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YES TO AGREEMENTS, YES TO INTERVENTIONS, YES TO SOLAR PANELS

FORMALIZATION OF AN AGENT-BASED MODEL TO MODEL THE SOLAR ADOPTION RATE AND EXPLORE THE EFFECT OF GOVERNMENTAL INTERVENTIONS

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Formalization of an Agent-based Model to Model the Solar Adoption Rate and Explore the Effect of Governmental Interventions

A thesis submitted in partial fulfillment for the degree of Master of Science

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I. Abstract

Although there is an increasing necessity for renewable energy, governments still have difficulties understanding how to stimulate households in their adoption of solar panels. It is the understanding of the human behaviour and actions that is the biggest myopia of the climate change system, which has direct effects on the adoption rate (IPCC [2014]). This thesis aims to better understand how human behaviour influences the solar adoption rate using agent-based modeling as the characteristics of both agents and environment can be altered and interventions can be introduced.

This thesis uses the theory of planned behaviour and agent-based modeling to gain insight in the effect of recent governmental interventions. We approach this by determining the beliefs which have the greatest impact on the acquisition rate by using multiple meta-analyses and checking the validity of the model in its completeness. We adjust the model in such a way that it perfectly represents the past and present solar adoption rate leading to an increased credibility of the model and more reliable exploration of future interventions. We present an experiment that tests subsidies, green current certificates and tax cuts for different times but equal cost to make the comparison as fair as possible.

The analysis showed that the introduction of tax cuts resulted the biggest instant increase in solar panel adoption rate. However, whenever the government stops this intervention, the acquisition rate weakens again. Green current certificates on the other hand are subjected to a lower initial increase but reach a maximum which is higher than the one of tax cuts making the latter even more fruitful on a long-term basis. We therefore have a recommendation which is twofold: we advise the government to determine its maximum releasable budget to promote solar panels and set the target of the minimum number of transitioned households before inserting any intervention. Next, we recommend the government to invest in both green current certificates, which start to be fruitful after 4 years instead of the other two interventions, and non-financial interventions to make households aware of the large positive influence of this new type of technology.

II. Acknowledgements

The path towards this thesis has not been without hurdles. Its completion is thanks for a great extent to the people who challenged, supported, and guided me along the way. I am tremendously lucky to have had guidance by my advisers Dr. Virginia Dignum and Rijk Mercuur of University of Technology Delft and I thank them for their endless support during my research, for for their patience, motivation, willingness to succeed, and immense knowledge. They consistently recognized this dissertation to be my own work, but pointed me in the most appropriate direction whenever they thought I needed the guidance. I am very grateful for their help and could not have envisioned having better supervisors for this MSc research.

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Jesse D'Haens
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Introduction

1.1. Motivation

An increasing population means an increasing necessity for energy. It is indispensable in every walk of life. Energy sources can be categorized as being a renewable or non-renewable source. Knowing the dreadful fact that the globe is affected by land pollution and atmospheric effects due to the use of non-renewable energy sources, the importance of a renewable energy expansion cannot be underestimated. Slowly but surely people are starting to understand the significance to change towards renewable energy sources whereof the progress in developing cleaner, more efficient energy technologies plays a big role. Together, we are counting on global agreements, like the Paris agreement, to set our mind on a more sustainable path and to set goals for the future even more. As a result, governments, including Belgium, are actively promoting the adoption of solar panels. Many reasons exist to boost this type of renewable energy. First and foremost, solar energy is depicted as a renewable energy source as it can be harnessed in every region and is available every day. Second, solar power prevents adopters from paying a large electricity bill as the generated solar energy can directly be used. Lastly, the solar technology is predicted to be improving due to an ameliorating knowledge of quantum physics and nanotechnology which will intensify in the future (Masouleh et al. [2016]).

However, despite the advantages, governments have difficulties understanding how to stimulate households in their adoption of solar panels. It is the understanding of the human behaviour and actions that is the biggest myopia of the climate change system, which has direct effects on the adoption rate (IPCC [2014]). One possible major defect regarding this matter is the non-existence of a model that investigates the decision of households in their acquisition choice; a model that both questions the different weights of beliefs regarding solar panel acquisition and the effect of interventions. By having a working model one could better understand how households make decisions what could help mitigate climate change.

1.2. Knowledge Gap

Previously stated, solar panels concern one of the technologies that is likely to gain momentum, albeit, for all people, under different conditions where the attractiveness to buy increases and the government introduces stimulating measures. The majority of reports conducted by researchers mainly focus on economic parameters and underestimate the importance of social interactions and decisions on a micro-level. Keeping in mind that the decision to adopt solar panels happens on a household level, where the social aspect is of utmost importance, one can say that a large share of information gets lost leaving us with a lot of uncertainties considering the adoption of solar panels.

Agent-based modelling is a useful tool that enables modelling the diffusion of innovations by describing a system from the perspective of its constituent units, since this is an area where typically emergent phenomena arise (Bonabeau [2002]). Therefore, a large variety of simulations exist that display the adoption behaviour of individuals or households (Rai and Robinson [2015], Johnson et al. [2017], Zhang et al. [2016]). Others used ABM for instance for environmental innovations (Palmer et al. [2015], Sopha and Klöckner [2011]), social media (Rand et al. [2015], El-Sayed et al. [2012]) and green electricity (Krebs and Ernst [2017]).

An overview of different sources is given in Table 1.1. The sources were categorized based on their occurrence in academic reports describing agent-based modeling and the theory of planned behaviour. Studies have been executed focusing on the adoption of solar panels using agent-based modeling as the main tool (Lee [2013], Rai and Beck [2015], Robinson and Rai [2015]) whereas others largely focused on forecasting the diffusion of solar panels by using stochastic simulations (Jager [2006], De Groote and Verboven [2016]). In addition, a large set of reports has been written on the energy diffusion across countries using agent-based modeling or mathematical equations, however the minority was devoted to solar panels specifically (Brannon et al. [2000], Veneman et al. [1999], Bauner et al. [2013]). Alongside these reports, research has been executed on the willingness to pay for renewable energy and the adoption of water saving innovations using the agent-based modelling principle (Kowalska-Pyzalska [2017], Schwarz and Ernst [2009]). These study solely focused solely on Germany and Poland.

To assure that we do not reinvent the wheel we assured that multiple aspects remained different from the reports already conducted. The research performed in the past differs from this dissertation on four levels: first, the country whereon we focus is different. Secondly, this dissertation focuses on long-term recommendations, whereas the cited sources either investigate the past or concentrate on short term recommendations. Thirdly, we only use one theory and effectively try to match real data by only using this theory. Other reports on the other hand include multiple theories and mainly neglect the power of using only one individual technique. Lastly, in contrast with reports using empirical modeling techniques, the effect of neighbours and social interactions are incorporated.

Table 1.1: Literature Overview on the Adoption of Solar Panels

TOPIC	ARTICLE
Solar Panel diffusion studies using ABM	Lee [2013], Rai and Beck [2015], Robinson and Rai [2015]
Solar panel diffusion studies with a case study and a combination of forecasting and stochastic simulation	Jager [2006], De Groote and Verboven [2016]
Renewable energy diffusion using ABM	Brannon et al. [2000], Veneman et al. [1999]
Renewable energy diffusion using mathematical equations	Bauner et al. [2013], Robinson and Rai [2015]
Studies using ABM for modelling the energy sector	Lempert [2002]
Studies analyzing the diffusion of innovations using ABM	Schwartz [1977], Kowalska-Pyzalska [2017]
Studies about innovation diffusion in Belgium	Jordi Suriñach, Nadine Massard [2009]
Studies concerning factors influencing micro generation or innovation diffusion	Swart [2017], Perin [2015], Kauppakorkeakoulu [2008], Gerarden [2017], Khare [2015], Rogers [1995]

1.3. Purpose of the Research

The following dissertation is intended to answer two levels of lack of insights and decrease the knowledge gap in the field of modeling the buying behaviour of renewable energy products. After identifying the most suitable theory to display the decision making behaviour of Belgian households, it can serve as a preliminary framework for designing an agent-based model resulting in certain answer to decrease the first lack of insight. The objective of using an agent-based model is to provide a bottom-up approach to get a grip on the effect of multiple interventions on both micro- and macro-level influencing the solar panel adoption. Providing exact information concerning the numbers of the adoption rate will be difficult. However, the dissertation can help understand the influence of multiple interventions.

Important to mention is that this dissertation is a curiosity-driven exploration that researches the effect of various interventions. In reality, the Belgian government has the possibility to introduce interventions to their choice and even introduce multiple together. However, due to time constraints, the latter has not been included in the dissertation. Finally, it can serve as the foundation of any other research in the same field of solar panel adoption. namely, it can be used to test other interventions or to estimate the adoption rate of other renewable energy types.

1.4. Scientific & Public Relevance

The outcome of this dissertation is both of importance for scientific and public purposes. Scientifically, an acceleration in the number of households with solar panels is essential to comply with the terms set by the Paris Climate agreement and to limit the effect of ever-increasing CO_2 emissions. One of the most important barriers which is overcome by modeling the behaviour of households in the area of solar panel adoption is the lack of understanding why people do certain actions. The model aids by evaluating interventions which is very important as implementing ineffective interventions are costly and only slightly improves or even reduces the quality of life.

In addition, this dissertation is useful for the public as it involves a large amount of involved parties that might be interested in a model that maps the solar adoption behaviour of Belgian households. Interested organizations can range from PV panel manufacturers, developers, researchers, suppliers to policy makers or the government. This thesis is helpful for manufacturers, developers and suppliers for an identical reason. As the outcome of this thesis is a preliminary exploration of the future adoption rate of Belgian households manufacturers, developers and suppliers can better prepare themselves for the future as a more precise adoption rate is known after this dissertation. Beneficial for the policy makers or government is the addition of interventions to the model. This dissertation compares multiple interventions and delineates the effect of each intervention individually. The most suitable intervention can be selected to be implemented depending on the wishes of the government.

The agreements, whereof the Paris Agreement is one, require all countries to put forward their best effort through nationally determined contributions and to strengthen these efforts in the years ahead. At the forefront are governments having the power to steer its nation towards achieving the set goals in the agreement and in that sense creating a greener future. It is the power of every nations' government whereon the agreements are build upon as they can introduce interventions that can convince households to buy solar panels. We therefore solely focus upon the government in this dissertation. We write this thesis in such a way that the government is aided. Both the experiment and discussion are therefore aimed to help minimize the knowledge gap or the human decision behaviour to buy solar panels.

1.5. Research Questions & Structure of the Thesis

The main research question is therefore the following:

"To what extent can a model present the current PV adoption rate of households and give insights into the governmental interventions in the future?"

To come up with valuable results we identified the following sub questions to assure correct areas are touched upon. The sub questions are the following:

1. *Which interventions affect the adoption of solar panels?*

   We first need to understand how the Belgian government initiated PV adoption and alleviated households in their particularly generous acquisition process before it is possible to answer the research question. The program first relied on upfront subsidies, but shortly started introducing green current certificates (GCC's), which is a tradable good that proves that the generated electricity is defined as being renewable. Because the program largely made use of future production subsidies, it created the possibility to shift the financial burden to future electricity consumers as well (De Groote and Verboven [2016]). In addition, the Belgian government initiated a tax cut which had an enormous effect on the adoption of solar panels. All individual interventions, in combination with the chosen theory will be elaborated upon in Chapter 2 and will therefore answer the first sub question.

2. *Which theory is best suited to represent the decision-making process of households?*

   Prior to creating a working model to test governmental interventions, we first need a suitable theory on which the model can be based. This second sub question is thus relevant because it can firstly reduce the existing gap in modeling human buying behaviour and secondly can easily increase the model's efficiency and usability for PV adoption. In short, after the literature study (executed before this thesis), one could conclude that almost all models of innovation adoption exclusively focus on conscious cognitive drivers. However, there is evidence of the role of affective reactions in consumer decision making. Traditional innovation models have largely ignored the role of emotions and beliefs, especially in the case of high involvement decisions about complex products (Pham [2008] & Steg et al. [2001]). First, a small elaboration is given on why we use agent-based modeling in the proceeding of this dissertation and why, for this topic, better displays the reality compared to other modeling techniques. Thereafter we select upon the most suitable theory to accompany the modeling technique. A further elaboration on the modeling technique and theory selection is given in Chapter 2.

3. *Which values and norms motivate people to acquire solar panels?*

   We aim to define and quantify the norms that have the biggest impact on the adoption behaviour of solar panels by using literature and simulation techniques in Chapter 3 and 4. This element serves as the core of this thesis as information is gathered and variables are tweaked to match the reality. Without a credible model the further exploration of the data loses trustworthiness. In Chapter 5 we check upon the validity of the model and reflect whether the right thing is built.

4. *What interventions are best introduced to maximize the households' solar adoption rate?*

   Finally, In Chapter 6, we investigate the optimal way of introducing interventions to maximize the households' solar panel adoption rate. We specifically introduce the effect of new interventions and, together with the old interventions, we explore their effect on solar adoption in the future. Lastly, we discuss the relevance and the generalization (outside the domain of solar adoption by households) of these insights and make suggestions for further work in Chapter 7.

