MODELING THE DIFFUSION OF MICRO-CHP IN A RESIDENTIAL AREA

by

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ABSTRACT

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A thesis presented on the diffusion of micro-CHP in a residential area consisting of houses with multiple owners, currently using condensing boilers. The thesis shows that micro-CHP will not reach 50% of the market in less than 20 years. Furthermore it analyses the impact of the heat demands, the gas electricity and feedback prices as well as the subsidies on the speed and time of adoption of micro-CHP.

DECLARATION

I declare that:

this work has been prepared by myself,

all literal or content based quotations are clearly pointed out,

and no other sources or aids than the declared ones have been used.

Hamburg, Germany

September 14th, 2009

Christian Chemaly

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I would like to start by thanking Prof. Möller and Prof. Peters for examination evaluating of this project. Furthermore I am very grateful to Mr. Schäfers for the guidance provided into the discipline of energy which was new to me, and who was always ready to meet when I needed advices. This thesis could not evolve from the draft it was to its current state without the help of Mr Marrone.

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At last but not least, I would have never managed to stand where I stand today without my family's support and the friends who surround me. Thank you.

CHAPTER I - INTRODUCTION

MOTIVATION

According to the first law of thermodynamics, “energy may neither be created nor destroyed, it can only be transformed”. According to the law of conservation of energy, it is clear that energy cannot come from void. That said, the primary sources of energy are, to this day, non-sustainable and non-renewable fossil fuel such as coal and petrol. Once burnt, the latter cannot be reused. Ironically, the process of creation takes millions of years. Therefore, now that the fossil fuels are becoming scarce, alternatives are being researched, in order to satisfy the constantly increasing energy needs of the planet. Factories, cars, houses, shops and almost everything requires energy for light, heat, travel and communication.

On the other hand, in almost all combustion reactions, toxic gases are emitted in the atmosphere as a result of the reaction between oxygen and fuel. Carbon oxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxide (N_2O)are but a few examples of those toxic gases released. Once emitted, these gases create a “shell” in the atmosphere thus retaining the highly carcinogen ultraviolet rays and subsequently increasing the global temperature. Moreover these gases are toxic and carcinogenic for humans, inducing many illnesses, including lung cancer [EPA09]. Therefore a new requirement emerged, supporting the need for a substitute for fossil fuel and the reduction of gaseous emissions. After the ratification of the Kyoto convention which took place in January 2009, Germany was committed to lower overall emissions of a group of greenhouse gases (including carbon dioxide, methane (CH_4), and nitrogen oxide) from 2008 to 2012 by 8%. Having achieved a reduction of 17% between 1990 and 2004, Germany is on the right track. However, the EU assigned the objective of reducing by 21% the emission of these gases by 2012, a goal yet to be reached [UNCC09].

The so-called "green" technologies such as solar, tidal or wind energy generation available today on the market are not mature enough to replace the current electricity factories [PM06]. Therefore, in this thesis, we decided to approach the problem in a different manner by managing the energy we are creating rather than changing the way we are generating that energy.

Towards a better management of our energy.

Since we currently cannot generate energy in a clean way, we have to learn how to make the best usage of the energy we create, mainly - by minimizing waste. Taking a closer look at the way a power station functions, we notice that generating electricity creates a large amount of heat, that is not only being lost, but requires cooling (and therefore uses more energy) and pollutes the environment [RE05].

Cogeneration of Heat and Power (CHP) is a technology where excess heat released during industrial processes or during centralized electricity generation is captured and transformed into a useful application, usually domestic heating. CHP thus uses the heat that would otherwise be wasted in a conventional power plant, potentially reaching an efficiency of about 70% or greater for the overall system as compared to roughly 40% efficiency in a conventional plant. The most recent goal of the German government is to double CHP's share of electricity generation by up to 25 % by 2020. Biogas CHP capacity has grown from 180 MW in 2000 to over 1 GW in 2006, reflecting a strong interest from the German market [IEA08]. By analyzing the depredation of energy, it is noticeable that heat is not transferable over a long distance [SD04]. Therefore the CHP station is more efficient when it has a restricted area to cover. With this strategy in mind, we move from the classical centralized energy generation (with a big power station supplying a whole city or region sometimes), to a distributed generation, where every district has its own power generation (defined as “district heating”). This system’s main advantage is the ability to use the heat produced during electricity generation, without overlooking the control of the amount of electricity produced. A power station should predict the demand of its network during electricity production; when using the centralized generation, it is harder to estimate the demand due to the size of the network. This usually generates an excess of electricity, heat and pollution. Using smaller power stations reduces the margin of error and increases the efficiency of the production.

Decentralizing does not have to stop at a district level. Decentralizing decentralized systems can occur by having a small CHP for every building, adapted to one’s needs. This transition will be revolutionary for the energy market that was, until now, controlled by monopolist electricity providers [SF08]. With every building generating its own heat and electricity, the production’s control can be optimized. Contrary to most industrial CHP plants, micro-CHP generally meets the needs for heat first, with electricity production as the secondary product. Micro-CHP is therefore designed to replace domestic heating systems, with the additional feature of electricity production. A good definition of micro-CHP is the simultaneous generation of heat, cooling, in other words energy and power in an individual building, based on small conversion units below 15 kW_{el} [PM06]. Electricity produced in this way can be used within the house or business, or (if permitted by the grid management) sold back into the electric power grid. Considering a micro-CHP in every construction, all of which connected to one national grid, a so-called virtual power station can be reached. Virtual in the sense that it is not one concrete factory, but a multitude of cells scattered over the city, exchanging the excess of electricity produced and regulating each other [PM06].

The relationship between the heat and electricity production is given by the Heat to Power Ratio (HPR), which describes the amount of heat generated for each unit of electricity produced. In middle and large-scale CHP, the core product is electricity and the power station is planned according to the electricity demand. A micro-CHP choice is based on the heat demand of the house, the electricity being considered as an advantageous bonus. In the same manner, every micro-CHP engine has an HPR; every household can derive its HPR by representing the ratio of the heat over electricity demand. The HPR of buildings is expected to decrease with the age of buildings, or their renovation date; a better insulation requires less heat, while the electricity demand remains rather constant.

Practical comparison of a condensing boiler and a micro-CHP

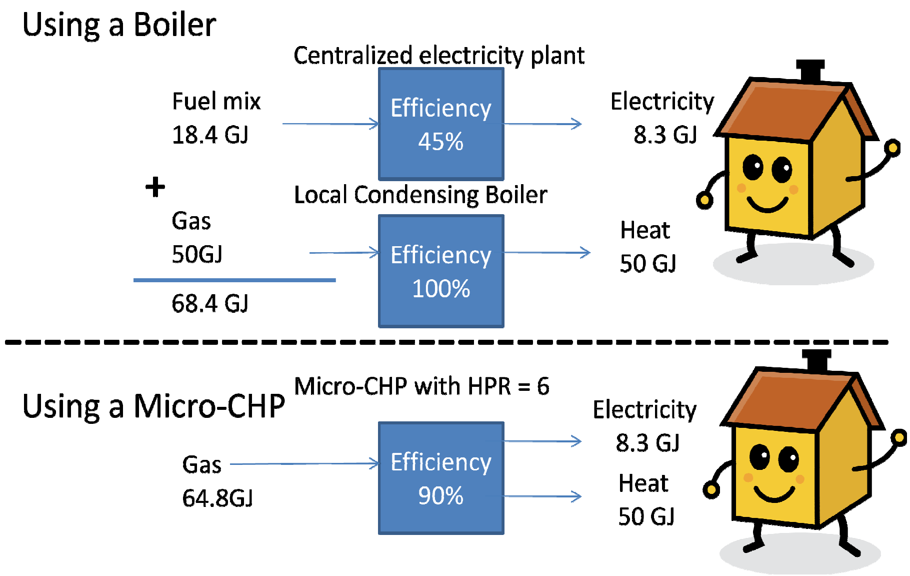

Figure 1: Comparison of the fuel requirement when using a boiler and a micro-CHP

A condensing boiler uses natural gas for space and water heating at an efficiency of over 100% (recovering the heat from water vapor). An example household with a 100% efficiency boiler system and a heat demand of 50GJ requires natural gas of input 1582m^3. If the household was using a micro-CHP system, it would have co-generated electricity at a level relative to the HPR. Assuming an average HPR of 6, the micro-CHP would produce 50/6=8.3 GJ of electricity. Adding the electricity and heat produced, the micro-CHP therefore produces 58.3GJ of energy. With an assumed aggregate efficiency of 90%, this micro-CHP requires 64.8GJ of natural gas input. Therefore, in this example, the micro-CHP requires an additional amount of 465 m^3 of natural gas, but produces 2300kWh (equivalent of 8.3 GJ) of electricity for domestic use or sale. A centralized power plant, with average efficiency of 45%, would require for that electricity around 582 m^3 of natural gas. Every CHP is therefore allowing a saving of 117 m^3 of natural gas per year.

AIM AND SCOPE

In this thesis, we will be modeling many of the aspects of the micro-CHP system in regards to decision process, increase of the distribution of this model over time in a representative German population.

The decision process of house owners with regards to their heating system will be modeled. The proportion of households using micro-CHP will be modeled over time in order to see if micro-CHP could become standard heating systems instead of boilers, by reaching a market share of 50% within the next 20 years. A representation of the German population will be distributed over residential lodging based on the district of Lokstedt in Hamburg. Many factors, like the construction type and its renovation date, can influence the decision regarding changing the heating system. The focus of this thesis will be manifolds, mainly the social class, the orientation towards change of the owner' mindset, as well as the consideration of the household size. The heat demand will be the only parameter reflecting the construction type of the house, since, in this study, heat is evaluated in function of the building type, the construction year, the renovations that it underwent, the livable area, the number of inhabitants, to mention only the main parameters determining heat demand.

