.step., y=amountofpatchesinsit2, group=X.run.number., colour = "sit2")) +
geom_line(aes(x=X.step., y=amountofpatchesinsit3, group=X.run.number., colour = "sit3")) +
geom_line(aes(x=X.step., y=amountofpatchesinsit4, group=X.run.number., colour = "sit4")) +
geom_line(aes(x=X.step., y=amountofpatchesinsit5, group=X.run.number., colour = "sit5")) +


facet_grid(beginelecprice ~ cleangasbeginpricelevel, scales ="free")

    ggsave(facetGridScatterPlot, file="exp70.3.jpg")

facetGridScatterPlot = ggplot(data=myDataFrame) +
 geom_line(aes(x=X.step., y=amountofpatchesinsit1, colour = "sit1")) +
 geom_line(aes(x=X.step., y=amountofpatchesinsit2, colour = "sit2")) +
 geom_line(aes(x=X.step., y=amountofpatchesinsit3, colour = "sit3")) +
 geom_line(aes(x=X.step., y=amountofpatchesinsit4, colour = "sit4")) +
 geom_line(aes(x=X.step., y=amountofpatchesinsit5, colour = "sit5")) +


 facet_grid(cleangasbeginpricelevel ~ percentageminamountofneighbors.cleangas, scales
="free")
print(facetGridScatterPlot)
ggsave(facetGridScatterPlot, file="exp22.5.jpg")
```