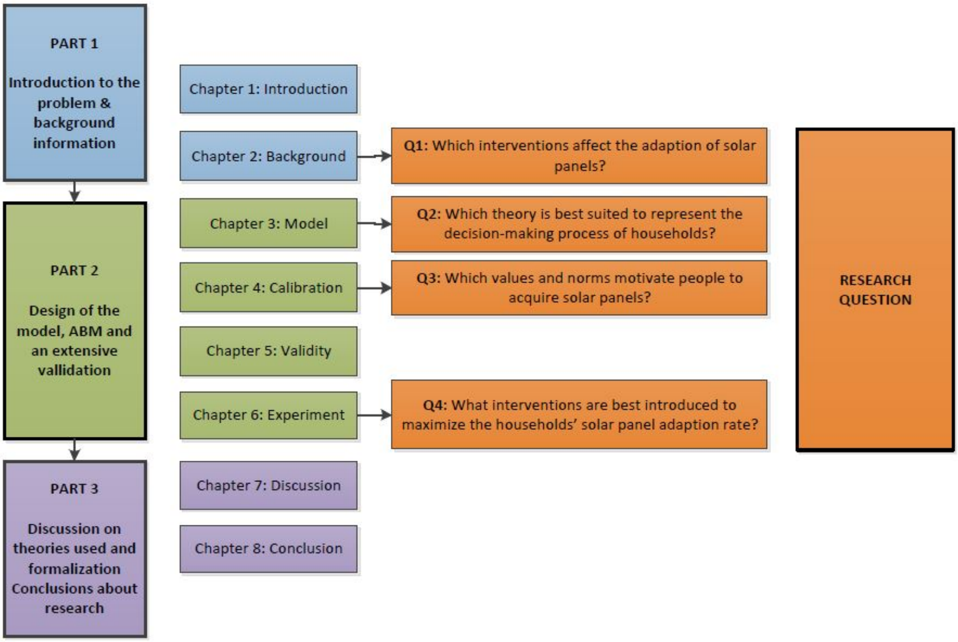

Figure 1.1: Structure of the Thesis

2
Background

In this chapter a description of the background literature is given which is necessary to construct a model that can explain the adoption rate of solar panels. We will start this chapter with an elaboration upon the selection of used modeling technique. We first elaborate upon our selection of researched modeling techniques and substantiate why these are of importance for this dissertation. Thereafter, we give a short explanation of the investigated techniques followed by how it could be used throughout this dissertation. Afterwards, each section is concluded with the individual techniques' advantages and disadvantages prior to the actual selection of modeling technique. Once the modeling technique is known, we look for the optimal theory given our research aim. Just as for the selection of the modeling technique we first introduce all the researched theories followed by a selection. Lastly, we end this chapter by giving a small background on the current adoption trend of solar panels in the household market and the different interventions inserted by the government.

2.1. Selection of Modeling Technique

As mentioned in the Introduction, legal commitments to reduce CO_2 emissions are set in place that require policy makers to find cost-efficient means to comply to the obligations. As part of the literature study, multiple modeling techniques have been investigated upon their usability to correctly contemplate the social, economical and technological problem of acquiring solar panels. As a result, both the Marginal Abatement Cost Curves (MAC) and Agent Based Modeling (ABM) are elaborated upon in this thesis as they both can display, albeit in completely different ways, the effect of interventions on the solar adoption rate. In addition, they have already been frequently used in the context of greenhouse gas abatement. The following sections elaborate upon both concepts individually whereas the final section consists of a comparison and a further explanation on why to use ABM as core technique.

2.1.1. Marginal Abatement Cost Curve (MAC)

MAC curves have historically been used and are still used nowadays to assess the economics of climate change mitigation options. This is for a large extent thanks to its simple representation of the complexity of climate cost-effective emissions reduction. In addition, economic criteria have been selected to be of uttermost importance in the policy discussion. In other words, by using MAC curves one tries to find the optimal solution (policy) to achieve an emission target by the lowest amount of money.

A marginal abatement cost curve is defined as an descriptive graph that illustrates the cost, associated with the the marginal cost of emission abatement for differing amounts of emission reduction represented as millions or billions tons of CO2. Over the past 20 years, a large number of MAC curves have been developed making it inevitable for policy makers to find themselves confronted with MAC curves constructed in different ways (e.g. changes in sectors, countries, years). Two of the most common approaches are the expert-based and model-derived MAC curves. The former uses individual assessment of abatement measures, such that the cost and emission reduction potential of each measure is assessed in isolation, and subsequently ranked according to their cost from cheapest to most expensive whereas the latter uses a systems approach to run the model with a varying CO_2 tax levels and to record its corresponding emission reduction (Kesicki and Strachan [2011]).

Both approaches however are subjected to multiple shortcomings. One issue is the impossibility to represent the abatement cost at multiple points in time. Ward [2014] explains that MAC curves cannot capture differences in the emission pathway and are subject to intertemporal dynamics (scilicet the marginal abatement cost depend on abatement actions realised in earlier time periods and expectations about later time periods). Secondly, MAC curves are strictly an economical tool whereas the adoption of solar panels and the selection of the most suitable governmental intervention includes emotional, social and technological influences. Whenever one decides to solely base his/her decision (intervention) on the basis of MAC curves large areas of interest are neglected (Kesicki [2010] & Kesicki and Strachan [2011]). Lastly, whenever the marginal abatement cost curves contain technological detail, one argues that adding any abatement measure is perfectly tolerable when one wants to increase the abatement amount. As a result, a clear representation of path dependency of the technological structure is not permitted (Kesicki [2010]).

2.1.2. Agent Based Modeling (ABM)

Up until now, computer simulation used for engineering and natural science purposes heavily relied on equation-based modeling. This way of approaching the problem is relevant for sectors like hard sciences, but are difficult to transfer to softer sciences, as most system behaviours have not yet been formalized mathematically. The second technique that looks promising for the computer simulation of socio-economic systems is agent-based modeling (ABM) (Epstein [1996]; Parker [2009]). Agents can represent individuals or institutions and their interactions vary heavily on the field of focus. These interactions can be either formalized by equations or can be specified through decision rules, such as if-then rules or logical operations. Agent-based modeling is therefore said to be more applicable and individual variations in the behavioural rules and random influences are far easier to test than when using equation-based models. In addition, ABM facilitates the research for interdependencies between different human activities making it possible to get new insights on social and economic systems. (Helbing and Balietti [2011]; Kesting et al. [2008])

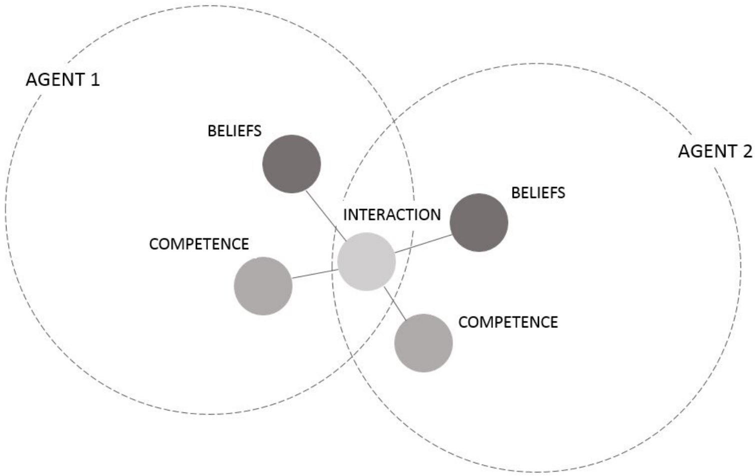

Figure 2.1: Beliefs and social interactions define the outcome of an agent-based model

In recent years, ABM gained interest and more books and articles have been written than ever before. Many articles link ABM to a specific research question and use ABM as a practical domain-oriented technique (e.g., Axelrod [1997]; Lempert [2002]; Schelling [1971]) while others provide theoretical work using ABM in the social sciences such as Gilbert, Nigel & Troitzsch [2005]. Epstein [2008] executed an analysis on emergence in agent-based modeling and Nowak [2004] elaborated upon the usefulness of simple models for simulating complicated processes. Out of these sources some advantages of the modeling technique came to light that are particularly appealing and interesting.

Firstly, Deguchi [2010] state that agent-based modeling is a technique perfectly appropriate to model complex adaptive systems in a bottom-up and top-down approach. In other words, the effects originating at an individual, agent level can be measured on a collective scale and vise versa. In addition, consequences on a higher, cumulative level are often not straight-forward, nor foreseeable, even in the majority of cases where the assumptions on the individual level are very straight-forward. The capability of generating complex and intriguing emergent properties largely arises from the complexity of the network of interaction among the agents and not the rules given to each agent individually (Srbljinovic et al. [2003]). Lastly, Bazghandi [2012] proclaims that ABM is most natural for describing and simulating a system composed of 'behavioural' entities. Whether one tries to experiment with traffic jams, stock markets, voters or how an organization works, ABM makes the model seem closer to reality. A good example is the representation of a driving car. It feels far more natural to describe an entity, in this example a car, moving in a lane than to come up with equations that govern the dynamics of that entity.

Despite all the virtues of agent-based modeling, one should not forget its downsides and limitations. Helbing and Balietti [2011] argues that mankind still does not know which phenomena can be understood by agent-based models, and what the fundamental limits are. Another problem that can be encountered is to overestimate the power of models. This phenomenon already showed its harmfulness for society several times (e.g. financial crises). Stating the known limitations of a model or range of validity is therefore crucial. Lastly, the lack of testing possibilities could be perceived as a major problem. Coming up with a working theory and simulation associated with the working principle of agents is important, testing the model on its correctness using real data is evenly important. For certain areas it is difficult to find correct data that defines each group of agents.

2.1.3. Comparison & Selection

This thesis chooses to use ABM over MAC curves for a number of reasons. First of all, ABM can successfully deliver useful results by creating an imaginary fantasy world where the characteristics and behaviour of agents, and the environment wherein they interact, can be adjusted and the results observed over the course of many simulation runs. Being able to introduce interventions and measure the resulting system behaviour makes ABM a useful tool for studying the effect on processes that operate on multiple scales and organisational levels (Biphenyls [2015]). Secondly, agent-based modeling is more wide-spread than MAC curves which makes it a good tool to use during this dissertation. In other words, because solar adoption and selecting the most suitable governmental intervention is defined as being a multi-layered social, economical & technological problem, we opt for agent-based modeling. Not only would marginal abatement cost curves neglect large areas of interest (as it solely serves as an economical tool), it would also be of less value in a bottom-up approach like the one being used in a later stage.

2.2. Selection of Decision-Making Theory

To represent the decision-making of the agent, we need a theory that represents the decision-making behaviour of the agents, representing Belgian households. Prior to this dissertation, a first selection of different plausible techniques has been executed. This selection was based on the compatibility of the relevant technology with agent-based modeling. The theories listed better represent the problem under consideration than the others.

2.2.1. Theory of Planned Behaviour (TPB)

A theory that focuses on the beliefs of the agents is the theory of planned behaviour (TPB) (Ajzen [1991]). One can see this as a framework mostly used to examine behaviours and the reasons why those are subjected to changes. According to the theory, human social behaviour is guided by three types of considerations or beliefs which will eventually determine whether a behaviour is going to be executed or not: beliefs about the action's likely effective or unfavourable outcomes, known as behavioural beliefs; beliefs about other's expectations, being normative beliefs; and beliefs about the presence of aspects that can ease or obstruct the performance of a behaviour, termed control beliefs. A good example to clarify the differences in beliefs is seen in the recycling industry. People may believe that recycling is a possible solution for the large amount of plastic ending up in the oceans (behavioural belief), that their close relatives think they should start or continue recycling (normative belief), and that the lack of information about how to recycle hurts the recycling rate (control belief). Whenever all the behavioural beliefs are taken into account a positive or negative attitude is created towards the topic under consideration; the total set of normative beliefs results in perceived social pressure to perform the behaviour, or subjective norm; and lastly, control beliefs lead to a certain perceived control over the behaviour. These three main direct determinants predict, in their turn and in the most general form of TPB, the behavioural intention.

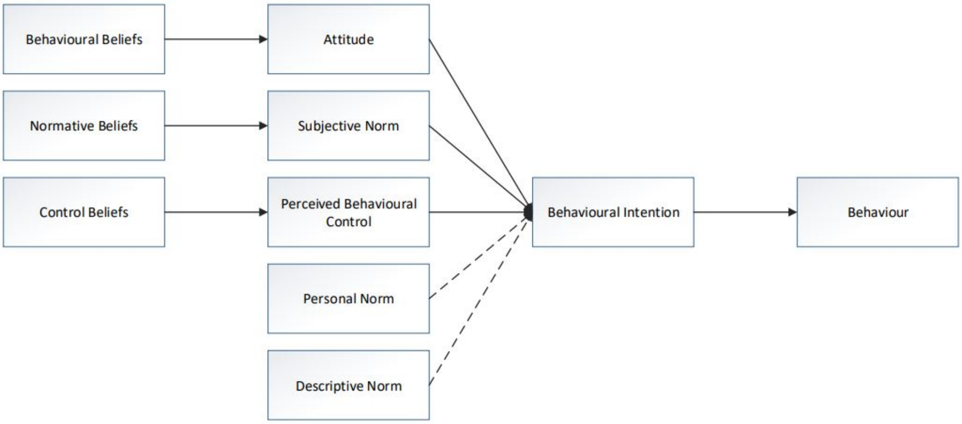

Figure 2.2: Structure of the (Extended) Theory of Planned Behaviour

To make the simulation even more realistic, the model could be extended by two extra determinants: a personal and descriptive norm. The personal norm defines the agents individual perspective on a certain behaviour while the descriptive norm contains information on how close relatives see the behaviour. All determinants jointly lead to the formation of a behavioural intention. The relative weight of each of these determinants of intention is both behaviour and population specific. However, as a general rule, the higher the weights of the five determinants are, the more likely the person intends to perform the behaviour in question. In addition, people are expected to carry out their intentions when the appropriate opportunity arises. However, an interplay exists between having enough volitional control and having a favorable intention. Because many behaviours pose difficulties of execution, the TPB adds perceived behavioural control to the prediction of behaviour. To the extent that perceived behavioural control is accurate, it can serve as a proxy of actual control and can, together with intention, be used to predict behaviour (Sheeran [2011]).