The status quo situation will be modeled as well as other scenarios to see what particular circumstances are needed to improve the diffusion of micro-CHP. Results of the simulations showed that diffusion will take 43 years for the CHP to achieve 50% market share under the current parameters. An expected heat demand reduction through the insulation of houses will make it harder for the CHP to impose itself on the market, while an increase of electricity prices will facilitate its diffusion. In all the scenarios simulated, the micro-CHP market share has not reached 50% with 20 years, refuting the hypothesis of considering it as a standard heating system.

OVERVIEW

In order to understand the mechanism behind the diffusion of micro-CHP, this chapter presents a brief overview of the procedure taking place.

At the start of each simulation, the market has to be initialized: the prices of utilities are set, the subsidy schemes are defined and all houses declared to be equipped with a condensing boiler. This is how we define the world in which we run the simulation. At the end of each year, house owners are able to decide whether they would like to replace their actual system or not. A house council meeting then takes place in which every owner votes for what he believes is the best option. Each owner has his own perspective, expectation and needs in regard of replacing the current unit. At the end of the vote, a decision is taken and an action regarding the heating system is executed. Afterwards, the market status will be updated and the cycle will take place once again.

What is required is therefore to:

1. Represent the market and its evolution.
2. Classify and represent the different owners.
3. Enable the owners to evaluate the different options and choose the one most corresponding to their needs.
4. Choose an optimal voting protocol according to house ownership regulations.
5. Predict the outcome of the vote based on one owner's view.
6. Monitor the evolution of the market and the decisions taken.

In order to successfully reach the target, we will combine an economical model representing the market, with a social model representing the people and an agent-based approach to model the decision network.

OUTLINE

Chapter 1 has discussed the motivation to write the thesis and its aim, as well as introduced the CHP system. In chapter 2, an overview of the project will be displayed and the environment as well as the market parameters is described. Chapter 3 will handle the agent model, the representation of the individuals as well as the way they take decisions. Chapter 4 will deal with the simulation and will discuss the results obtained. The conclusion and the future applications and improvements will be presented in Chapter 5.

CHAPTER II - THE ENVIRONMENT

A model is a reduction. It extracts only those elements of a more complex reality which are necessary to reveal the underlying relationships [SH73]. Depending on the objectives of the modeler and of the problem to be solved, some assumptions will be made in order to convert the real world into the model. Based on the categorization of environment used by Russel [RS03], the task environment defined as in this application is semi-dynamic, partially observable, stochastic, episodic and discrete.

A semi-dynamic environment

The physical world is a highly dynamic environment. The market is in a constant change. Just by looking at the stock market, one can see that prices change every minute. People can decide to change their heating system at any time, and do not have to do it synchronously in every area. The environment of the model is however semi-dynamic., it can be divided in two separate layers, the market and the agents, components that communicate together. The outcome of each of those layers influences the other, but they never change concurrently. The environment sets its parameters regarding the cost of gas and electricity, the market share of each product, the subsidies offered and so on. Once parameters are set, the agents come into play and start deliberating to decide what to do, based on the latest market parameters. Once all agents have taken all their decisions, they freeze and the market updates its status. This is how the simulation will be running, the environment only changing after all the buyers have taken their decisions, and the agents basing their decisions only on the current version of the market, without speculating or predicting how the market is going to vary. The market has no knowledge about how the agents function and vice versa. The diffusion of the technology will be tracked by following the change in the market, which is triggered by the decisions of the agents.

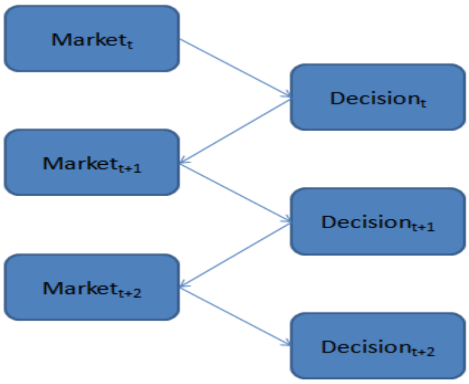

Figure 2: The evolution of the market and the agents

A partially observable environment

Also called inaccessible in some literatures, the agent cannot obtain complete, accurate, and up-to-date information of the environment's state. However some assumption will be made to reduce the unknown factor without biasing the model, especially those parameters considered to have a weak impact, or those not directly related to the results monitored. An owner can not know how the market will evolve because it doesn't know the actions of the other house owners. The model considers that the owners are aware of all the parameters of the market in order to calculate the costs of each technology, which in reality is not true. This assumption will be counterbalanced by assigning preferences to agents in order to differentiate them from pure "homo-economicus" entities. Some parameters like the price of gas and electricity for example are global parameters, governed by many external factors, like the political situation in the Middle East. The policy for subsidies might change with the change of government, or might adapt to the financial crisis.

A stochastic environment

When modeling people's decisions, it is not true that every agent's action is a reaction to the change in the environment. Such factors as personal preferences, family background or simply daily mood will sometimes affect the decision [RAM04]. Similarly, while considering the market evolution, one cannot predict that the decisions of the agents will definitely lead to some increase or decrease in the market share of a product. The model is therefore non-deterministic. we will consider that every action increases or decreases the probability to reach other states, with no certainty.

An episodic environment

The performance of some agents is dependent only on a number of discrete episodes, not on the complete simulation. Every year is a new episode, where the decisions of house owners are taken according to the current environment, not to their previous decision. The previous episode would affect the environment, but we can consider only the observation on the new environment, simplifying the problem by separating the procedure to be executed every year. When it comes to the subsidy implementers, as well as for the micro-CHP companies, their decisions are the result of a chain consisting of the complete history. The environment is therefore in general non-episodic.

A discrete environment

There are an infinite number of actions and percepts in the environment. People might decide to change their residence or to use an unknown product. People might pass away and ownership of a house will change. In the real world, everything is possible. In the model, we will reduce the continuous environment to a discrete one, specifying the actions states and percepts that we will take in consideration.

MARKET PARAMETERS

The market parameters have to be defined, in order for the agents to have a percept of the world. The agents' decision process will be modeled, based on the environment in which they evolve. The market share of each technology has to be monitored to evaluate the diffusion of the micro-CHP. Capital and operational costs will be used to evaluate the possible decisions to be taken by the agents.

The world will be resumed to the available market. On one side of the market stand the supply, which consists of the two products, the condensing boiler and the micro-CHP. On the other side is the demand, which consists of the houses inhabited by their owners and having a particular heating system installed. The market parameters consist of the price of gas electricity and feedback as well as the various types of subsidies.

MARKET SHARE

The market share is the ratio of the available units in the market over the number of houses. This is the main monitor for the diffusion of the technology: Most technology diffusion models focus on the fact that the time path of usage usually follows a S-shaped curve. Diffusion rates first rise and then fall over time, leading to a period of slow take up. Then a relatively rapid adoption follows and finally a period of a slow approach to saturation terminates the cycle [GP00]. In the beginning of each simulation, the market share of micro-CHP is set to zero: condensing boilers own the complete market ($ms_{boiler} = 1$). In a market where the number of houses is invariant like the one simulated, the number of units sold is proportional to the market share if the product was non-existent on the market before the start. The number of units sold denotes how many units have been converted since the beginning of observation/simulation period. It is the output of the decisions of the agents that is used to update the market share.

CAPITAL COSTS

Capital costs are one-time setup cost of a project, after which there will only be recurring operational or running costs [BD09]. It includes the purchasing cost (the price of the product), its installation and the eventual subsidy provided upon purchasing. We will consider the purchasing and installation cost as one parameter that we will call price. The price of a product will vary with time according to its presence in the market. For calculation purposes, the micro-CHP will be assumed to own 1 percent of the market. Therefore the initial price will be the product of the cumulated output X(t) of the product by a constant Price0. Price0 will be chosen so that the price of boiler with a market share of 99% (and the price of micro-CHP with a market share of 1%) will be equal to its initial price. Because different products have different effects on customer, a constant alpha called measure of responsiveness will be used to weight the cumulated output [PM06]. The subsidy of purchase still has to be included as a part of costs, giving the following formula for capital costs:

$$Ms = \frac{Number\ installed}{Number\ of\ houses}$$

$$\text{Capital Cost} = \text{Price0} * X(t)^{ß} + \text{PurchaseSubsidy}$$

Subsidy of purchase: The subsidy of purchase is the subvention provided by the state to a consumer in order to reduce the capital costs, stimulate the economy and encourage the consumers to buy a new product. In the simulation, there is no subsidy for the condensing boiler, while 2 different options have been studied for the micro-CHP:

- Zero subsidy: Used as a reference scenario, the assumption is that there is no encouragement from the state towards any technology
- Constant subsidy: A fixed subsidy is offered for each successful acquirement of a micro-CHP. The available budget can be set, so that the subsidies will stop once the budget has been used up.

USAGE COSTS

There are different ways to make money and reduce operational costs using a CHP. The subsidy of production "Sp" rewards the CHP owners for each kWh (kilowatt-hour) produced. Part of the electricity produced is used, and the rest "r", will be sold back onto the grid at the feedback price. In addition to Sp, the state may promote the sale by offering an additional subsidy on every kWh sold, called the subsidy of feedback "Sf". Both subsidies are only fixed values, limited by the available budget.

The usage costs (also called running costs) are the day to day cost incurred while operating the product [BD09]. They are usually defined over a certain period of time called Horizon. In this model, only the annual operational costs are required because the calculation over the horizon will be done by the agents.

The generated costs are:

- The cost of gas: The gas used for both heating "G_{th}" and producing electricity - "G_e", multiplied by the price of gas "Pg".
- The savings made thanks to the electricity produced: When comparing a CHP station to a boiler, we have to include the money that we would have

spent on electricity if we had not produced it ourselves. (1-r) is the share of electricity produced that is used and that should have been bought at a price P_e when using a boiler.

- The profit made from the electricity sold: The excess of electricity produced by the CHP (unused by the home) is sold on the grid, at a feedback tariff P_f. In addition to the money generated by the sale, the state can offer as mentioned earlier, subventions to promote electricity generation at home.

- The maintenance costs that include spare parts, cleaning of the engine, oiling and other operations.

The annual operational costs can therefore be expressed using the following formula: $Uc = Pg(Gth + Ge) - Pe * E(1 - r) + rE(Pf + Sf)) + SE + Cm$ where Pg is the price of gas, Gth is the quantity of gas used for heating, Ge is the quantity of gas used for electricity production, Pe is the price of electricity E is the quantity of electricity produced, r is the quantity of electricity sold to the grid, Pf is the price of feedback electricity, Sf is the Subsidy for feedback, Sp is the subsidy for production of electricity and Cm are the maintenance costs.

CHAPTER III - THE AGENT MODEL

The heart of the model revolves around the active elements, i.e. the people deciding and acting. The market around them is reactive, since it evolves over time following certain rules, without taking any internal decisions. When a new micro-CHP appears on the market, the market share and the visibility will be increased. However when it comes to handle people, we need the additional capability of making independent decisions [MC05]. This is a capital difference between objects and agents, and we will therefore introduce agent based modeling (ABM) in our simulation.

An agent is an identifiable discrete individual with a set of characteristics and rules governing his behavior and decision making abilities. Thank to his discreteness, the agent boundaries are clear and one can easily differentiate between what is part of the agent, what is not, and what is a shared characteristic among agents. The agent lives in an environment with which he interacts with other agents. Agents have protocols for interaction with other agents, such as the voting protocol, and the capability of responding to changes in their environment [MC05]. This clearly fits the description of house owners, who interact with the remaining owners in the buildings and react to the change in their micro-environment (the status of the heating system) as well as changes in the macro-environment (variation of subsidies or gas price).

DIFFERENT AGENT TYPES

Agent types range from the simple reflex agents to the learning agent, as described in figure 3 [RS03].

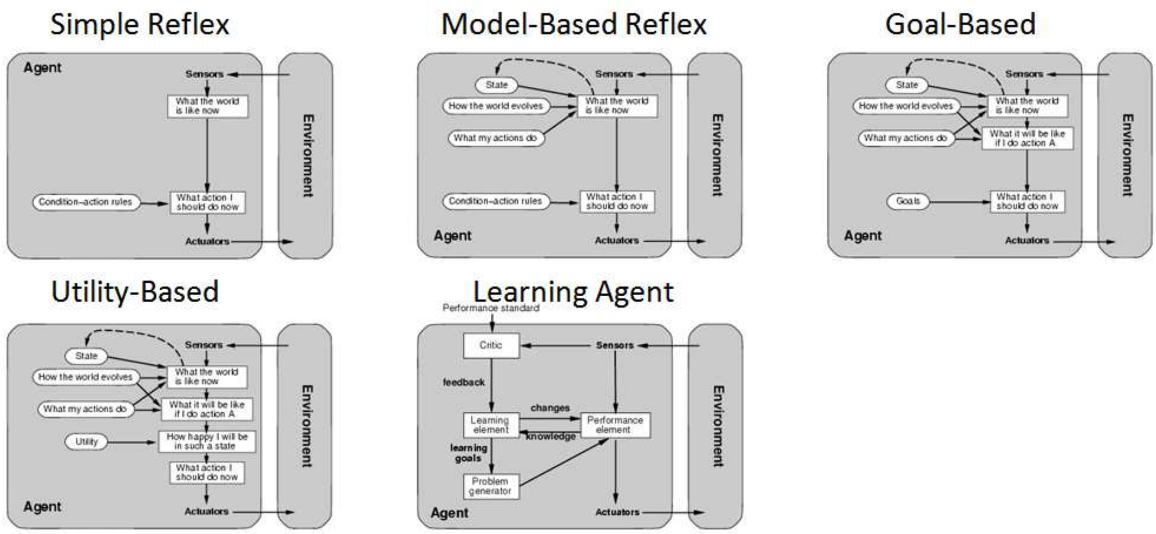

Figure 3: Different types of agents

Simple reflex agents act solely upon the inputs they receive from their sensors. They can be summarized in a table of condition-action rules, a sophisticated way to call a list of "if" statements. In addition, model-based reflex agents take into account the state of the environment and how it evolves.

However, agents' structure can be more complex, according to which they have a broader sight, looking to reach a goal or do the most useful action. Goal-based agents combine their percepts with the actual state to see what could be the possible outcomes of each of their actions. They can be considered as qualitative analyzing agents since they decided for the action that will lead to a world in which they achieve their goals. On the other hand, utility based agents are quantitative analyzing agents since they evaluate how happy they will be with every action they undertake. While modeling, it is very useful to use utility based agents when having numerical values because the various costs and profits can be used as utility. Utility-based agents are also very dynamic and fit well in a changing environment.

Another important notion in ABM is the goal-orientation where agents take decisions in order to achieve their goals. The differentiation in goals will make agents behave differently in the same environment. Subsequently, their perception of events differs also according to their goals. For example, a person who cares much about his or her comfort will be more affected by a non functioning heating system than someone who would prefer to spare money and exploit his system till the end of its lifetime.

ADVANTAGES OF AGENT BASED MODELING

Agent based modeling (ABM) is useful for analyzing the choice of people for several reasons (based on [MC05]):

- First, ABM provides the appropriate modeling approach to understand the aggregate consequences of agents interacting on the basis of heterogeneous preferences. Because the dynamics of purchase are contingent on the decisions of multiple heterogeneous agents, which themselves are contingent on each other, finding equation-based solutions to the diffusion problems is difficult, if not impossible.

- Second, it allows for time-series data analysis. An issue faced during the data collection is that empirical data relevant to house owner's choice criteria are difficult to obtain, especially in order to be relevant enough to reflect the diffusion of a technology. It is practically impossible to ask people what they thought the year before, while taking a particular decision, not to mention over a longer timeframe.

- Third, an agent-based approach allows for experimentation and exploration of historical and spatial contingencies. With empirical data, it can be difficult to model what would have happened if other conditions applied at certain point in time.

For these reasons, the agent representation has been chosen to model the population. The utility-based model is the most corresponding to the requirement of the project, because it allows incorporating the preferences of the user and the cost of the heating system in the decision process.

USING MARKOV DECISION PROCESSES AND DECISION TREES

The Markov Decision Process (MDP) is a mathematical framework for modeling decision-making in situations where outcomes are partly random and partly under the control of a decision maker [GB01]. It is a discrete time stochastic process, in which the process (or the agent in this case) finds itself in a state S at every point of time. The decision maker may choose any action that is available in this S. The process will then reply by moving to a new state S' and give the decision maker a corresponding reward $R_a(s,s')$, to another by taking decisions. The probability that the process chooses S' as its new state depends on the taken action and can be represented by the state transition function $P_a(s,s')$. The MDP model contains:

• A set of possible world states S

• A set of possible actions A

• A real valued reward function R(s,a)

• A description T of each action's effects in each state [GB01].

The sequence of states and actions is best represented in a decision tree that will be used to determine the optimal action.

The decision of the agents will be evaluated using a Markov Decision Process model. They may have a boiler installed or a micro-CHP installed. The installed product may be working or not. The set of states is therefore defined as S= {(working Boiler), (working CHP), (not working Boiler), (not working CHP)}. Each agent has the choice between 3 actions, either to keep the old system or to install one of the two competitors. The set of actions is therefore A= {(do nothing), (new boiler), (new CHP)}.

The process evaluated by each agent will be represented by a decision tree as the one displayed in figure 4. Each action will lead to only two of the 4 states: Installing a new boiler can only lead to a working boiler or a working boiler. It is impossible that the action "install a micro-CHP" results in the state "working boiler" after, and therefore the two other states will be pruned.

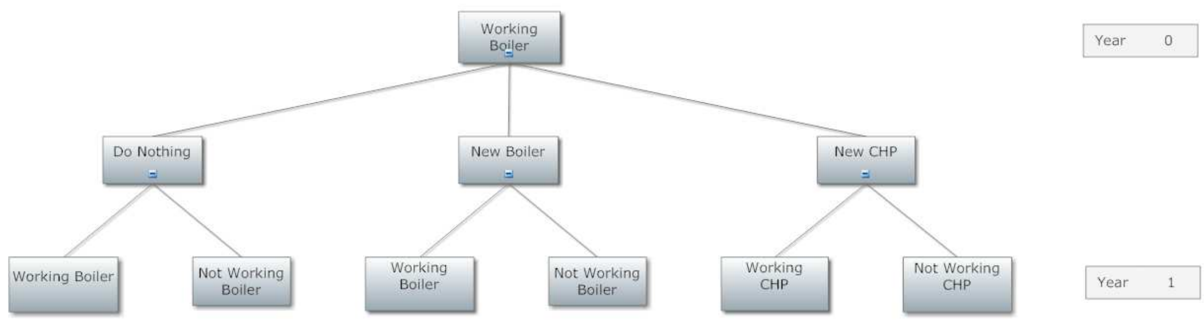

Figure 4: Decision tree with actions and states

Once a new state is reached, a new decision tree can be appended to the previous one. The same decision tree derives from each of the 3 other states. To be able to evaluate each of the leaves, the agent will need to assign a cost to each of the actions and a reward to each of the reached states.

Action cost

One cannot win the lottery without buying a ticket. A student will surely be happier if he owns a Ferrari rather than Golf, but this happiness comes at a cost which would prevent the student to own a Ferrari or would make the purchase of a smaller car more valuable for him.

We need therefore to define the reward of each state and the cost of each action as shown in figure 5. The cost of the action “buy a CHP” or “buy a boiler” is the capital cost of this investment, in other words the money spent upon purchasing. Doing nothing is therefore an action with no cost.

After each year, the best way to differentiate between the installed products is based on the usage costs generated during the year. Therefore we will use negative reward on each state, preferring to take the action which generates less overall costs. The reward of having a non-functional heating system will be discussed in the next section, but it will temporally be set to 10000 to be able to calculate the reward of each action.