2.2.2. Choice Modeling (CM)

Hanley et al. [2002] describes choice modeling as a family of survey-based methodologies for modelling preferences for goods. It is a technique based on the concept of utility, which represents how well a product or service fulfills one's needs for a certain purpose. Jansen et al. [2011] sees CM as an empirical research technique which is fruitful for market researches, because it nicely shows the choices that consumers make and the underlying preferences regarding the product characteristics. Through a choice modeling experiment, one can gather preference data to estimate the utility of all the options. This data is either gathered in the form of revealed preference data or stated preference data. The first type of data consists of data collected from the real market and uses real choices made by consumers in the past. The latter one, stated preference data, represents choices that people make through surveys. The person filling in the questionnaire selects the alternatives that suits him/her in the best possible way (Hensher et al. [2015]).

Choice modeling is subjected to several potential strengths that other stated techniques do not possess. First and foremost, it forces people to deal with trade-offs between different attributes. In addition, it permits estimating implicit prices and can be used to estimate welfare impacts for multiple scenarios. Furthermore, the center of international economics states that researchers can better define the range of attributes choice modeling and to communicate the frame of reference to respondents in a meaningful way (Adamowicz and Louviere [1998]).

Negative about choice modeling is the great pressure it exerts on respondents. Consequently, a large amount of focus is needed to process the task of filling in a questionnaire using CM making it impossible to execute a questionnaire by phone. Only emailed or face-to-face surveys are therefore possible which has a big impact on the cost of the survey. Second, due to the high complexity of choice modeling a large amount of people will stop filling in the survey. The combination of increased complexity and higher costs mean that some organizations shrink their survey in sample size leading to a lower thrustworthiness of the results (Hanley [1996]).

2.2.3. Diffusion of Innovation

One of the most well-known theories in entering and expanding markets is the diffusion theory. Diffusion is a special type of communication where the message consists of an innovation. The diffusion literature has developed across many disciplines to explain the flow of new ideas and practices and the adoption of new products and services throughout a social system (Robertson [1985]).

Rogers [1995] believes that the diffusion process is made up of four different aspects: the innovation, social system on which the innovation has an impact, the communication channels and time. The focus of the theory of diffusion of innovations is on the means by which information about an innovation is diffused within a social system. He furthermore defines innovativeness as ”the degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a social system”. he proposes to categorize people in 5 different groups: the innovators, early adapters, early majority, late majority and laggards. Thereafter, Rogers made profiles based on demographic, socioeconomic, and personality characteristics as detailed as possible for each of the adapter categories given above. A good example can be that innovators are most of the time good educated, curious and more socially inclined than the peers in the other four categories (Hawkins, I.; Coney, K.; Best [1980]). After a vast amount of time and effort the profiles of these adopter categories have been validated. Most of the research tried to find correlations between age, sex, education, etc. with the time of adoption. Rogers identified 31 of these correlations which are now used as the basis of prescriptive guideline for speeding up the diffusion process by using different communication programs to reach out to one specific category.

Problematic about using this model is the lack of consistency between innovation and other personality characteristics. For example, 203 studies found out that the higher the level of education, the higher interest in innovation, but 72 others found no such relationships (Rogers [1995]). Furthermore, in every research several simplifying assumptions are being used which are often not recognized even if they have a great effect on matters as the inclusion of certain research topics in a study.

2.2.4. Complex Networks

The study of complex networks has known a great increase in popularity in the twenty first century. Complex systems are ubiquitous in nature and man-made systems, and as a complex network can be seen as the main asset of a complex system they appear in a wide range of scenarios ranging from social or technical to biological and ecological systems. Complexity can refer to either a quality of a system or to a quantitative characterization of that system (Amaral and Ottino [2004]) (Standish [2008]). In the latter meaning of complexity it refers to the amount of information needed to specify the system.

The most well-known networks are regular, small-world and random networks and are in this way already ordered from low to high randomness. Regular networks are networks in which the nodes are connected to the nearest neighbors, whether it is in a ring, or in a two-dimensional lattice. Because regular networks are scarcer in real life and less studied in other reports the focus will be on the small-world and random networks. In a small-world network some kind of structure is combined with randomness (highly clustered like regular networks and short path length like random networks). The most arbitrary network are random networks where the nodes are connected to each other in a completely random way.

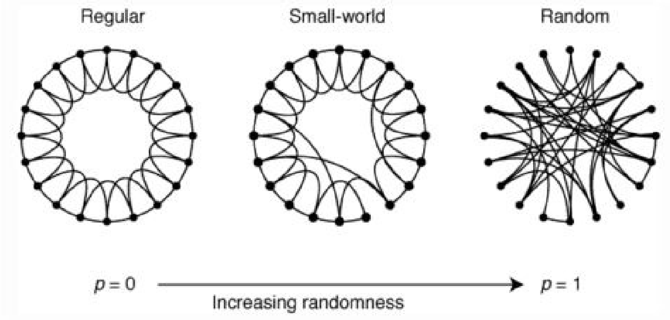

Figure 2.3: Regular, Small-world & Random Network

2.2.5. Social Practices

Social practices refer to everyday practices and the way these are typically and habitually performed in a society. These habits, such as going to school, cleaning and brushing your teeth, are meaningful to people as parts of their everyday live. These behaviours are, according to Reckwitz [2008], executed a lot and integrate different types of elements, such as bodily and mental activities, knowledge and emotions. These practices are considered social as they are performed by different people on different times and locations. It consumes energy and/or material. An example to clarify this statement is given by Shove and Pantzar [2005] showering requires water and influences directly the society's resources. Understanding social practices better would hence enhance the possibility to stimulate behavioural change towards reduced resource use (Holtz [2014]).

As mentioned earlier, social practices refer to regularities or patterns of how certain activities are typically performed in a (part of) society. Warde [2005] believes a social practice consists of an attractor for the behaviour of individuals from which single individuals do not (easily) deviate, e.g. when one studies the way fast food is made he/she can have a disgust of fast food and won't eat it anymore.

In the literature available about social practices, there is no generally accepted or dominant list of elements. Gram-Hanssen [2010] lists a set of different conceptualizations by Schatzki, Reckwitz, Shove-Pantzar and Warde. Especially promising for this thesis is the conceptualization of Shove who sees a practice as a configuration of three components: material, meaning and competence. These components can be understood to be broad categories without set boundaries and are partly embodied in the practitioner. Social practice theories see the individuals as carriers of a practice.

Material: It is a sequence of bodily activities involving the usage of materials. The different actions can vary greatly and can be for example taking the car to work or going by foot.

Meaning: Understanding, beliefs and emotions are all part which are relevant with respect to the material. Issues of relevance corresponding with our example are price, safety, emission, flexibility, etc

Competence: All necessary competences and knowledge you must have before you can use the object or perform the practice. In the 'going-to-work-case' this will be driving skills, knowledge of the signs and knowledge of public transport routes.

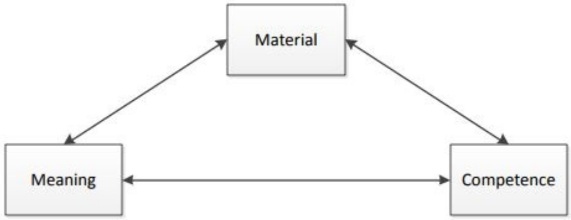

Figure 2.4: Shove's Material, Meaning & Competence Concept

The individual integrates the three components in the performance of a practice. The selection process of the individual towards one of the practices is of major interest. Assuming that a person makes decisions out of a few options according to some sort of criteria inserts some sort of individualism which is odd with the strict interpretation of social practices Røpke [2009] discussed.

2.2.6. Comparison & Selection

After researching all different options we can conclude that the theory of planned behaviour is the most appropriate tool to model the decision making behaviour process because of the following reasons. Firstly, One can use the theory of planned behaviour as a basis of the decision-making process. In comparison to other techniques, TPB also focuses on the intention developing which can be seen as an additional important part of the human decision-making process. Secondly, the method shows a clear decision-making path. As a start, the modeler assigns all the different factors that have an influence on the outcome to three groups: attitude, perceived behavioural control and subjective norm. Once all the characteristics are listed, every agent will get its own values and norms, making it possible for every individual agent to determine its intention and thereafter its decision. The theory of planned behaviour therefore clearly shows a path in the decision-making process. In other words, one first creates values which are thereafter converted into an intention to do something leading to an actual decision to act accordingly. Lastly, Based on the plurality of literature available one can state that using the theory of planned behaviour in combination with agent-based modeling is a well-known principle/practice. Schwarz and Ernst [2009], for example, used TPB in combination with agent-based modeling to simulate the diffusion of environmental innovations related to the use of water. Litvine and Wüstenhagen [2011] uses TPB to perform a behavioural intervention survey in the Swiss electricity market with the focus on stimulating green, renewable electricity. To conclude, the TPB is a well-developed tool that has been used to simulate similar research questions which gives me enough confidence that the outcome will be relevant.

As for every method, TPB is subjected to criticism and debate. Some researchers reject it outright as an adequate explanation of human social behaviour. Wegner [2012] and Wegener, D.M., Wheatley [1999] deny the importance of consciousness as a causal agent and believe that agents tend to make decisions without always being aware of the consequences. However, both reports based their work on everyday decisions which have lower impacts than a decision you once need to take, just as adopting solar panels. Due to pragmatic reasons we can therefore state that adopting solar panels has a too large consequence to not base your decision on.

In addition, much criticism exists on the TPB to be too rational; not taking sufficient account of cognitive processes that are known to bias human judgment and behaviour. To assure that the theory of planned behaviour fulfills its task of serving as an all-encompassing theory two determinants of intention were added as was stated before.

Lastly, critique exists on the relationship between having an intention (within the theory of planned behaviour) and actually making the decision of adopting certain behaviour or buy something. Some researchers, whereof Mr. Kroesen (Kroesen et al. [2017]) is one, refute the way of working of TPB and are convinced that acting a certain way leads to a certain attitude and not vice versa. An article written by Anthony Alu has criticized this claim and sees the relationship between attitude and behaviour more as a ”egg and hen or chicken - which came first?”-question. He observed that attitudes predict our behaviour on three conditions – if ‘other influences’ are minimized; if the attitude corresponds very closely to the predicted behaviour; and if the attitude is potent. Other influences in this sense consist of multiple separate factors that have a real affect or lead to complications between the attitude and behaviour (eg. consciousness and unconsciousness). Next, whem the attitude is specific to the action, then there is likelihood of it predicting behaviour. For instance, attitude towards eating meat predict the buying behaviour of meat. Lastly, if the attitude is strong or potent, it can predict actions or behaviours as well. Attitude could be strong either because something reminds us of it or because we gained it in a manner that makes it strong.

2.3. Domain Knowledge: Solar Panels in Belgium

The majority of traditional sources of electricity production are connected with a staggering amount of emissions and the exhaustion of natural resources. Governments are therefore promoting investments in renewable energy sources and support the expansion of these new technologies to switch towards a more environmental friendly way of producing electricity. One of the more promising types of renewable energy is solar energy which generates electricity by converting the absorbed sunlight by using a PV system consisting of solar panels. We limit ourselves to residential PV systems which can generate 10 kW at most. Mainly because households can decide for themselves if they want to install residential PV systems while industrial PV systems lack volitional behaviour. Whenever a household decides to install solar panels they have to pay an upfront investment price for their system, and, dependent on the acquisition period, receive four main sources of future benefits from installing a PV system: green current certificates (GCC's), acquisition cost savings from subsidies and tax reduction. All elements are treated in turn:

Investment price: One defines the investment price as the total price a household must pay to install a PV system. The investment costs vary widely and depend greatly on the capacity (which is measured in kW). In 2006 and 2007, Belgium introduced a subsidy stating that households could apply for a subsidy of 10% whenever they installed PV installations. Six year later, the tax credits for PV installations were abolished and only a few other aiding mechanism were inserted by the government whereof a reduced tax rate of 6% instead of 21% for houses that were built at least 5 years ago was one.

Upfront Subsidies: A second intervention that has been introduced are subsidies. Generally speaking, dictionaries define subsidies as: *"A sum of money granted from public funds to help an industry or business keep the price of its commodity or service low"*. More specific in the solar panel industry, subsidies have been introduced in the first phase where adoption was still very modest. It served mainly as a tool to convince the bigger crowd and to keep the ball rolling.