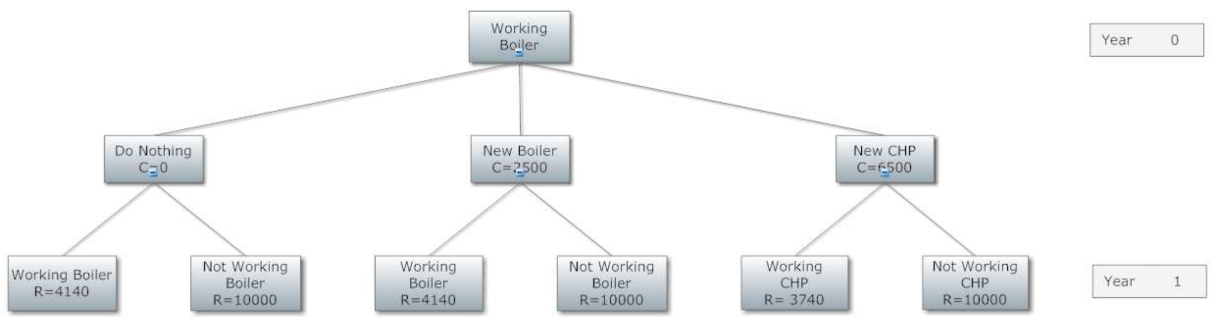

Figure 5: Decision Tree with rewards and costs.

Now considering an action is taken, there is no deterministic way to predict the state reached, whether the heating system will be working next year. A probabilistic model is required.

Agents do not know whether the heating system they have currently will not get broken before the next house council meeting. A probabilistic model has to be used to represent the possible states reached and their likeness. Both the boiler and the micro-CHP will be considered equivalent in term of durability. The expectation is that for a technological life time of 15 years, the probability of failure is very low during the first 10 years, then this probability starts increasing gradually over the last 5 years. Most heating system, when well maintained, will function beyond their technological life time. The probability of failure over age is represented in figure 6.

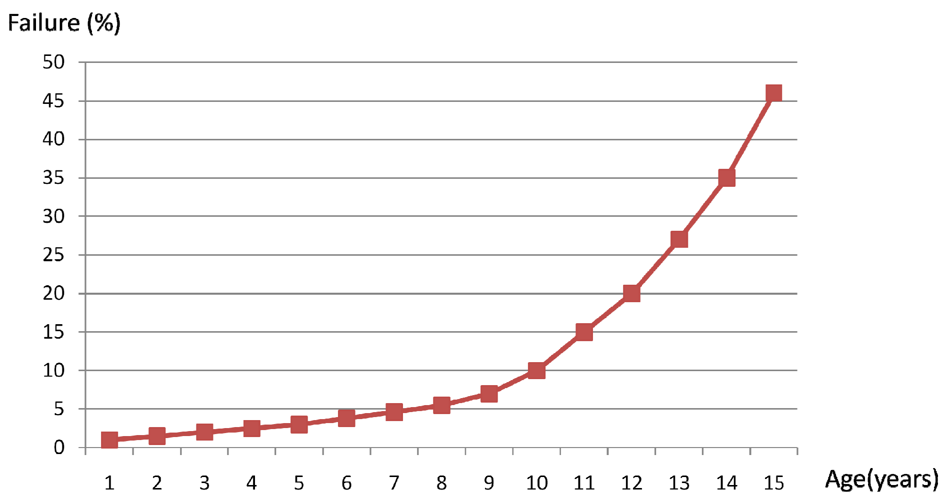

Figure 6: Probability of failure of a heating system with respect to its age

Prob(S) represents the distribution P(s'|s, a), probability to be in state **s'** knowing that the previous state was **s** and action **a** was executed [GB01].

For each state and action we specify a probability distribution over next states.

$$T: S \times A \rightarrow Prob(S)$$

Agents have to choose between three different actions, namely to do nothing, to install a new CHP or to install a new boiler. However, they need to be able to compare the outcome of each of the decisions in order to decide. Therefore we introduce the notion of expected reward, which is a ratio of the reward of a state over the probability of reaching this state. Consequently, the expected reward of an action is the sum of the reward of the aforementioned product.

$$ER[A] = \sum_{i=1..n} R(Si)/p(Si|A)$$

Where ER[A] is the expected reward of an action, $R(S_i)$ are the rewards obtained by reaching state S_i and $p(S_i|A)$ is the probability of reaching state S_i knowing that action A was executed.

By combining the states and actions defined, and assigning the probabilities of failure of the engines as well as the costs of each action and reward of each state, a generic decision tree for all agents is created as shown in figure 7.

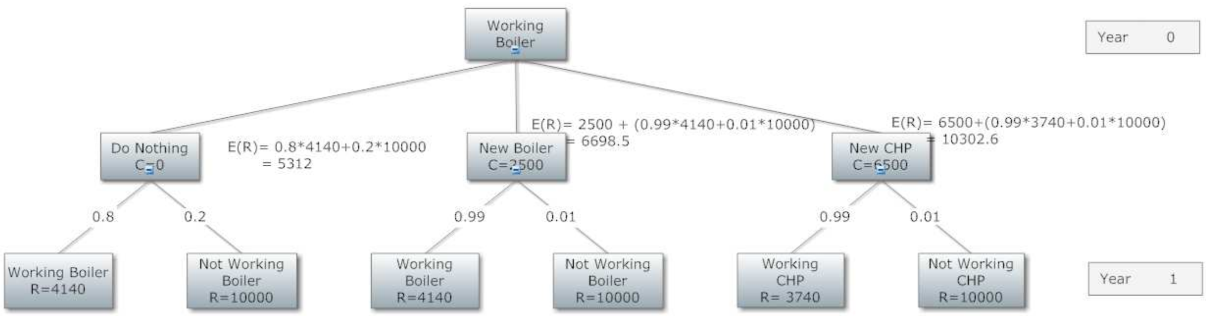

Figure 7: Decision tree with expected rewards

The difference between the agents is how they regard each of the actions, according to their preferences. In the next section, the agent types representing the population will be defined and individualized decision trees will be modeled.

In various classic engineering-economic studies, it has been proven that potential investments in energy efficiency, which rationally appear to be cost-effective, remain unexploited [IWG00]. In order to understand why the observed investment behavior of building owners differ from estimated scenarios, researchers have developed different frameworks. The three major ones are neoclassical economics, behavioral economics and institutional economics [SS00].

The neoclassical economics will be the framework of this thesis. It is characterized by imperfect information, asymmetrical information, hidden cost and heterogeneity of actors. The actors are individuals considered as rational and utility maximizing.

Imperfect information

When considering changing the heating system, building owners have to choose between a large variety of complex products offered by a wide range of firms. Choosing among different energy supply technologies is a decision task that investors take rather rarely, and most technology will have undergone major changes since the previous purchase. They face a difficult task when evaluating the performance of those technologies because of their complexity, a lack of detailed energy consumption data and feedback on current performance [HM98]. In contrast, buying energy as an end product (whether heat or electricity) is a much simpler decision to take, as the product is supplied from a manageable number of large, well established and normally trusted firms. Viewing the purchase of energy efficiency and energy supply as different means to deliver energy services, people tend to over-consume energy supply and under consume energy efficiency [HM98].

Asymmetrical information

A well known example of asymmetrical information is the split incentives problems between landlords and tenants. Landlords might not be willing to change the heating system to reduce long term costs because they would not be able to recapitalize their investments by increasing the rent. The same will happen when the owner believes that potential future tenants are not able to value the energy efficiency standards of an apartment in comparison to the additional rent burden. This can lead to situations where an investment is not made because of the actual or perceived inability of future tenants to value this investment appropriately.

Heterogeneity

Building owners may have a range of independent goals when making investment decisions. These goals might include minimization of environmental impact. Decision makers might evaluate and adjust for the risks and inflexibilities associated with investments differently. These risks include technical risks (reliability, technical performance) and external risks (economic trends, energy prices, policy change). Low income household might face severe budget constraint and are not able to access the necessary capital [SS00].

In addition to these buyers'goals, many real world problems involve a high degree of uncertainty, so that optimal solutions are unknown. People "act by habit, imitation of others and trust in institutions, on reputation or a good name" [GG06] instead of reasoning and objectively calculating utilities. From the behavioral perspective, heuristic and decision rules are needed to cope with the complexity of the outside world.

Moreover, experiments have shown that people prefer to stay with the status quo instead of changing [SW88].

Categorizing the population

Reporting to the decision tree in figure 7, there are 3 parameters missing.

The first parameter is the preference of the agent to do a particular action. The monetary utility of an action is influenced by the goals of the agent. Some agents do not like change, but rather prefer to keep the status quo, even if it is a little more expensive. Others are curious to try new things and like to use state-of-the-art technologies. These goals will be represented as the probability to do a certain action.

The second parameter is the utility of the state “not working CHP” or “not working Boiler”. This value depends on a secondary goal, namely on how much people care about their comfort and safety.

The third parameter is the user horizon. After one year, the agents will reach a state that will require taking a new action, and this could last forever. Once again, each type of agents has a different horizon which is mainly based on the available budget and the age of the agent.

The demand side of the micro-CHP market includes private households, housing associations as well as non-residential buildings like offices. The offices will not be considered in this paper, because their dynamics and motivation in purchasing micro-CHP are different. According to the federal association of German building companies (GdW), housing corporations (“Wohnungsgenossenschaften”) own about 25% of all residential dwellings in Germany. They are in position to quickly articulate demand through procurement of large numbers of a new technology, which can be applied in large housing complexes. Nevertheless, their core business not being technology, they usually prefer to invest in already proven technologies, sparing themselves the hassle of risking on a new product. They are sensitive to short-term price changes and prefer to keep a routine maintenance. In other words, they do not like the risk factor brought along with an innovation, despite the possible gains. They could be considered as an individual entity, however for this simulation, the housing corporation dwellings will be considered to be owned by individuals.

According to Sinus Milieus, a research made by Sinus Sociovision GmbH, the German consumers can be classified in 9 target groups called social milieus. Sociovision is a research institute based in Heidelberg, studying the socio-cultural change, the constitution of society as well as the correlation between the "Sinus Researches" and the market, trends and target groups. Individuals in the same social milieu share the same preferences, basically according to their financial wellness and their values [SV09].