Tax Reduction: Tax reductions are another technique that has been used by the Belgian government to encourage people to make the decision to adapt solar panels. A tax cut is defined as a decrease in tax asked by the government whenever people acquire a commodity. A direct result of this intervention is an immediate reduction of income the government receives from those whose tax rates have been lowered. As the results of tax cuts are advantageous for households but are harmful for the government the government usually only makes use of this intervention for a short amount of time. This also applies to the solar adoption market where the Belgian government only introduced tax cuts from 2006 to 2012.

Subsidies from green current certificates (GCC's): Lastly, The Flemish government has actively promoted the PV system adoption through the means of Green Current Certificated. Households acquired a GCC for every MWh of electricity they produce by means of their solar panels which they could sell to the distribution system operators (DSO's) at a guaranteed price for a fixed number of years. The pre-arranged price was substantially higher than the market price of GCC's. When GCC's were first introduced in Belgium, in 2006, the arrangement was very generous; for every MWh generated by a PV system a total sum of 450 Euro would be paid for 20 years. Soon the Belgian government realized that the set price was too high and the program became therefore less feasible in 2010 and was subsequently gradually eliminated. By November 2012 the guaranteed price for the GCC's was only 90 Euros which would be payed for 10 years. In January 2013, the government introduced a so-called banding factor. This restricted the number of GCCs per MWh, and effectively led to an abolishment of the entire GCC system in February 2014.

PV adopters see green current certificates as another type of subsidy for future electricity production, whereas DSO's and electricity suppliers perceive it as a cost which is passed on to the consumers in the form of increased electricity prices. Green current certificates are thus not financed through taxes, but through an increment in the price of electricity. The way this works is as follows: DSO's are in charge of buying GCC's at the contracted price. Thereafter, they resell the certificates at the predominant market price to the electricity suppliers, and these costs are eventually passed on to the retail electricity price.

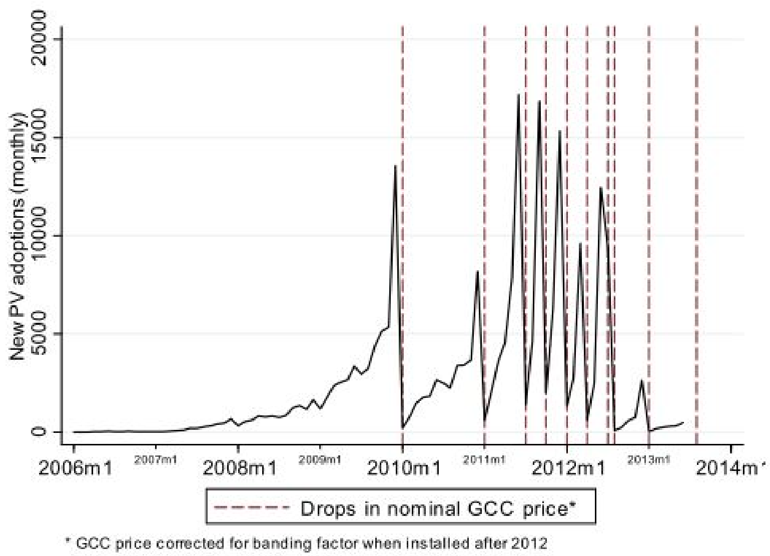

Figure 2.5: Actual adoption Rate of Solar Panels in Belgium

Figure 2.5 depicts the adoption rate of solar panels per month between January 2006 and June 2013. Important to notice are the vertical red lines that correlate to the reductions in the GCC prices which are typically announced a few months in advance. First, the adoption rate of PV systems remained low until 2009, which could be explained by the fact that households did not fully value the benefits or because they postponed their adoption in anticipation of better future investment opportunities. From 2009 onwards, more and more PV systems were installed which led to a local maximum in January 2010 just before the government announced the first reduction of the GCC price. Just after this reduction, the number of adopters increased gradually until a second peak occurred in January 2011.

The same pattern of continuous increases and peaks just before the government announces a drop in the GCC price has been repeated multiple times until the start of 2013 when the GCC policy changed drastically and became less generous. This adoption pattern clarifies the dynamic nature of the household's decision problem to acquire solar panels. Furthermore, the graph illustrates that households partly base their decision on the financial aid the government gives them in adopting solar panels. Whenever the government announces a drop in GCC prices, households may be triggered to purchase solar panels directly to avoid falling under a less advantageous future subsidy scheme or will wait longer hoping the prices of GCC's will increase again.

3
The Model

In this chapter, we elaborate more upon our first aim; creating a model that captures the influence of interventions using the concept of agents and the theory of planned behaviour (TPB). One must keep in mind that whenever 'the influence of interventions' is used we limit ourselves to interventions initiated by the government as the result of these interventions are better illustrated and occur more frequently than other interventions.

We aim to make a model that (1) gives insight in our research question - how can the government increase the number of households with solar panels given the influence of interventions - (2) is concrete and frugal, and at the same time (3) clearly shows the result of interventions as stated in literature. The sub-question tackled in this chapter is thus: *"Which interventions have a beneficial result on the amount of people adopting solar panels"*. While this chapter solely focuses on solar panel adoption, we discuss if we can extrapolate these results to the more general case of the acquisition of green products on a household level in Chapter 7.

This chapter is structured as follows: first we describe the target scenario in Section 3.1. Thereafter, high-level modeling choices are discussed in Section 3.2, followed by the content of the model and agents in Section 3.3. Lastly, section 3.4 dives into the deliberation procedure of agents and tries to get a grip on how an agent actually decides to execute the behaviour of acquiring solar panels.

3

3.1. Description of Target Scenario

To determine the effect of interventions on the adoption rate of solar panels a hypothetical world is created which contains enough information so that valuable conclusions can be drawn, but which is at the same time robust enough to model and simulate. The world used in this model comprises of a group of Belgian households who will have to make the decision whether to adopt solar panels each month.

The aforementioned deliberation is influenced by intentions, interventions by the government (by giving subsidies, green certificates and promoting renewable energy) and neighbours. Within this environment one aims on exploring on how the government can stimulate the adoption of solar panels and therefore increase the adoption rate.

3.2. Some High-level Modeling Choices

As the real world is too complicated to model and the adoption of solar panels is dependent for a large extend on variables one tries to focus on the most important ones:

- One tick represents one month. Every tick the agents look whether interventions are undertaken by the government and what actions were undertaken by its neighbours leading to a decision whether to adopt solar panels or not. Increasing the amount of moments of consideration would lead to unnecessary, superfluous data as one does not decide each day whether to install solar panels or not. In addition, decreasing the amount of measurements would result in unclear data as multiple factors could have changed (the efficiency, price, the number of neighbors with solar panels etc.). In other words, decreasing the time between ticks is not harmful and doesn't affect the model by a large extend while increasing the time between two ticks on the other hand has a negative effect and must by all means be avoided.
- Households are fixed to one place and therefore can't move to other places. This assumption facilitates the model for a great extent as little is known about the role of individuals in the adoption of solar panels and therefore a large amount of extra assumptions must be set in place. Furthermore, this thesis' main focus is the adoption of solar panels by households making the possibility to move independent from the adoption of solar panels. This assumption has a clear effect on the model's outcome as households with a positive mindset on solar panels are more inclined on acquiring the technology in the house they're moving to. In the end, logically, a higher rate of houses adopted solar panels
- Every agent owns a house and has the option to acquire solar panels. Options just as renting a house and/or living in an apartment are therefore not included in the model. The main reason to make this assumption is pragmatic as the inclusion of different household types would increase the necessary modeling time by a large extend.

3.3. Agents

A wide heterogeneity exists in the simulated outcomes because of influences from very different research areas. We already mentioned that solar adoption specifically is not only influenced by its price, but also social aspects such as neighbours or attitudes from close relations with respect to implementing solar panels. Nevertheless, all approaches share a common viewpoint on the modeled system; the analytic unit is represented by an individual agent, acting and interacting within one shared environment (Bandini et al. [2009]). In this model, the agents represent households and will only own characteristics that have a certain impact on the adoption rate.

AGENT	
STATIC	DYNAMIC
	Attitude
Number of houses	Perceived behavioural control
Position of houses	Subjective norm
Influence of neighbors	Descriptive norm
	Personal norm

Figure 3.1: Static & Dynamic Variables of an Agent

Every agent possesses static and dynamic variables as illustrated in Figure 3.1. the static variables will stay identical throughout the whole simulation, while the dynamic variables can change at each tick. To keep the number of variables to a bare minimum only three static variables are included in the model: the number of houses in the environment, the position of the houses, the influence neighbours have on the buying behaviour of the agent. The number of agents is fixed at the beginning of each simulation and will, during the simulation, not change. Secondly, houses are randomly placed in the environment and will not be demolished, and no new houses will be built. Lastly, Graziano and Gillingham [2015] states that whenever houses with solar panels are in close neighbourhood to houses without solar panels the latter are more inclined to acquire solar panels themselves.

In addition, agents possess dynamic characteristics that together cause an agent to adapt solar panels or not. As every agent has experienced different incentives and has created his/her personality, the importance of all determinants is different for every agent. After taking into account all various importances, this model assumes that the decision whether to adapt solar panels postulates out of five conceptually independent determinants of intention: the attitude, perceived behavioural control, subjective norm, descriptive norm and personal norm. After every tick, these five values are subjected to change due to external inputs (e.g. neighbors installed solar panels) or internal inputs (I have a more positive attitude towards solar panels). A small description of the different dynamic elements agents is given:

Attitude: The attitude towards the behaviour (in this case installing solar panel) refers to the personal opinion of agents, a degree to which a person has an approving or disapproving evaluation of the behaviour in question.
Perceived behavioural control: The second antecedent that influences the intention is the degree of perceived behavioural control. It refers to the perceived ease or difficulty of performing the behaviour and it is assumed to reflect previous influences.
Subjective norm: The third predictor comprises the more social side of the adoption of solar panels. It refers to the perceived social pressure to perform a certain behaviour.
Personal norm: The fourth predictor takes personal beliefs into account. It states the agents' perception of the action under consideration.
Descriptive norm: The last predictor encompasses the individual's perception about what significant others do.

3.4. Deliberation of the Agent

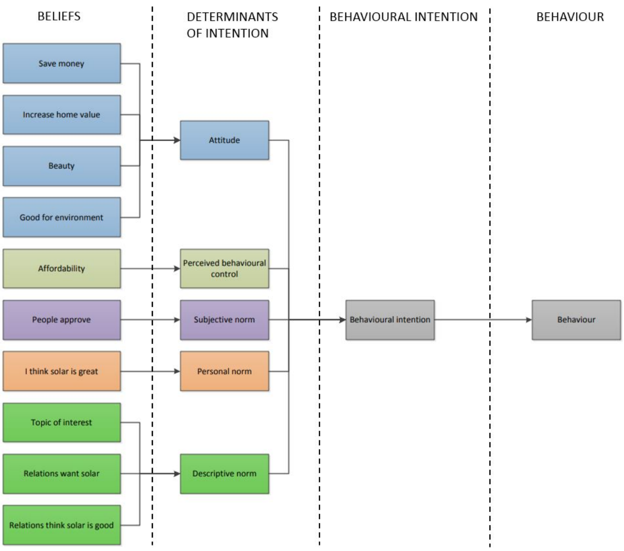

Figure 3.2: Complete Representation of an Agents Deliberation to Adapt Solar Panels

The theory of planned behaviour (TPB) is a well-used tool and has proven to be effective in understanding the intentions and behaviour surrounding the adoption of new technologies. Armitage and Conner [2001] executed a meta analysis which contained 200 TPB studies. The authors discovered that 39% of variance in intention and 27% of variance in behaviour could be explained through TPB. In addition, Bamberg et al. [2003] have applied the TPB in a study on the choice of travel-mode going beyond understanding behaviour and leveraging the theory to evaluate the effectiveness of a behavioural intervention. They concluded that past behaviour has a limited effect on future behaviour if the conditions or context of the behavioural decision change. This statement is particularly relevant in the case of fast-changing technologies just as solar or wind energy, for which prices have dropped largely and the technology has improved for a large extent in the previous years. Keeping agents up to date about improvements or other changes in context therefore becomes an important step to the process of reassessing the decision to adopt or reject a technology as it evolves. As a result, the agents in this model will get their context updated at every tick and will be aware of given subsidies, green certificates and tax reductions. (Faiers and Neame [2006], Jager [2006], Margolis and Zuboy [2006], Denholm et al. [2009], Shih and Chou [2011], Bollinger and Gillingham [2012]).

Having argued about the background in the previous chapter, we already know that the TPB expects the behaviour of individuals to be determined by intentions, the antecedents of which are the attitude toward the behaviour, subjective norms, PBC, personal norms and descriptive norms who are again dependent on beliefs (Ajzen [1991] & Icek Ajzen [2002]). In the continuation of this chapter we will first give a small introduction on how an agent chooses whether to acquire solar panels. Once that is finalized, every step in the process of acting a certain way is described individually. For every module we first try to check the requirements for an adequate model given our object of study, intuition and the literature. Secondly we describe the necessary choices starting from these requirements to a precise well-defined model whereafter we describe the model itself and finally show that, given a certain parameter setting, the requirements hold in the defined model.

Figure 3.2 elucidates the complete process. It divides the procedure using vertical lines and indicates the area of study at the top. The process starts of by shaping the agents' own 'personality' and assign weights to the beliefs used in this model.

Once that is done, the determinants of intention are created. In more detail, beliefs directly influence the determinants of intention which were already cited above. As every agent behaves in its own certain way and find certain things more important than others the weights of the determinants with respect to creating the intention of acquiring solar panels would ideally differ as well. In this model, we opted for a normal distribution similar to how the average person would weigh the importance of the determinants of intention.

The third step in the process of behaviour creation consist of adding up all different determinants of intention and research the intention with respect to acquiring solar panels.

Finally, one must bear in mind that having the intention of adopting solar panels is not the same as actually acting and installing solar panels. By using data from different studies or by executing a questionnaire one can calibrate how many people who have the intention of adopting solar panels actually proceed to install them.

After every month, displayed as a tick, the agents can change their behaviour. Firstly, by updating their history of decisions by keeping track of the past performance context in adopting solar panels. Secondly, by evaluating if it wants to proceed the active behaviour and thirdly, by re-evaluating whether the active interventions fulfill the agents' requirements.

Note that for the ease of explanation and validation we will sometimes treat modules as if they were isolated from the others. In reality, these modules are intertwined and the separate results might have limited validity. We acknowledge that for further validation of the model the interaction as proposed in this section should be validated against micro-empirical data. For example, we need to substantiate why we choose to include certain beliefs and exclude others. Limited amount of work is available to support this decision which makes it an important limitation of this thesis.

3.4.1. Creation of Beliefs

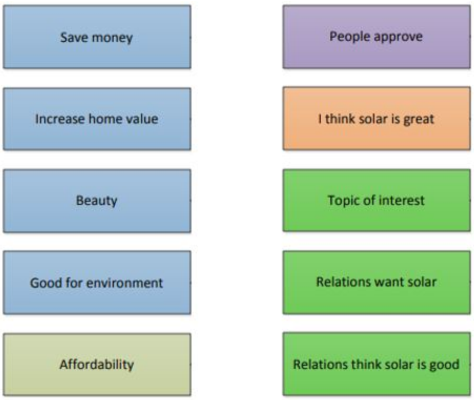

Figure 3.3: Structure of the Creation of Beliefs

This section describes how beliefs come about and how they are part of the decision-making process. We aim to study how one selects the beliefs which influence the amount of solar panels the most. For us, beliefs are thus interesting as major influences that often prevent or stimulate the buying behaviour. Our primary requirement states that all agents can change the importance of their beliefs, and therefore, their behaviour, at any tick or moment in time. Intuitively, we think that people are constantly affected by impulses every day which can possibly lead to a switch in an agents' behaviour. Due to the fact that a tick represents 1 month, we can validly say that this requirement hold place or even further, one can say that this requirement must be true. Without changes in one's beliefs, people without the intention of buying solar panels would never be willing to change their perspective leading to the acquisition of no new solar panels. The first requirement is defined as:

1. Every tick an agent can change its beliefs

We think an agents' decision can deviate from its normal one in two cases. The first case occurs when an agent is stimulated whenever interventions in the form of subsidies, green certificates or tax cuts are included. These interventions are imposed by the government and will influence the affordability and behavioural intention of solar panels. To clarify this statement, a small example is given. Let us assume Mark lives in a house without solar panels and does not see the added value of this new technology. At a specific moment in time the price drops drastically due to subsidies and green certificates resulting in the fact that Mark will have a harder time deciding to adapt or not. The second possible case where an agent may act different to its normal behaviour is when neighbours decide to install solar panels and therefore influence adjacent households. Graziano and Gillingham [2015] indicated that adding one more installation within 0.5 miles of adopting households in the year prior to the adoption increased the number of installations in a block group by 0.44 PV systems on average. As a result the following requirements must hold:

2. External interventions can change the beliefs of agents

3. Neighbours have a positive impact on the adoption behaviour of people

What makes the TPB an interesting toolkit is the large variety within the theory itself. Not only new configurations exist, but the weights of the included actors are subjected to changes as well. In this thesis, an extended configuration will be used together with real-life data and weights from other, relevant reports and scientific articles. All investigated sources, such as Rai and Beck [2015], Sig and Sig, use the identical theory to determine the public's perception and the diffusion of photovoltaics in the market. Interestingly enough, all beliefs positively affect the behaviour of the agents. As this thesis is in line with the aforementioned sources, one can substantiate that there will be a positive relationship between the listed beliefs and the intention to purchase solar panels as well.

4. There is a positive relationship between the listed beliefs and the intention to purchase solar panels

Some Modeling Choices

A large variety of believes exist with weights having the tendency to change frequently. Every single action an agent, in this case a human being, experiences leads to a change in perspective of the topic of interest. If we again use Mark as an example, who holds the same negative attitude/view towards solar panels as previously stated, one can say that Mark experienced difficulties or saw certain drawbacks that stopped him of adopting solar panels. If Mark's neighbours decide to adopt solar panels or already adopted solar panels and embellish this new technology, Mark's beliefs change by a certain extent.

Taking all different influences into account would allow the model to reflect more accurate, real-world conditions. But on the other hand, not enough information on every different influence can be found and certain beliefs have a much higher weight than others. The model will therefore only take the most important influences with their respective weights into account which have already been used in different meta-analyses such as Rai and Beck [2015] and Turaga et al. [2010].

Note that our model is thus limited in capturing the nuances of creation of beliefs. For example, an influence of a belief might have been important in the past, but this does not guarantee that it will be important in the future. This turns out to be an important limitation as we will further discuss in Chapter 7.

Model Details

Once all the requirements to create beliefs are listed, it is important to describe by the usage of pseudo-code how the model will look like. We will begin by presenting how households are created and will then further elaborate upon the importances and weights of every belief.

The process of creating houses is fairly straightforward. A slider was introduced in NetLogo to vary the amount of houses which will randomly be positioned in the world. One must keep in mind that we assume all houses to be of equal age and that households are fixed to one place and cannot move from one place to another. Once houses (and households) are created, they are all simultaneously given beliefs with according weights on how much the belief affects the determinants. Literature on the beliefs in the acquisition of solar panels is extensive. Each of the literature studies consider certain beliefs more important than others. These beliefs stood out and will therefore have a larger importance.

A tool largely applied by researchers to quantify the strength of a belief is the mean and standard deviation of a normal distribution. This is not only easy to work with mathematically, but is also widely applicable, which makes the outcome easier to understand. Note that the mean of the normal distribution will further be called the 'importance' of the belief mainly because importance better displays the essence of the mean of a normal distribution. In the model made for this thesis, we have combined the most influential beliefs together with their normal distribution. Afterwards, the beliefs have been categorized into different groups representing the determinants of intention. In that way, each belief influences only one determinant.

In addition to giving each belief a certain importance, a weight must be given that represents how much influence the belief under consideration has on the determinant of intention. As multiple sources have used different beliefs, it was irrelevant to reuse their findings as this would lead to unnecessary errors. Instead of using existing data, the model has completed more than 50.000 runs with varying weights. The variables that give results closest to the real data are used in the final model. More information on the selection of the optimal weights will be provided in Chapter 4.

The following small example aids to clarify the principle used: one of the major influences on the adoption of solar panels is whether or not the new technology will save money in the long run. Rai and Beck [2015] executed a study that comprises the importance of all beliefs in respect to adopting solar panels and stated that the belief 'saving money' has a mean of 5.42 and a standard deviation of 1.81. Finally, one needs to find out which determinant is directly affected by the belief of 'saving money'. In this case, this will be 'attitude' as a favorable evaluation is created by stating that one can save money.

In addition, the accompanying pseudo-code (Figure 3.4) describes the process in a notation resembling a simplified programming language and support the reader in the understanding of the process.

Algorithm 1: The algorithm to give every belief a weight and importance.

```
Require: A list of used beliefs with corresponding characteristics
   category1 = {}                                    category4 = {}
   category2 = {}                                    category5 = {}
   category3 = {}
for all beliefs do
         set importance = Ñ(A,B)
         set weight = belief.weight
if belief.category = category1
         category1.add(belief)
else if belief.category = category2
         category2.add(belief)
.....
else category5.add(belief)
```

Figure 3.4: Pseudocode to clarify how importance and weights are given to beliefs

Parameter Settings, Validation and Verification

Parameter Settings:

Earlier in this chapter we clarified that beliefs, the starting point of the theory of planned behaviour, will be quantified by the means of normal distributions with their accompanying standard deviation. To assure that correct data is being used, one must execute a large scale questionnaire where the beliefs with respect to adopting solar panels are individually treated for Belgian households. Due to time constraints, we opted to find a better balance between the accuracy and the time necessary to get a grip on usable data. In the opinion of the writer, the report of Rai and Beck [2015] on the public perceptions and information gaps in solar energy in Texas had the best data. Not only does the scope perfectly complement the scope of this thesis, but also the used determinants of intention in both studies are identical. Taking this into account, enough evidence exists to make use of the data. Table 3.1 and 3.2 reflect all beliefs along with their normal distribution characteristics.

Table 3.1: All Beliefs with Accompanying Mean and Standard Deviation (Part 1)

ATTITUDE	MEAN	SD	PBC	MEAN	SD	SN	MEAN	SD
Save money	5.42	1.81	Affordability	3.15	1.65	People approve	5.28	1.70
Increase home value	5.34	1.79						
Beauty	4.27	2.08						
Good for environment	6.20	1.38						

Table 3.2: All Beliefs with Accompanying Mean and Standard Deviation (Part 2)

PERSONAL NORM	MEAN	SD	DESCRIPTIVE NORM	MEAN	SD
I think solar is great	5.47	1.74	Topic of interest	2.81	1.68
Relations want solar	3.93	1.93			
Relations think solar is good	4.51	1.89			

Validation & Verification:
The requirements as stated in section 3.4.1 (with exception of requirement 4) are mainly fulfilled by choosing the model instead of using the correct parameter settings. Nevertheless, to assure that the model meets all the requirements, a short description of the verification and validation techniques is given here.

To substantiate the first requirement we investigate 5 agents individually. All agents are selected while keeping in mind that an as big as possible variety must exist. Table 3.3 summarizes that the values of beliefs differ at every tick. In this case the belief under investigation is 'save money'.

Table 3.3: Believe 'save money' of 5 agents at different ticks

	AGENT 1	AGENT 2	AGENT 3	AGENT 4	AGENT 5
TICK 1	6.08	2.93	1.44	5.68	6.67
TICK 2	5.89	4.21	2.33	7.01	8.24
TICK 3	6.25	4.45	3.21	8.22	6.88
TICK 4	6.44	5.18	3.02	8.09	7.13
TICK 5	7.63	5.98	3.65	8.54	7.38

The second and third requirement are validated by creating two graphs. In the first graph, one combines three datasets. The first dataset consists of information on the solar adoption rate of households where no interventions are set in place. The next datasets uses the exact same information, but differs by always having one intervention set in place by the government to stimulate adoption. Hence, the second dataset contains information on the solar panel adoption rate whenever subsidy is introduced and the third dataset encloses data whenever GCC's are used.

The same is done to test whether the influence of neighbours is being correctly modulated. Due to time-constraints, it was not possible to track down whether households are 144 percent more inclined to adapt solar panels due to the fact that neighbours installed them (as was cited in Graziano and Gillingham [2015]). However, as the neighbours' behaviour is considered an important factor in the mode, this thesis focuses on validating that neighbours aid in the stimulation of solar panel adoption. Moreover, another graph is made to clarify on what extent the neighbouring effect influences the adoption rate. Two datasets are included; both have identical parameter settings, but only one includes the 'neighbouring effect'.

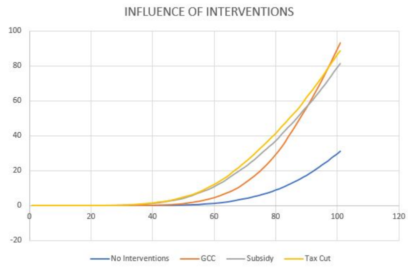

Figure 3.5: Influence of Interventions

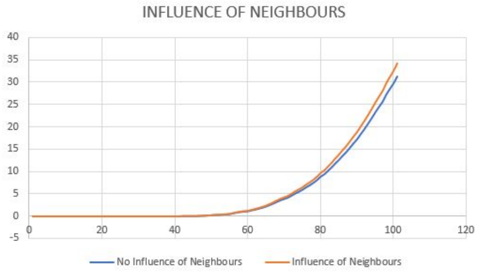

Figure 3.6: Influence of Neighbours

After a simulation of 100 runs the average amount of houses with solar panels are displayed. Figure 3.5 clearly demonstrates that the influence of interventions largely affects the adoption rate under consideration. All interventions are subjected to an increase of the amount of households with solar panels. On the basis of this validation, we conclude that almost an extra number of 50 households have installed solar panels which without subsidy would not have installed the matter under consideration. The same holds for GCC and tax cuts where more than 62 and 50 more households installed solar panels.
The 'neighbouring effect' is validated the exact same way interventions were validated. A graph was made of the average amount of houses with solar panels per tick whenever neighbours do have an effect on each other and whenever they do not. An explicit difference exists between the two datasets which gradually increases over time. One can argue that this gradual increase is largely due to the fact that more neighbourhoods are affected later in time. At tick 100, 4 more households have adapted solar panels whenever the neighborhood effect was taken into account.