The description of each target group has been adapted to the requirement of the thesis, in order to define the horizon according to which the people evaluate the benefits of a purchase. Their position with respect to the factor of change will be used to define the preference of each action (do nothing, buy CHP, buy Boiler) they may take. The preferences of an agent, like probabilities, sum up to 1. The importance of comfort will define the reward of the states "Not Working CHP" and "Not Working Boiler".

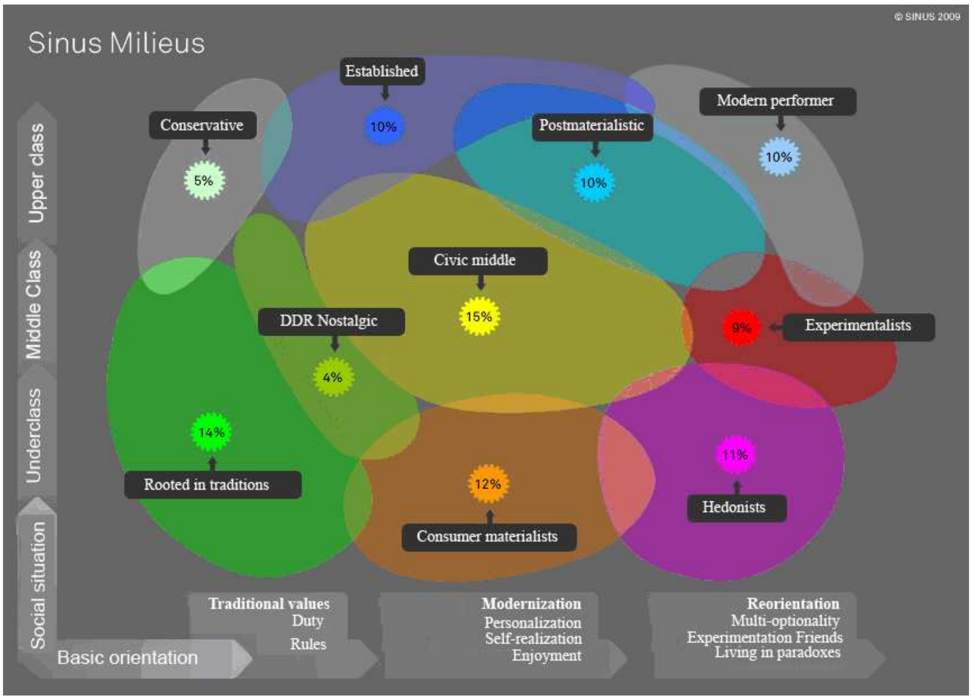

Figure 8: Classification of the German population according to their orientation and social class.

<u>Conservatives (5%):</u> With a majority older than 60 years, the conservatives are rather wealthy and consist of a majority of retired couples living alone in their flat. They prefer therefore to stick to the system that they are using, therefore they prefer to do nothing if the current system is working (Pref=0.5). If they have to change the system, they have a slight preference to a system they know and would rather install a new boiler (Pref=0.3) than a micro-CHP (Pref=0.2). Additionally, it has been shown through simulations that small households are less attracted to using CHP. Mainly because of their age, they look for short term profitability (Horizon=5 years).

<u>Established (10%):</u> Their age ranges between 40 and 60 years. Very comfortable financially, they have a good monetary understanding. Their finances allow them to give importance to their comfort and make longer term investments (Horizon= 15

years). Their rationality in analyzing investments makes their preference for the three actions very similar. They have a preference toward innovation because they give a particular importance to their style and appearance in society, and therefore would be inclined to buy a micro-CHP (Pref=0.4)

Post Materialists (10%): Post materialists are mainly families with kids. The age spans extends from 30 to 70 years. They have a high budget (Horizon = 15 years) and give importance to comfort and safety. They are dynamic and open to change, hence a preference for a new technology (Pref = 0.4).

Modern Performers (10%): They are young, they are wealthy and they want to improve their lifestyle. A majority below 30, they tend to prefer newer technology (Pref = 0.4) and can afford it (Horizon = 15 years).

Experimentalists (9%): As young as the modern performers, the experimentalists have a more restricted budget (Horizon = 5 years). Consisting mainly of high school and university students, they support change and environment friendly technologies as long as their budget allows them to do so. Hence they have a bigger preference for micro-CHP (Pref = 0.4)

Civic Middle (15%): They represent the mainstream. Average on all fronts, they have no preference whatsoever. They would choose the most profitable option (all Pref = 0.33). An important remark is that they care a lot about their comfort.

Rooted in Traditions (14%): Over 65 years old, the traditionalists like it the way it has been till now, and do not see a need to change. They prefer to keep it the way it is, and not risk their money on something new and “unproven”. They also tend to calculate short term investments.

DDR Nostalgic (4%): Regarding their decision concerning the heating system, they can be considered as “rooted in traditions”.

Consumer materialist (12%): The fruits of the consumer society like to buy over their budget, to show that they can follow the trend. They do not base their decisions on the prices, but rather on the behavior of other people. Their slogan is “if they can buy it, then I can”.

Hedonists (11%): The “followers of pleasure and lust” have no money to spend on installing a new system. They prefer to keep the current one and spend their money on something else. They do not like to invest, and prefer to use their money to enjoy the moment.

Based on the previous description, the following tables have been derived, according to which state the people find themselves in. It consists on the preference of every type of consumer to take a particular action (do nothing, buy a new CHP or buy a new boiler), the time horizon on which they compare the different options, and their risk aversion, based on the factor comfort. Some of the values of preferences and horizons have been given through the description. The complete list is to be found in table 1.

When considering a non-working system, the preference of an agent to do nothing is almost inexistent. The consumers having the same behavior can now be grouped into one class of agents. The comfort parameter will be converted into a numerical value, the negative utility of having a non working device. 15000 will be selected for comfort-seeking agents, while 10000 will be chosen for the others. We now have determined 5 classes of agents, representing the population concerned.

consumer class	%	Pref (Action|Working) Action=Nothing	Action=Boiler	Action=CHP	Horizon	Seek Comfort
Conservative	5	0.5	0.3	0.2	5	No
Established	10	0.3	0.3	0.4	15	Yes
post materialistic	10	0.3	0.3	0.4	15	Yes
modern performers	10	0.3	0.3	0.4	15	Yes
Experimentalists	9	0.3	0.3	0.4	5	No
Civic Middle	15	0.33	0.33	0.33	15	No
Rooted in traditions	14	0.5	0.3	0.2	5	No
DDR nostalgic	4	0.5	0.3	0.2	5	No
Consumer materialist	12	Do not look at the utility, but rather on the distribution in the market.				
Hedonists	11	0.5	0.3	0.2	5	No

Table 1: Characteristics of consumer classes when their heating system is working.

consumer class	%	Pref (Action|NOT Working) Action=Nothing	Action=Boiler	Action=CHP	Horizon	Seek Comfort
Conservative	5	0.01	0.54	0.45	5	No
Established	10	0.01	0.4	0.59	15	Yes
post materialistic	10	0.01	0.4	0.59	15	Yes
modern performers	10	0.01	0.4	0.59	15	Yes
Experimentalists	9	0.01	0.4	0.59	5	No
Civic Middle	15	0.01	0.475	0.475	15	No
Rooted in traditions	14	0.01	0.54	0.45	5	No
GDR nostalgic	4	0.01	0.54	0.45	5	No
Consumer materialist	12	Do not look at the utility, but rather on the distribution in the market.				
Hedonists	11	0.01	0.5	0.4	5	No

Table 2: Characteristics of consumer classes when their heating system is not working.

agent type	%	Pref (Action|Working) / Pref (Action|NOT Working) Action=Nothing	Action=Boiler	Action=CHP	Horizon	R(not working)
Conservatives	34	0.5/0.01	0.3/0.54	0.2/0.45	5	10000
Innovators	30	0.3/0.01	0.3/0.4	0.4/0.59	15	15000
Experimentalists	9	0.3/0.01	0.3/0.4	0.4/0.59	5	10000
Civic Middle	15	0.33/0.01	0.33/0.475	0.33/0.475	15	10000
Materialist	12	Do not look at the utility, but rather on the distribution in the market.				

Table 3: Description of the agents and their characteristics in every situation

The utility of an action is the ratio of its utility over the preference of the agent. We used the ratio to cope with the negative rewarding system used. We can now represent the decision trees of 2 agents, an experimentalist and a conservative, having a 12 years old working boiler over one year as follows. While they both prefer to do nothing, leaving the CHP as a third option, we clearly notice the gap between the utilities in the conservative agent side, while it is less perceptible in the experimentalist decision tree. Running the decision tree over more years might lead the experimentalist to reduce the gap and choose a micro CHP, while the conservative will still be choosing to do nothing.