Different from the other requirements, the fourth requirement is checked by analyzing the actual model itself instead of the outcome of the model. The beliefs of the agents are quantified as a positive normal distribution which will never obtain a negative value. The following steps are largely just multiplication and summation of positive numbers. In addition, due to the same reason, whenever the strength of the agents' belief with respect to the adoption of solar panels increases, the behavioural intention increases as well.

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3

3.4.2. Creation of Determinants of Intention

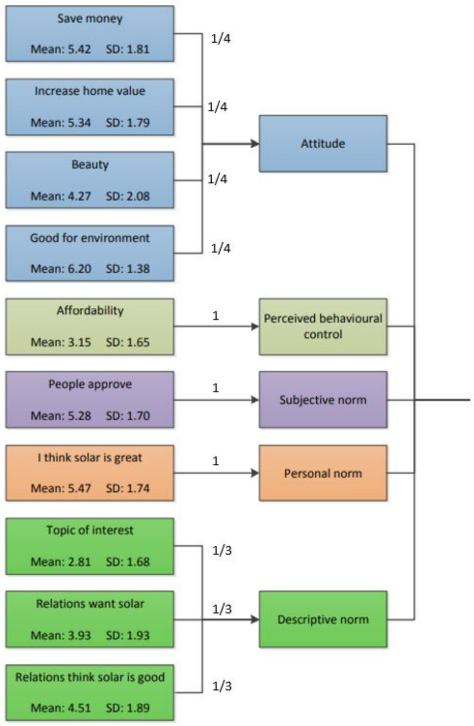

Figure 3.7: Determinants & their Weights

The second stage in the theory of planned behaviour is the formation of the agents' attitude, perceived behavioural control, subjective norm, personal norm and descriptive norm. These terms, which are named determinants of intention in the further continuation of this thesis, are weighted again and will, just as the beliefs influencing the determinants, have an impact on the behavioural intention. Especially important for this step are the unique weights (representing the influence on the behavioural intention) given to each determinant. A short description of the main determinants of intentions is given below:

Attitude:

Section 3.3 stated that having a certain attitude towards a behaviour refers to the 'degree' to which an agent has a positive or negative evaluation of the behaviour in question (Ajzen [1991]). Furthermore, attitude encompasses judgment on whether or not a certain behaviour is imagined to be positive or negative, and whether the agent wants to perform that action (Leonard et al. [2004]).

A large amount of studies have been researching the relationship between the attitude and intention. In a majority of them, and in all reports investigated for this thesis, a positive relationship exists (Garcia and Yang [2008]). For example, this pro-position has been claimed to be true in the green hotel industry (Han and Yoon [2015]). In addition, an identical relationship has been reported by Dean [2012] that prevails the attitude-intention rationale in green consumption settings. Thus, in line with the literature we argue for the following requirement:

1. Attitude towards solar panel purchasing is positively related to solar panel purchase intention.

Subjective Norm:

The second determinant of the behavioural intention according to the theory of planned behaviour is defined as the subjective norm. Ajzen [1991] identifies this as "the perceived social pressure to perform or not to perform the behaviour". This pressure, according to Park [2000], originates largely because of the fear what other 'close friends, relatives, colleagues or partners' would think. Multiple studies have demonstrated that the subjective norm is an important determinant of intention and found out that a positive link exists between the subjective norm and intention (Paul et al. [2016]; White Baker et al. [2007]; Dean [2012]). From the moment people see their relatives and important others endorse the adoption of solar panels, they become more willing to consider the installation of a PV system as well. From literature, one can therefore expect that agents will more likely adopt the behaviour of influencers which leads to the following requirements:

2. Subjective norm is positively related to solar panel purchase intention.

Perceived Behavioural control:

Among the three antecedents of the theory of planned behaviour and the two extra determinants, perceived behavioural control is said to be the most influential determinant whenever behaviours are partially under volitional control. Ajzen [1991] accredits PBC as nothing more than 'the perceived ease or difficulty of performing the behaviour". Furthermore, the perceived behavioural control includes non-motivational factors, namely concept of resources, opportunities, facilitating factors, and action control items (Ajzen [1991]; Thomas [1983]). Just like the attitude and subjective norm, many studies show a positive relationship between perceived behavioural control and intention (Paul et al. [2016]; Albayrak et al. [2011]; Han et al. [2010]). In light of the above, we propose that:

3. PBC is positively related to solar panel purchase intention.

Some Modeling Choices

In the previous subsection, we argued that given our research question, one theory will be followed. First, we elaborate on our decision to use TPB instead of TRA, which is the less extended version of TPB, as the big difference occurs on the level of determinants of intention. Next, we define why adding the other two determinants (personal and descriptive norm) improves the model. The selection of the different determinants of intention is therefore considered the first modeling choice.

The theory of planned behaviour distinguishes itself from the theory of reasoned action by including measures of control belief and perceived behavioural control. The main advantage is that it allows prediction of behaviours that are not under complete volitional control. Thus, while the TRA could appropriately predict behaviours that were relatively straightforward (i.e. under volitional control), under circumstances where there were constraints on certain actions, the mere formation of an intention was insufficient to predict behaviour. The addition holds information about the plausible restrictions on actions as perceived by the actor and is used to explain why intentions do not always lead to a certain behaviour (Armitage and Conner [2001]).

Whenever one thinks about adding new determinants one logically sees personal & descriptive norms as the two main options. In his norm-activation theory, Schwartz [1968] defines personal norms as self-expectations that are based on internalized values. Personal norms reflect commitment with internalized values and are experienced as feelings of personal obligation to engage in a certain behaviour. It is said to be some kind of feeling of personal obligation that guides a certain behaviour. In an environmental context, multiple studies have investigated the relationship between personal norms and willingness to engage in a pro-environmental behaviour. One common result was that people with a high moral obligation to protect the environment are also more determined to buy renewable energy systems (Harland, Paul, Staats, Henk, Wilke, A., M. [1999]). On the basis of the preceding section and the outcomes of other relevant reports, the inclusion of personal norm is considered to be beneficial.

Descriptive norms, on the other hand, refer to perceptions of significant others' attitudes and behaviours in the domain. This highlights that opinions and actions of others provide information that agents can use in choosing to decide what to do themselves (e.g. if the rest of the world does this, then it must be the right thing to do) (Cialdini et al. [1991]). In line with this thesis, one could have thoughts as: regardless of what others think, I think installing a solar system is a good thing to do. Multiple researchers have concluded that the descriptive norm construct may qualify as an additional predictor in the TPB. One of them is Rivis and Sheeran [2003] who executed a meta-analysis to quantify the relationship between descriptive norm and intentions. This report states that adding descriptive norms to the TPB contributed to an additional 5 percent to the variance in intention after attitudes, subjective norms, and perceived behavioural control have been taken into account.

A second modeling choice that is made within this sub-chapter is to not include place-dependent, physical factors in the perceived behavioural control determinant. Drury et al. [2012] discovered that the installed cost of solar panels, and in particular the upfront costs, are a real hurdle for people which is partly influenced by physical factors (trees in the neighborhood, roof area, irradiation). These elements are site specific and can vary considerably across sites. We decided therefore only to focus on the affordability factor of PBC for the TPB models, both due to it being a more universal factor in solar energy decision-making and an accessible target for policy intervention. The introduction of this assumption has a great effect on the outcome of the model. It makes it impossible to simulate the acquisition period on a personal level where personal advantages are taken into account.

Model Details

The previous model described how beliefs acquire their supporting weight and importance, and how all beliefs are subdivided into categories representing the determinants of intention. Whenever the subcategories have been created, the importance and weight of each factor must be multiplied and than added together. In the end, five values will have been subjected to the five different categories or determinants of intentions included in this study as illustrated by the pseudo-code in Figure 3.8.

```
Algorithm 2: Creating determinants of behaviour from beliefs.
Require: Weights and importance from the beliefs
   determinant1 = null                         determinant4 = null
   determinant2 = null                         determinant5 = null
   determinant3 = null
if category = category1
        set determinant1 determinant1 + belief.weight * importance
else if category = category2
        set determinant2 determinant2 + belief.weight * importance
...
else set determinant5 determinant5 + belief.weight * importance
```

Figure 3.8: Pseudocode to clarify how determinants of intentions result out of beliefs

Parameter Settings, Validation and Verification

Parameter Settings

In the previous section about the creation of beliefs, a short introduction has been given on how each belief is assigned a weight. Up until now, we have not found any usable data, mainly because either other beliefs or other determinants of intention have been used. Instead of using existing data, which would result in unnecessary errors, the different weights have been set variable. Data from more than 50.000 runs has been gathered for a large set of different combinations. More information on how the the optimal combination of variables was selected can be found in Chapter 4.

3

Validation and Verification
To assure that the determinants of intention within the model are built correctly or whenever one wants to check whether the determinants of intention serve the right purpose, one can either investigate the model itself or the outcomes of the model. In the case of validating the first three requirements of the determinants of intention, one dives into the mathematics, the constitution of the model. As the beliefs are quantified as normal distributions without ever being negative and only summation and multiplication occur with positive numbers, the outcomes can only be positive as well. Solely, focusing on the determinants of intention, the same can be said to be true. Whenever the 5 determinants of intention used in the extended theory of planned behaviour increase, the final result will get bigger as well.

3.4.3. Creation of Behavioural Intention

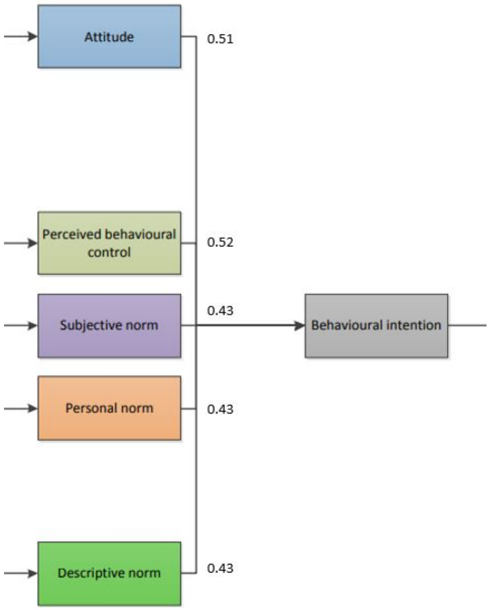

Figure 3.9: Creation of Behavioural Intention

The theory of planned behaviour considers the individual's intention to perform a certain behaviour an important asset in a model. The main reasoning is that intentions are said to capture the motivational factors that influence a behaviour. It serves as a signal of how badly people want something or how much an effort they are going to put into performing this behaviour. Generally speaking, the stronger the intention to act a certain way and/or do a behaviour, the more likely it will actually be done. One must keep in mind that a behavioural intention can find expression in a behaviour only whenever it is under volitional control, when the person can choose to perform the action or not. In general, it mostly looks like almost all behaviours do meet this requirement, but the performance of most does have some sort of dependency on non-motivational factors such as availability of requisite opportunities and resources (e.g. time, money, skills, cooperation of others) (Ajzen [1985]). Collectively, these factors represent people's actual control over the behaviour. To the extent that a person has the required opportunities and resources, and intends to perform the behaviour, he or she should succeed in doing so. The following requirements must hold in the model:

1. The stronger the intention to act a certain way the larger the possibility the action is performed.

Now that it is clarified how the creation of intention has a direct relation with the actual performance of a behaviour one can elaborate on how the relation between determinants of intention and intention itself are and how well the determinants of intention describe intentions. As mentioned earlier and largely used in reports, the extended theory of planned behaviour used postulates five conceptually independent determinants of intention. From multiple sources, one can conclude that the relative importance in defining the intention varies per performances or behaviour. Thus, in some applications the only real determinant that significantly impacts the behavioural intention is the perceived behavioural control, in others that will be attitude or a combination of all five determinants. The next requirement must therefore hold:

2. The five conceptually independent determinants defining the intentional behaviour are set and dependent on the problem that is solved.

Multiple researchers have started to rely on the theory of planned behaviour in their attempts to predict and understand people's behaviour and intentions to contribute or act upon something. Ajzen concluded that a considerable amount of variance in intentions can be accounted for by the five predictors in the theory of planned behaviour. The multiple correlations ranged from as low as 0.43 to as high as 0.94 with an average of 0.71 (Ajzen [1985]).

Rai and Beck [2015] investigated the public perception and information gaps in solar energy in Texas and found out that given the novelty, potential complexity of installation, and cost of solar PV, adoption requires both the knowledge and financial means to act. We therefore expect the decision to adapt to be strongly dependent and influenced by the perceived behavioural control, as measured through the perception of affordability. The same result came out of a report written by Maichum et al. [2016]. This source once more stated that perceived behavioural control is the most important determinant in the theory of planned behaviour.

Once the right incentives are set in place, the required upfront cost can be drastically reduced leading to an increasing adoption rate of solar panels (Kann et al. [2015]). The only condition that comes into place is the necessary awareness the agents must have (both the awareness of new incentives as the improvement in technology). Accordingly, we find the two following requirements:

3. PBC will be the strongest determinant/predictor in the theory of planned behaviour in the case of adopting solar panels.

4. Awareness of incentives and the incentives themselves have clear effects on the adoption rate of solar panels.

3

Some Modeling Choices

The most important modeling choice made in this sub-section is that we assume the determinants used in the extended theory of planned behaviour to be the only sources of information to predict the behavioural intention. Furthermore, one assumes that the behavioural intention carries enough information to be of relevance (together with perceived behavioural control) to determine the behaviour.

Model Details

Figure 3.10 represents a small algorithm that indicates how an agent unconsciously changes its determinants of intention into behavioural intention and thereafter into a real behaviour. Identically to the previous pseudocode, weights are expressed as fixed numbers which are for this specific case derived from a meta-analysis that examined the effectiveness of the constructs of the theory of planned behaviour in predicting the adoption of preventive innovations (Overstreet et al. [2013]). Again, the intention can be calculated by summing up all determinants of intention multiplied by its corresponding weights.

As the pseudo-code of the following step, the creation of behaviour out of the behavioural intention, only consists of one step it is elaborated upon here. Various sources assign a constant number to the relationship between having an intention and doing the actual behaviour. Just like before, the behavioural intention must be multiplied by a factor that represents how certain intentions are successfully executed.

Algorithm 3: Creating a behavioural intention from determinants of intention & behaviour from a behavioural intention

```
Require: Weights and importance from the determinants of intention & the chance of doing a behaviour
once an intention exists
   determinant.weight1 = #                    determinant.weight4 = #
   determinant.weight2 = #                    determinant.weight5 = #
   determinant.weight3 = #                    behaviour.weight = #
set intention = determinant1 * weight1 + determinant2 * weight2 + ... + determinant5 * weight5
set behaviour = intention * behaviour.weight
```

Figure 3.10: Pseudocode to clarify how behavioural intention result out of determinants of intention

Parameter Settings, Validation and Verification

Parameter Settings:

As the largest part of the data comes from previous steps, the only essential values that need to be determined in this section are the weights subjected to each determinant of intention. As only a handful of meta-analyses have been executed where solar panel adoption is combined with the TPB a source is used that examines the effectiveness of the constructs of the above mentioned theory on predicting the adoption of preventive innovations. Instead of using an extended TPB, Overstreet et al. [2013] found weights only for the attitude, perceived behavioural control and subjective norm. We therefore had to make the assumption that both additions to the model, descriptive and personal norms, will have the same weight as the subjective norm. Attitude will consequently have a weight of 0.51, PBC is weighted a 0.52 and subjective norm 0.43. As was just mentioned, personal and descriptive norms will be given the exact same value.

Verification and Validation

We executed a simulation and investigated 3 agents individually for 5 ticks. As figure 3.4 indicates, both the behavioural intention and behaviour differ for every agent, but also for every tick. It is visible that whenever an agents behavioural intention drops in time the value of behaviour goes down as well which is equal to a lower possibility that an agent will execute a certain behaviour. The same holds for situations where the behavioural intention increases leading to an incremented possibility of the behaviour.

Table 3.4: Behavioural Intention and Behaviour of 3 agents

	AGENT 1		**AGENT 2**		**AGENT 3**	
	INTENTION	**BEHAVIOUR**	**INTENTION**	**BEHAVIOUR**	**INTENTION**	**BEHAVIOUR**
TICK 1	24.26	12.86	13.54	7.17	12.05	6.39
TICK 2	21.08	11.17	11.95	6.33	9.89	5.24
TICK 3	20.00	10.60	11.93	6.32	9.96	5.28
TICK 4	19.64	10.41	12.14	6.43	9.23	4.89
TICK 5	20.90	11.08	11.77	6.24	9.02	4.78

The third requirement, the requirement that states that the perceived behavioural control is the strongest determinant of the theory of planned behaviour in the niche of adapting solar panels, will also be verified by looking at the weights of the determinants of intention individually. In the model, all determinants of intention that contain any type of norm have the lowest weight, followed by the attitude, and eventually the perceived behavioural control (as can be seen in Figure 3.9 and in the section above).

3.4.4. Creation of Behaviour

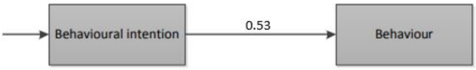

Figure 3.11: Creation of a Behaviour

3

Ajzen and Fishbein [1977] states that the performance of a behaviour is a joint function of intentions and perceived behavioural control. Whenever one wants to assure great results, several conditions must be met. First, some sort of correspondence must exist between intentions & perceived behavioural control. It must be clear in which context the specified behaviour must occur; for example, if the behaviour to be predicted is to 'buy Trina Solar solar panels', then we must assess intentions 'to buy Trina Solar solar panels' (not intentions to 'buy solar panels' as well as 'buying something from Trina Solar'), as well as perceived control over 'buying Trina Solar solar panels'. Secondly, intentions and perceived behavioural control must remain stable in the interval between their assessment and observation of the behaviour. Interceding events may cause changes in intentions or in the perceptions of behavioural control with the result that the original measures of these variables are no longer useful to accurately predict a behaviour. Lastly, the third requirement holds that prediction of behaviour from perceived behavioural control should improve to the extent that perceptions of behavioural control realistically reflect actual control (Bogers et al. [2004]).

1. Correspondence must exist between intentions, perceived behavioural control and the context in which the specified behaviour must occur.

2. Intentions and perceived behavioural control must remain stable in the interval between their assessment and observation of the behaviour.

3. Adding perceived behavioural control to the system will affect the ultimate behaviour due to its direct linkage.

Intention and Behaviour

The relation between intention and behaviour has been a topic of interest in many different studies focusing on a large variety of behaviours, with much of the work done in the framework of the theory of reasoned action, but also multiple within the TPB (Ajzen [1991]; Ajzen [1985]; Canary D.J [1977]; Sheppard et al. [1988]). The behaviours under the loop in aforementioned studies range from very simple strategy choices in laboratory games to actions of appreciable or personal significance, such as smoking cigarettes, donating to charity, and choosing among candidates in an election. The main rule affirms that behaviours that do not pose serious problems of control can be predicted from intentions with great accuracy. Great examples appear where one needs to choose among available options. For example, people's voting intentions, assessed a short time prior to a presidential election, tend to correlate with actual voting choice in the range of .75 to .80 (Ajzen [1985].

Perceived Behavioural control and Behaviour
Whenever situations without full controllability are focused upon, perceived behavioural control becomes an important aspect in the theory of planned behaviour. Ajzen conducted a research comparing several recent studies that have dealt with a great variety of activities, from playing video games and losing weight to cheating, shoplifting, and lying. The study concluded that both predictors (intentions and perceived behavioural control) correlate quite well with the behavioural performance. The first five studies show that both antecedent variables have a significant impact on the ultimate behaviour. In most of the remaining studies, intentions proved the more important of the two predictors; only in the case of weight loss (Netemeyer et al. [1991]; Schifter et al. [1985]) did perceived behavioural control overshadow the contribution of intention.

Table 3.5 illustrates that the combination of intentions and perceived behavioural control permitted the possibility of predicting behaviours in each case, and that many of the multiple correlations were of substantial magnitude. The correlation in every study differed ranging from 0.23 to 0.78 with an average of 0.53. Fascinating enough is that the weakest relation is found in studies where educating yourself to get an 'A' and losing weight were the main goals. We acknowledge these two subjects as the ones where you people have the least control which can be problematic in terms of the correspondence between perceived and actual control. Some confirmation of this speculation can be found in the study on academic performance Ajzen and Madden [1986] in which the predictive validity of perceived behavioural control improved from the beginning to the end of the semester, presumably because perceptions of ability to get an 'A' in the course became more realistic.

Some Modeling Choices

As described in detail in the earlier sections, the theory of planned behaviour divides any behavioural achievement in 2 components (intentions and perceived behavioural control). Two motivations can be given to support this claim.

First, whenever one holds the intention constant, the effort expended to bring a course of behaviour to a successful conclusion is likely to increase with perceived behavioural control. This even holds whenever 2 individuals have similar intentions to do something and eventually do it. The individual which has more confidence in succeeding this task is more likely to persevere than the individual with less confidence. A good example could be learning how to drive. The person that believes in his/her capacity to learn to drive will probably ride better and get his/her driving license sooner than the one who doubts his/her ability.

The second rationale for expecting a clear and direct link between perceived behavioural control and behaviour is that perceived behavioural control can often be used as a substitute for a measure of actual control. Whether this statement is true depends largely on which action is dealt with and the accuracy that comes with our model to simulate it. Perceived behavioural control may not be particularly realistic

Table 3.5: Prediction of Behaviour (B) from Intention (I) and Perceived Behavioural Control (PBC)

		CORRELATIONS		REGRESSION COEFFICIENT		
STUDY	ACTIVITY	I	PBC	I	PBC	R
van Ryn & Vinokur (1990)	Job search, 10-activity index 1-month behaviour post-test	.41	.20	.38	.13	.42
Doll & Ajzen (1990)	Playing six video games Mean within subjects	.49	.48	.14	.12	.51
Schlegl et al. (1990)	Problem drinking - frequency	.47	.48	.28	.32	.53
	- quantity	.41	.60	.29	.43	.64
Ajzen & Driver (N.A)	Five leisure activities Mean within subjects	.75	.73	.46	.37	.78
Locke et al. (1984)	Performance on cognitive task	.57	.61	.34	.42	.66
Watters (1989)	Election participation	.45	.31	.39	.19	.49
	Voting choice	.84	.76	.80	.05	.84
Netemeyer, Burton	Election participation	.41	.15	.52	.18	.43
& Johnston (1990)	Losing weight	.18	.22	.08	.18	.23
Schifter & Ajzen (1985)	Losing weight	.25	.41	.09	.39	.44
Madden, Ellen & Ajzen (in press)	10 common activities Mean within subjects	.38	.28	.34	.17	.42
Ajzen & Madden (1986)	Attending class	.36	.28	.30	.11	.37
	Getting an 'A' in a course					
	- Beginning of semester	.26	.11	.26	.01	.26
	- End of semester	.39	.38	.27	.26	.45
Beck & Ajzen (in press)	Cheating, shoplifting, lying	.52	.44	.46	.08	.53
Netemeyer, Andrews, & Durvasula (1990)	Giving a gift - mean over five items	.52	.24	.52	.02	.53

when a person has relatively little information about the behaviour, when requirements or available resources have changed, or when new and unfamiliar elements have entered into the situation. Under those conditions, a measure of perceived behavioural control may add little to the accuracy of behavioural prediction. However, to the extent that perceived control is realistic, it can be used to predict the probability of a successful behavioural attempt (Ajzen [1985]). The direct linkage between the perceived behavioural control and the behaviour itself was assumed to be minimal and is therefore excluded in the model due to the ever-changing resources.

Parameter Settings, Validation and Verification

Sheeran [2011] illustrates an important lesson; having an intention does not necessarily mean that the action is going to be executed. A fixed relationship is impossible to find as the figure linking the behavioural intention and the behaviour is subjected to variances. Instead, based on a sample size of n = 82107, the sample-weighted average correlation of 0.53 is used in the continuation of this thesis.

3.5. Interventions and their Influence on the Model

The previous sections defined how agents would make the decision to adapt solar panels on an individual level. However, agents are modeled in an environment in which actors from the outside influence the agents' behaviour. One of the most influential external actors are interventions whereof three different types exist: the improvement of the technology, interventions influencing the price of solar panels and the influence of neighbours. In the next section, a short description of every intervention is cited in addition with how it influences the model.

3

From the moment residential and commercial rooftop solar panels were released to the general public in the 1970's the efficiency of the technology increased both due to a better understanding and the availability of better materials. To accurately quantify how much influence the ever improving technology has on the adoption rate one adds up the differences in efficiencies in time of the four most available type of solar panels. The specific data is provided by the National Renewable Energy Labratory (NREL). The only downside of using data of the NREL is the fact that the efficiencies were achieved in a laboratory which does not perfectly correspond to the solar panels used by households. The outcome is therefore multiplied by a factor 0.5 to compensate for this error. As a result, on average, monocrystalline silicon solar cells, polycrystalline solar cells, thin film solar cells & cadmium telluride solar cells become 0.3 percent (or 0.025 percent per month) more efficient each year. Consequently the increasing efficiency will increase the affordability of the agents every tick by a factor 1.0125.

Frequently, and done by the majority of countries, interventions are installed such that the investment price decreases. In Belgium, three aiding mechanisms were inserted: subsidies, green certificates and a tax cut. In the primary stage, subsidies were given by the government to households as an upfront cost reduction. Subsidies typically remove some type of burden, and it is often considered to be in the overall interest of the public, given to promote a social good or an economic policy just as the adoption of solar panels. In 2006 and 2007, households had the possibility to apply for a 10 % investment subsidy for the acquisition of solar panels. This resulted to an increase of behavioural intention of 1 percent in the model.

Secondly, the Belgian government has promoted PV systems by the means of green current certificates (GCC's). As was explained earlier in the background, GCC's are a certain kind of tradable commodity proving that electricity is generated by renewable energy sources. Typically one certificate represents the generation of one Megawatthour (MWh) of electricity. Consumers could sell these certificates to the distribution system operators (DSOs) at a guaranteed price for a fixed number of years. GCC's have been used from the beginning of 2006 until February 2014. First, the program was very generous, but incrementally reduced in generosity leading to an abolishment in the beginning of 2014.