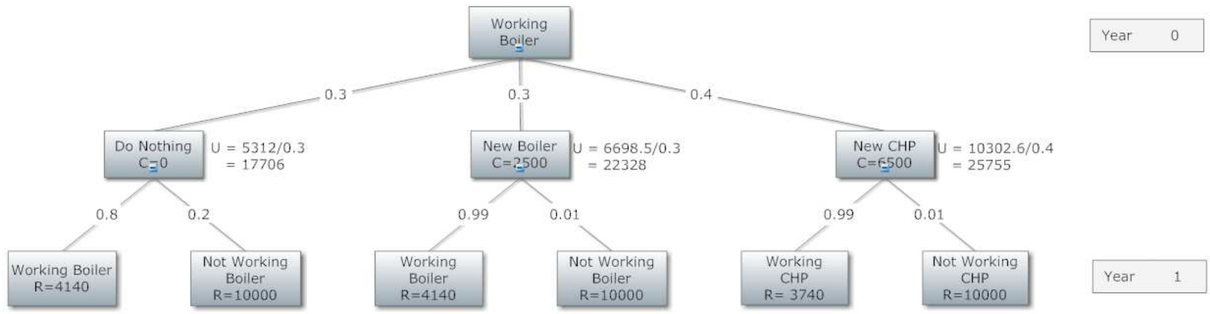

Figure 9: Utility of the action of an experimentalist agent having a working 12-years-old boiler

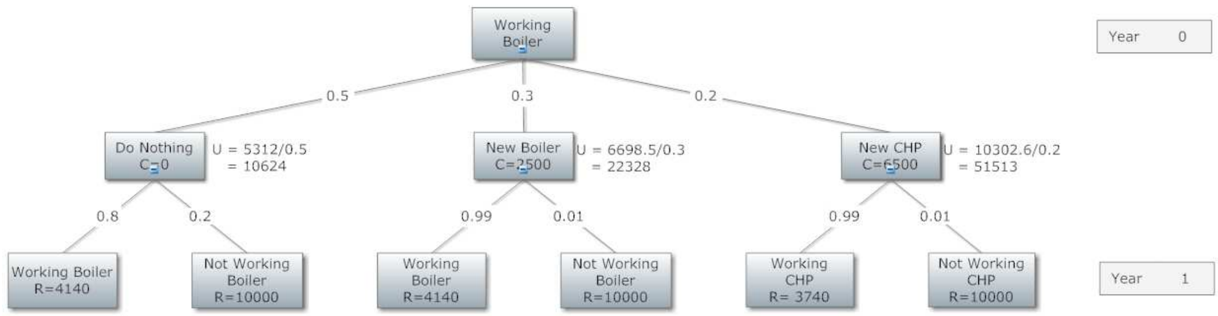

Figure 10: Utility of the action of a conservative agent having a working 12-years-old boiler

Identifying the optimal policy

A policy π is a mapping from state S to action A. In order to follow a policy, one has to determine the current state s, execute the action π(s), determine the achieved state and repeat the same procedure once again [GV01]. Full observability is assumed, meaning that the new state resulting from executing an action will be known to the agent. An objective function maps infinite sequences of rewards to single real numbers (representing utility). The objective function has a finite horizon defined for each type of agent and will be discounted over the years. The discount is used to prefer early investment taking depreciation of the heating system into account. The reward being actually the variable costs in this model, it is logical that the discounting function increases the numerical value of the reward. A value function $V\pi : S \rightarrow \mathcal{R}$ is used to represents the expected objective value obtained following policy from each state in S .

```
UA( action, t, type, state, age) {
if (action == "nothing")
        { A = p[age_HS] * US(type, t+1, state="working", age+1);
          B = (1-p[age_HS]) * US(type, t+1, state="broken", age+1);
          return A+B;
        }
else
        { A= C[action];
          B= p[1] * US(action, t+1, state="working",1);
          B = (1-p[1]) * US(action, t+1, state="broken",1);
        }
}

US ( system, t , state, age ){
if (t==horizon)
     if (state == "broken") return U[broken];
          else return U[system];// this is the stopping condition of the recursion.
A = U[system];
B = UA ("nothing", t, system,state,age_HS)/prefNothing;
C = UA ("CHP", t, system,state,age_HS)/prefCHP;
D = UA ("Boiler", t, system,state,age_HS)/prefBoiler;
return A+B+C+D;
}
```

Fi

11: Finite-horizon Bellman Equations in pseudo code

$$V^{\pi,0}(s) = R(s, \pi(s))$$

$$V^{\pi,n}(s) = R(s, a) + \sum_{s' \in S} T(s, a, s') \cdot \gamma \cdot V^{\pi,n-1}(s')$$

Figure 12: Finite-horizon Bellman Equations

Combining the agents' decisions.

Knowing each agent's decision is not enough to determine the next state. The heating system being a common facility, decisions in this regard will be taken commonly by the house owners' council. Assuming the environment to be semi-dynamic, the council will be considered to happen once every time period i.e. annually.

The council participants will vote to determine the action to execute. It will be assumed that all the owners participate and give a valid vote. Usually, a house is divided in units according to its habitable area. These units are then distributed over the house owners according to the area that they own. That way, votes are weighted and owners of larger flats have slightly more influence than the others. In this model, the house will be considered to be equally divided among owners and the votes will not be voted.

In a normal owner council meeting, a decision has to obtain a relative majority to be valid. Each person votes for one "candidate". When the relative majority is not reached, discussions take place until some persons change their mind and an agreement is reached. Modeling the communication between agents has been handled in a different way in the model. Due to the fact that each agent has calculated the utility of all possible actions, it is able to rank them. The agents' vote will consist of an ordered list of the actions

The voting protocol needed at that point should take the ordered list in consideration as a voting ballot and satisfy the plurality criterion. Nanson method, a variant of the Borda count combined with an instant runoff procedure will be used [AE09].

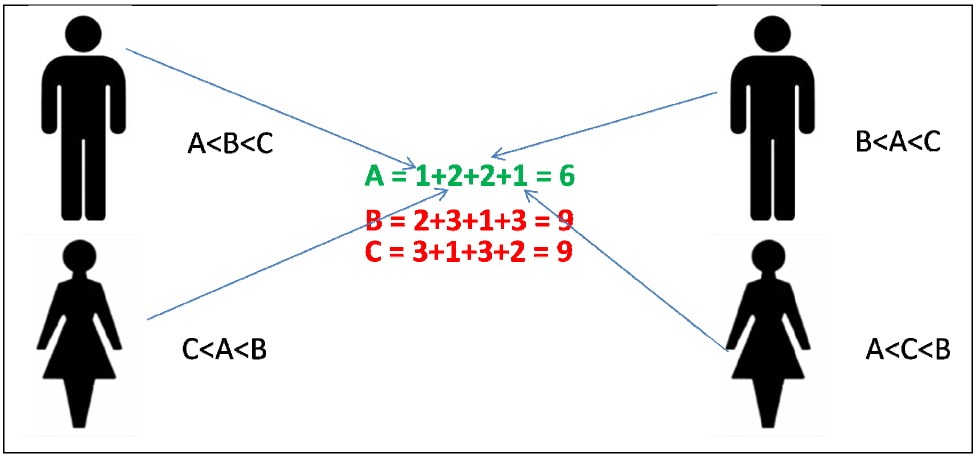

Figure 13: An example of the Borda Count Method.

The Borda Count Method works as follow: the action with the lowest priority will be given one point; the second lowest will be given two points, and so on. Summing the point achieved by each action will determine the Borda Count winner [MR08].

The advantage of the Borda Count Method is that it will always lead to a single winner; however the winner may not be the candidate with the majority of first votes [MR08]. To overcome this deficiency, Nanson proposed to eliminate the candidate with the maximum points, and then to do the Borda Count with the remaining candidates, disregarding the one eliminated. If the number of ballots ranking A as the first preference is greater than the number of ballots on which another candidate B is given any preference, then A's probability of winning must be no less than B's [AE09].

Having defined how each agent makes up its decision and how the resulting action of the house will be combined from their decision, the model design is now complete and can be implemented.

CHAPTER IV - SIMULATION

The simulation will now be run to acquire an understanding on the evolution of the market in different situations. We will therefore plot different scenarios to point out the parameters that influence the diffusion. The best way to achieve this is simulate first a reference scenario, change one parameter at a time and monitor the response.

LSD - THE SIMULATION TOOL

LSD is a simulation program written by Marco Valente, who is a professor of economics in University of L'Aquila in Italy. The beauty of LSD is its simplicity without losing functionality. LSD is aimed at non-computer scientists (mainly economics) needing a tool that is easy to use and requires very little programming background. The time parameter is automatically modeled for and incremented in each function. The code in LSD is based on C++; some macros have been created to satisfy the basic requirements of economists in reproducing functions and following their evolution over time. A pair of delimiters (MODELBEGIN and MODELEND) defines the area where the user can write their equations using the predefined macros, without excluding the possibility of writing traditional C++ functions and using them in the model. As a result, the utility of the software is there through maximized.

An object directed language

LSD uses objects that can be ordered in a tree structure like any regular object oriented program. However, there is no inheritance between them. The tree structure is only a logical support, to facilitate the access to variables and give some organization to the simulation that is running. The figure 14 shows the structure of the simulation discussed in this paper. While the code is written in LSD as independent functions, the relation between object is defined in Laboratory Model Manager (LMM) graphically using the tree, where the specific model is described. The objects are put together and the initial values are defined. The creation of multiple instances of an object is also done in LMM. Once the simulation is run, it offers multiple options to output the results, including a runtime plot to follow the calculations step by step, a report option and exporting the results to text or LaTeX files [VM01] .

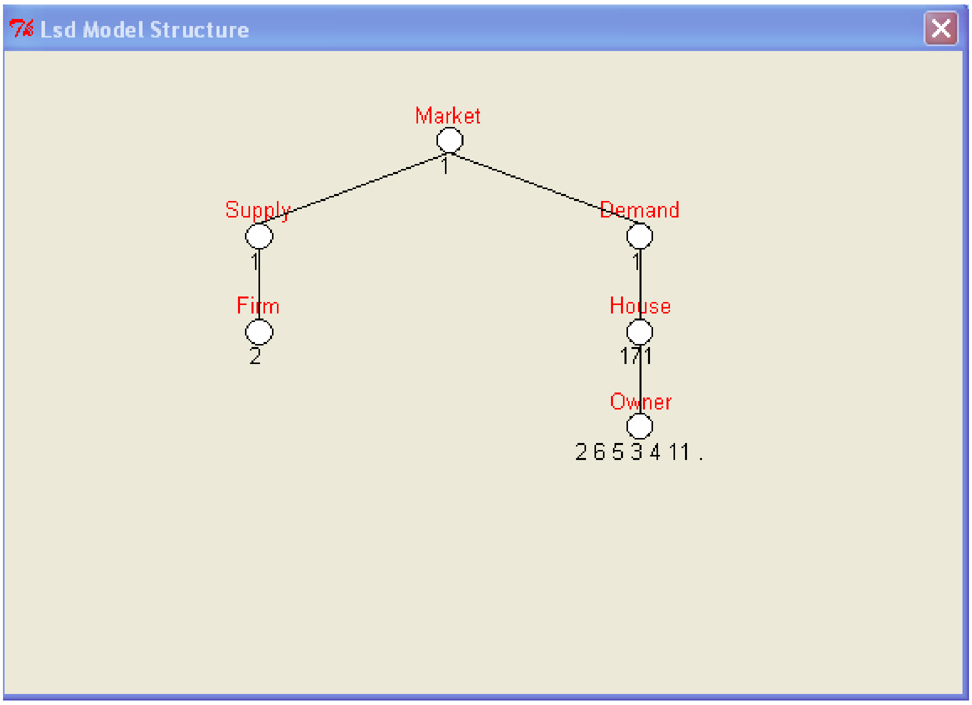

Figure 14: The LMM model

THE REFERENCE SCENARIO

The reference scenario is used to compare the other options. It uses very realistic data, but is in no way the exact value. Taking the price of electricity for example, it differs from a provider to another according to their marketing strategy. High consumers obtain a price pro kWh more advantageous than low consumers. Multi-utilities providers offer package in which the economies made in one product is compensated by another product.

The reference will be based on the following values:

Price of gas

The price of gas is based on eon Hanse tariff “StandardGas” (September 2009). It is composed of a yearly fee of 85,68EUR and price of usage 8,56c/kWh for less than 2500kWh, or a yearly fee of 28,56 EUR and 6.319ct/kWh for a usage ranging between 2500 and 5000kWh. This shows again that the price of gas cannot be uniformed in a region. In addition to that, if a household consumes gas for 4500kWh without producing electricity, replacing its boiler by a micro-CHP will allow the purchase of a cheaper gas. For modeling purposes, the overall price of gas will be considered to be 8,75c/kWh including base price.

Price of electricity:

Electricity is more expensive than gas. Vattenfall, the main electricity provider in Hamburg, proposes a tariff called “Basis Privatstrom” selling the kWh at a price of 19,04 ct, with a fee of 72 EUR p.a (September 2009). The assumption is that producing its own electricity will no allow the household to avoid paying the yearly fee. Electricity prices vary al. Therefore the reference price of electricity is set to 19,04 ct/kWh.

Price of feedback

The feedback price is of 11.67ct/kWh for a production of less than 150 kWh, which is less than the maximum produced in the studied houses [RU08].

Subsidy of production

A CHP bonus of 3 ct/kWh is added to the price of feedback when produced by a CHP of less than 50kW capacity. In addition to it, a subsidy of 1-2 ct/kWh is granted according to the technology used for combustion. The reference subsidy will be set to 4ct/kWh [RU08].

Subsidy of Purchase

The prices for subsidies depend on the size of the micro-CHP bought, which depend on the heat demand of the house. For a production of less than 4kW, a subsidy of 1550 EUR per kW is provided. The subsidy will nevertheless set to 1550 EUR taking assuming that a majority of the bought micro-CHP producing a power of 1 kW of electricity [RU08].

Price of purchase

Like any other product on the market, there are different prices for boilers and micro-CHP on the market. An average price for a condensing boiler is of 2500 EUR while the WhisperGen micro-CHP's cost are around 6500 EUR including installation (http://www.whispergen.com). WhisperGen has been chosen because of its power characteristic, regarding the 1kW electricity.

Houses heat demand and number of owners:

The houses heat demand has been evaluated from the available buildings in Lockstedt. They consist of a total of 171 constructions, each having a different estimated heat demand and number of inhabitants. The inhabitants have all been considered as decision makers, however with different profiles as discussed in Chapter III.

The distribution of people

There are 2071 individuals living in the area covered. They have all been considered as owners with an active participation to the decision process. They have been distributed in agent groups according to the ratio shown in table 3.

To recapitulate, the parameters set for the reference scenario are: price of gas: 8,75ct/kWh; price of electricity: 19,04ct/kWh; price of feedback: 11.67 ct/kWh; subsidy of production: 4ct/kWh; subsidy of purchase: 1550 EUR; price of purchase of CHP: 6500 EUR; price of purchase of boiler: 2500EUR; number of houses: 171 house; number of owners: 2071 individual.

RESULTS AND ANALYSIS

This chapter will describe the result of the different scenarios that have been assumed. The monitored parameters are the market shares of both technologies analyzed. The reference scenario will first be run and in the following simulation, the impact of the heat demand, the prices of gas and electricity and the subsidies will be studied by comparing the market shares variation over time with respect to the reference scenario.

Reference scenario

The results of the reference scenario show that under the aforementioned circumstances, it would take 34 year for the CHP to obtain 50% of the market (figure 15). The diffusion is represented by an S-shape function, as expected. The symmetry observed results from the availability of only 2 options: Houses have to be equipped with either a boiler or a micro-CHP. The market share lost by either of the technologies will be recuperated by the other. The market share of micro-CHP increase in the first 40 years, coming to a deceleration of the diffusion once half of the market is taken. The equilibrium state around 50% is due to the relative slow gain of market. However, 34 years is much too long of a period and the interest would lie in improving the time for the micro-CHP to reach half of the market.

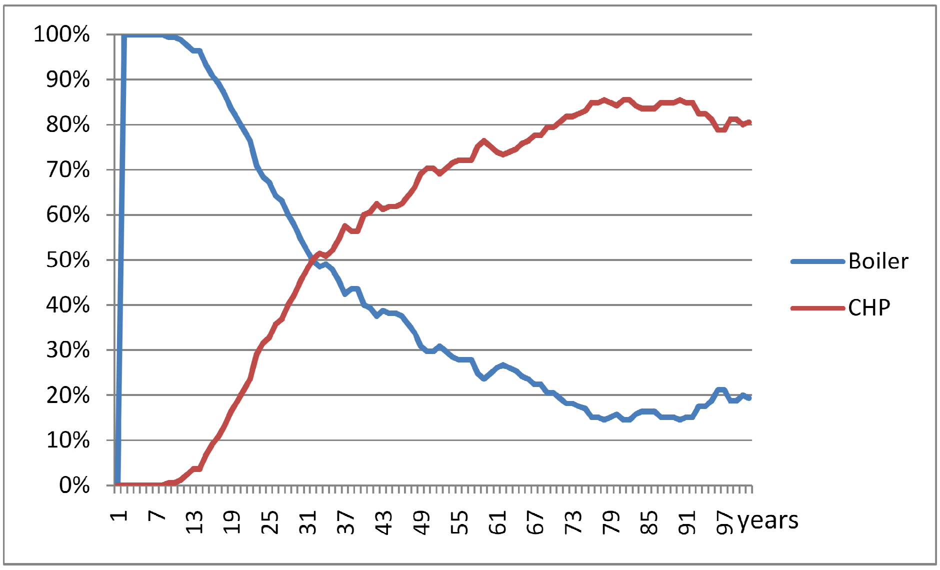

Figure 15: Reference scenario

Large versus low heat demand

The expectation over the upcoming years is for the buildings to become more sustainable. A better isolation and a more energy-efficient construction would reduce the heat demand of houses. While the regulation is already enforced for new construction, it is gradually encompassing the existing constructions [BM09]. The next trial would be to level all heat demands to 5 values, ranging from very low (34000kWh) to very high (42000kWh) in order to see if a lower demand will be beneficial for the diffusion of CHP. The difference in diffusion speed between the upper 3 classes is not very large. However low and very low demand houses (below 75000 kWh annually) do not have much interest in installing a micro-CHP, mainly because their electricity production is not being large enough to cover the other costs.

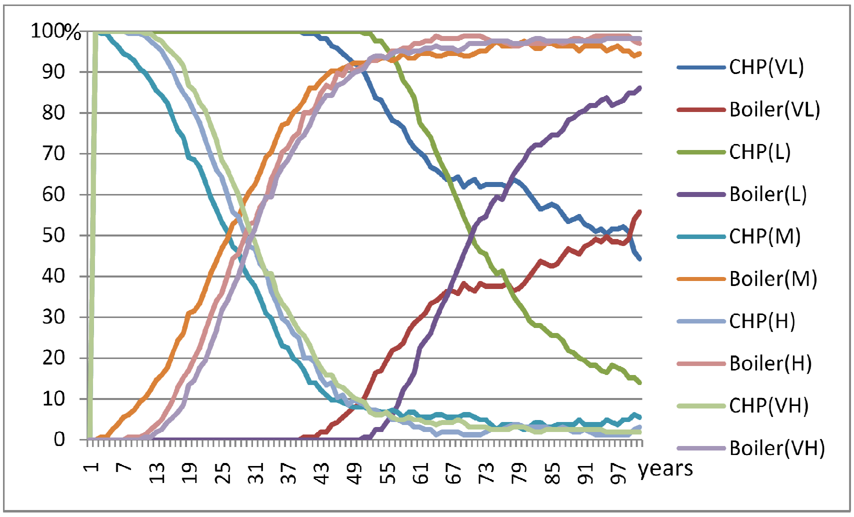

Figure 16: Houses with different heat demand

The electricity and gas price variation.

The electricity and gas prices have been assumed to remain constant over the years. The assumption set is that the price of gas and electricity will not exceed the double of their current values. By doubling the price of each of the commodity, an upper bound will be defined in which the expected diffusion will take place. The feedback price is assumed to behave the same as the electricity price, therefore it will be doubled as well. A very interesting conclusion is drawn if the price of gas raises without a change in the electricity cost, the diffusion of micro-CHP will stop.

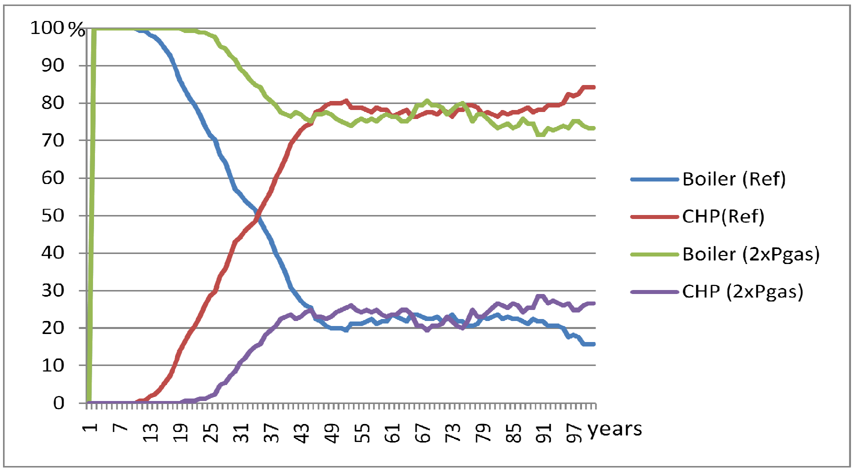

Figure 17: Reference scenario Vs doubled price of gas

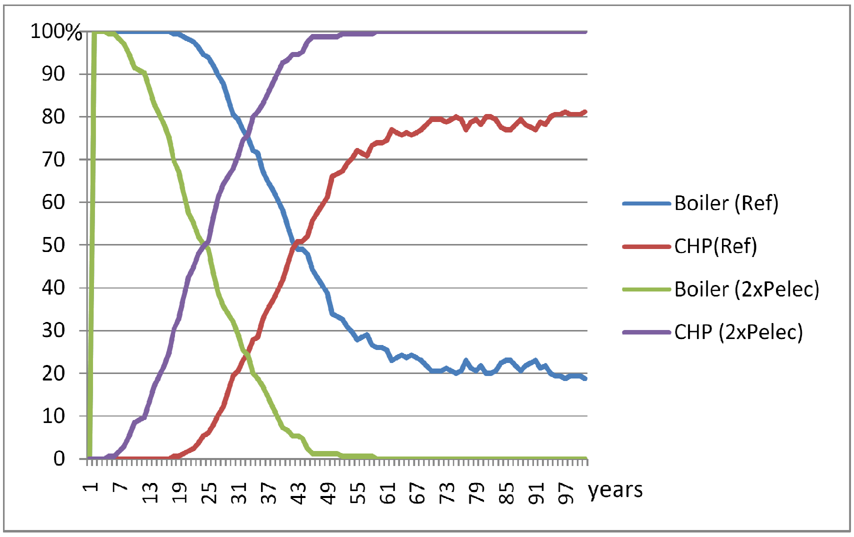

Figure 18: Reference scenario Vs doubled price of electricity

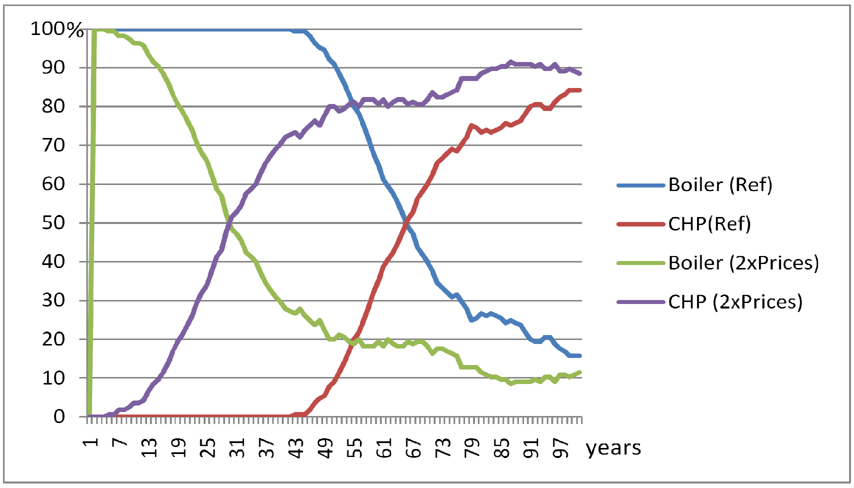

Figure 19: Reference scenario Vs doubled prices of gas and electricity

An increase in the price of electricity will improve the diffusion, independently of the price of gas. It turns out that the price of electricity can cope with the raise of the price of gas. However if the gap becomes too big, the market will stabilize and there would be no more evolution of micro-CHP. Therefore, a good strategy for the government would be to raise the electricity prices, or keep them high enough so that generating electricity at home would keep on being an attractive option.

The subsidy of purchase

Contrary to the expectations, a constant subsidy of purchase did not influence radically the diffusion. A subsidy smaller that 1000EUR will not be effective Varying the amount between 1000 and 10000 did not make any noticeable difference. The impact of a subsidy of purchase is null over 15 years, after which it oscillates between -1,2% and 4,8%. The subsidy of purchase has a positive effect between year 28 and year 44, which means that when the market share of micro-CHP is growing, the subsidy of purchase has no impact.

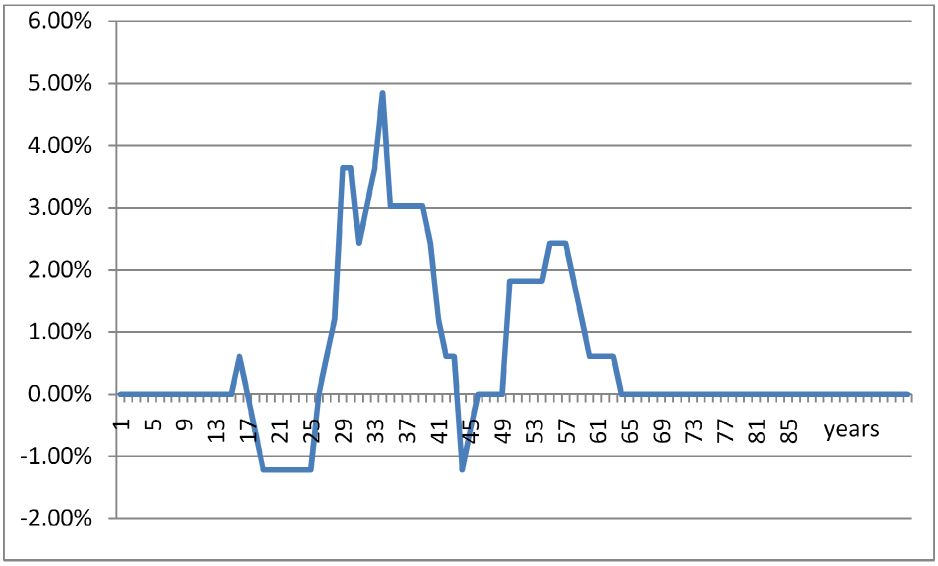

Figure 20: Market share variation with purchase subsidies of 1000EUR

The effect of the population distribution

In the figures shown previously (figures 15, 17, 19 and 19), the progress of the market share in the reference scenario was changing, despite the absence of change in the environment. This is due to the distribution of the agents in the houses. On every simulation, the agents are randomly distributed over the houses according to the percentages shown in table 3. This will create each time a different combination of agents in each house, which will lead to a different behavior regarding the heating system. Taking for example a house with a single owner, changing the type of the agent will be capital. In a bigger house, the effect of changing one agent would be smaller, sometimes even negligible. This can be better understood by referring to the voting method where the importance of individual votes is inversely proportional to the number of ballots. The more voters there is, the less importance each single vote has.

CHAPTER V - CONCLUSION

The aim of the thesis was to monitor the diffusion the micro-CHP technology and to see if it has potential to replace the conventional heating system. This has been managed by creating a model of the individuals taking decisions regarding their heating systems, and model the environment in which they will be behaving. The simulations have shown that under the current situation, the micro-CHP will not have enough diffusion speed to reach half of the market share within the next 20 years. In all the scenarios that have been modeled, the diffusion is estimated to take more than 30 years. The following major conclusions have been made:

- In the current situation, the micro-CHP will need 43 years to achieve 50% of the market.

- An increase in the prices of gas with respect to electricity will slow down the diffusion of micro-CHP.

- An increase in the price of electricity will improve the diffusion speed and will cope well with the change of price in gas.

- A subsidy of purchase below 1000 Euro will not influence the diffusion of micro-CHP. The subsidy will have a positive effect in the first 28 years, then it should be cut to prevent reducing the diffusion.

- Houses with low heat demand are less attracted to micro-CHP. This will be an important issue, taking into account that newer construction have a better insulation and have less heating demand.

FUTURE IMPROVEMENTS

While running the simulations, some issues were found to have a potential to be improved:

- The scenarios that have been run were always assuming a constant price of electricity, gas and feedback. A good way to improve the simulation is to append a model of the electricity and gas market, in order to have dynamic prices.

- The observed area allowed an individual definition of every house according to its heat demand and number of owners. The drawback is that it limited the market fluctuation: by monitoring a bigger number of houses, the simulation can be improved and normalized.

- In this simulation, we have considered a supply consisting of only two products. Adding other competitive products will improve the results and avoid having 2 symmetrical curves in the market share representation. This will nevertheless add an action and two new states per product added, increasing the complexity of the simulation.

- The population has all been characterized as owners. The tenants have been considered as owners of their apartments. Tenants, as well as owners not living in their apartments, are very different from the agents modeled in this thesis. The realism of the simulation has no equal but its complexity.

- The simulation has pointed out the need of profiles for the houses. By only defining the profile of owners, we created a very large possibility of combination of owners in each house. Determining specific composition of houses will allow a better understanding of the decision, and will result in a less randomized diffusion curve. This will allow the expansion of the model, which is currently limited by its structure around the people. In order to model a larger area, it is not recommended to consider each owner as an individual agent. Clustering agents together is not useful; one should rather group the similar houses together. By similar houses, we mean houses with a close heat demand and a similar owner mix. Grouping the houses in clusters will also allow to make more deductions and to learn from the houses behaviors. In the current model, agents had too many parameters differentiating them (preferences, cost of action, and reward of state) that it made it difficult to filter out the common factors and learn how there decision process happens.

FINAL WORD

With this thesis, the initial question has been answered and many new ones have been opened. “Perfection is the nightmare of scientists. When everything becomes perfect, there would be no more room for improvement.”

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