The last intervention that has a direct linkage to the affordability is the reduction of tax charged by the government. As explained in Section 2, does a tax reduction lead to a lower income for the government which is the main reason for its abrogation in 2012. From the perspective of Belgian households, tax cuts were advantageous. Once the tax cut was removed the affordability therefore decreased by 50 percent.

The last intervention, defined as the neighbouring effect, directly influences the agents' intention of adapting solar panels. Whenever households are in close neighbourhood of others with solar panels, they are more inclined to acquire the technology under consideration themselves. As discussed before, Graziano and Gillingham [2015] indicated that having a household with solar panels within a range of 0.5 miles increased the number of installations in a block group by 0.44 PV systems on average.

4

Calibration

Chapter 3 discussed how the theory of planned behaviour was built specifically for the adoption of solar panels in the country of Belgium. We first used short descriptions to clarify the different requirements, the model, the validation & the verification of every individual segment. Unfortunately, repeatedly, weights were missing which can, if handled incorrectly, lead to severe mismatches with the reality. The remainder of this chapter will dive into the process of down-scaling the amount of households into a model of only 500 households without losing reliability. We will define both known and unknown variables and discuss the setup of the simulation. Finally, the results are reviewed upon along with a small table presenting the final data.

Important here is to understand that the following chapter is the first component of a valuable validation. We calibrate unknown variables by the means of a model to match reality in Chapter 5. In other words, this chapter solely focuses on adjusting variables to match the past and present solar panel adoption rate such that the experiment (later executed in this thesis) is constructed upon a credible basis.

4.1. Scaling the Model

To accurately model the adoption rate of Belgian households it would be ideal to include all different households available. However, De Groote and Verboven [2016] illustrates that in total 2.7 million households exist which would, if we include all of them, make the simulation too big and therefore unusable. The first important step is therefore to find a good balance between computational complexity and realism. As a result, the model used for this thesis includes 500 agents (representing households) in a 40x40 world. In the continuation of this section two substantiations are given why decreasing the amount of households does not come with serious effects and why multiplication of certain data within the theory of planned behaviour does.

As the real world (with 2.7 million households) is represented by only 500 households the amount of households adapting solar panels is ideally lower by the same factor. On the grounds that households can only be modeled to be red or green some valid information goes lost whenever less households adapt solar panels. In the model one agent turns green whenever in real life 5400 households adapted solar panels. Again, it must be stated that by using models with more agents this ration would decrease leading to a more accurate final model. A valid thought is to multiply parts of the theory of planned behaviour leading to a higher amount of solar panels adapted by households in the model. Although this claim is valid whenever agents are not interacting among each other, one can refute this claim on the basis of the effect neighbours have on the end result. For example, whenever one increases the amount of houses with solar panels a larger group of households will convince non-adapters to acquire solar panels leading to invalid data.

4.2. Simulation Details

Although a large set of data is known, a need still exists to find the unknown weights. We tackled this problem by first analyzing the real data and specifically looking at the adoption rate of Belgian households per month. Thereafter, the data is reduced to a model with only 500 households. The unknown data has been set variable, leading to a total sum of more than 10.000 combinations, for more than 50.000 simulations. The outcome is compared to real data. To match the real data with the data derived from the simulation we calculated the differences in amount of adopters per month by means of an error function. The outcome showing the smallest difference between the real and simulated data is considered the optimal combination which will in the continuation of this dissertation be used in the experiment and validation. A more elaborated description is given in the following paragraphs.

De Groote and Verboven [2016] developed a traceable dynamic model for the adoption of solar panels in Belgium. One of their outcomes was a graph showing the evolution of the monthly number of adopters between January 2006 and June 2013 taking into account the effect of different interventions. As this data is a representation of the reality we have the possibility to validate the simulated data, the outcome of the model, on its correctness. Varying the unknown weights such that the optimal coefficients are used is therefore a suitable option. Table 4.1 entails information on whether we perceive data to be reliable or not. The components in the absence of sources are set variable within the simulation. In total, this leads to more than 50.000 simulation runs for more than 10.000 different arrangements.

Table 4.1: Reliability of Different Factors in the Model

RELIABLE	**UNRELIABLE**
Weights determinants of intention (Overstreet et al. [2013]) Importance of beliefs (Rai and Beck [2015]) Weight behavioural intention (Sheeran [2011])	Utility value (No source) Utility of beliefs (No source)

The selection of the optimal arrangement happened in 2 phases where the only difference can be recognized in the simulation runs for each combination. In the first phase the calculations for each combination were executed four times, while the calculations in the second phase were carried out 200 times. First, we compared the total amount of simulations with the real data obtained from De Groote and Verboven [2016]. This comparison is executed on the basis of an error function. We selected upon the combination that showed both the lowest difference between the summed up errors and had the lowest average error in total. After an extensive research the four most promising combinations have been investigated in more detail. They are each simulated for another 200 simulation runs to increase the credibility of the model and were again compared to real data. The pseudocode used to determine the unknown weights of the beliefs is illustrated in Figure 4.1.

Algorithm 4: determination of weights of beliefs.

```
Require: Data from multiple runs with varying weights of beliefs
   number = null                                             error.previous = {}
   difference = null
run experiment with varying variables (belief.weight1, belief.weight2, ..., belief.weight5)
        set number = behaviour > utility.behaviour
        set difference = number.present – number.previous
if belief.weight1 at run x = belief.weight1 at run y
        sum difference/amount of beliefs
for all number
        set error = \sum_{i=1}^{N}(number − real)_{positive}
        if error < error.previous
                set error error.previous
        else error.previous error.previous
give list with error.minimal
```

Figure 4.1: Pseudocode of the calibration of the importance of beliefs

4.3. Discussion of Results

Table 4.2 demonstrates both the weights of the beliefs and the average error coming out of the error function of the four most interesting combinations after 200 simulations. In addition Figure 4.2 displays the adoption rate of every combination. After analyzing this data, one can conclude that the average error of combination 4 (indicated in Figure 4.2 as a thick red line) is the lowest with a value of 0.335.

Important to notice is that the optimal combination will further be used in the validation phase as well as the experiments and discussion. At first sight, similarities exist between the real data (Fig 2.5) and the simulated data. Both exhibit maximums at the beginning of 2010 (tick 48) and a few between May 2011 (tick 65) and February 2013 (tick 86). Alongside that, both adoption rates demonstrate an exponential increment of solar adapters. Different from the real data, the simulated data features smaller oscillations after the second maximum which will need to be validated in the next chapter.

Table 4.2: Four Optimal Combinations where A1 until Utility_behaviour are weights and 1 until 5 are the Combinations

	1	2	3	4
A1	0.2	0.2	0.2	0.3
A2	0.3	0.2	0.25	0.2
A3	0.2	0.2	0.25	0.3
A4	0.2	0.2	0.25	0.3
D1	0.33	0.3	0.3	0.3
D2	0.33	0.36	0.36	0.36
D3	0.36	0.33	0.3	0.36
Utility_behaviour	13.2	13.4	13.4	13.4
Average_error	0.358	0.335	0.351	0.3771

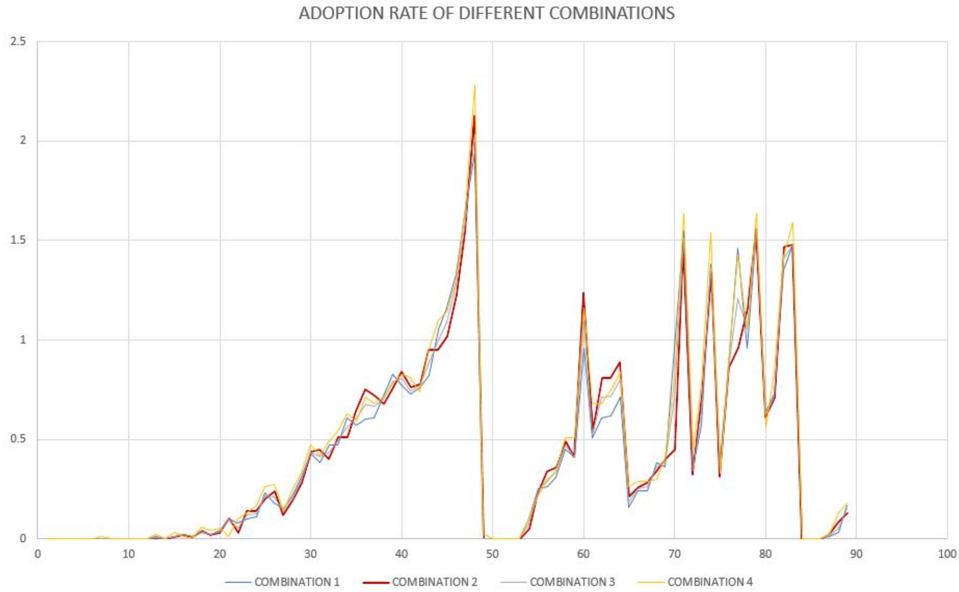

Figure 4.2: Adoption Rate of Different Combinations

5

Validity of the Model

This chapter criticizes the validity of the model and tries to address the question "*did we build the right thing?*". In other terms, we judge whether the model described in Chapter 3 and 4 is an accurate representation of the real-world system and answers the question of the problem owner. Largely applicable validation methods for agent-based models are denoted by Deguchi [2010] as expert consultation, model replication, historic replay and literature validation. Due to the imbalance between necessary time and quality results we opted to combine literature validation with historic replay. By replicating real data generated by De Groote and Verboven [2016] we hope to answer the following question: *"Can we explain the adoption rate of solar panels using an extended version of the theory of planned behaviour"*. The main requirement thus holds that the merged micro-concepts, cited in Chapter 3, together create unexpected results that can only be understood by analyzing the data in its totality. In the continuation of this chapter we first quickly elaborate on how we have validated the individual, smaller concepts of the big model whereafter we validate the totality of the model.

Before the actual validation can start it is important to keep in mind that both qualitative and quantitative requirements will be validated. In other words, both reproduction of exact data from empirical experiments and reproduction of categorical relations between variables will be used. Although, one would prefer to validate the model completely quantitatively, a lack of usable data withholds us from overusing the only source (De Groote and Verboven [2016]) too much. We made the decision to use qualitative validation where quantitative sources are missing. The usage of both quantitative and qualitative requirements is twofold. Firstly, using multiple sources is beneficial as the impact of a source containing errors reduces drastically. Secondly, as cited, only one single source contains enough details to be used in the continuation of the thesis which is considered too low.

The essence of this thesis is to find data that most accurately represents the real adoption rate of households, however due to time constraints this thesis has moved the focus on using high-level systems to get preliminary weights for every factor in the theory of planned behaviour. As a continuation, a more in-depth analysis of the different weights could be carried out. A more extensive description of relevant successions is presented in Chapter 7.

Let us advance on the subject of micro- and macro-validation. Firstly, within Chapter 3, we validated the micro-concepts and mechanisms by comparison with literature and intuition and multiple requirements were set in place itself. As discussed individually in Section 3.4.1, 3.4.2, 3.4.3 and 3.4.4, the separate modules hold up to these requirements and thus are valid. We recognize that validation of every individual micro-system enhances the credibility of the separate parts, but creates little validity for the complete system. The foremost reason is the absence of interactions between these modules. Not only is the inclusion of validation on a macro-level a good approach to define which factors have large effects on the model and therefore would lead to crucially different results, but it also helps in highlighting gaps of knowledge. The macro-phenomenon we want to examine is whether we can understand the adoption rate of solar panels by Belgian households and the effect of interventions by the usage of an extended version of the theory of planned behaviour.

In the continuation of this validation chapter we first elaborate upon the similarities that exist between the reality and the model whereafter we proceed to the differences along with its reasoning. The first macro-validation technique used is a comparison of the real world and the model on the basis of a graph representing the adoption rate of the model in relation with the decreasing upfront investment cost (Figure 5.1). It is clearly visible that a relationship exist as the adoption rate of solar panels increases whenever the upfront investment cost decreases. Maximums exists whenever the upfront investment cost, indicated by a black line, decreases. The answer to this occurrence is twofold whereof one answer can be found in Figure 5.2 where the perceived behavioural control has been modeled in combination with the other four determinants of intention for 200 simulation runs. The perceived behavioural control gradually increases as the technology gets better and cheaper. However, because of the decreasing benefits of green current certificates and the increased taxes households have to pay whenever they acquire solar panels the perceived behavioural control tends to decrease as well leading to a variation in behavioural intention and therefore behaviour. In other words, whenever the benefits from any intervention lessens, the behavioural intention goes down indirectly or directly depending on the intervention itself. Logically, one can state that interventions not only leave their mark whenever they are active, but also when they are subjected to changes. In the history of solar promotion, Belgium has already changed its promotional techniques multiple times (and most often decreases the governmental aid during the acquisition). The assumption was therefore made that whenever households know a decrease in financial assistance will occur in the near future, they are more inclined to acquire solar panels. As an example, in January

2010, the first reduction of GCC prices was set in place leading to a large increase in solar panel sales at the end of 2009. The model shows this behaviour as well; just before any intervention weakens, the behavioural intention increases, whereafter it returns to its normal state.

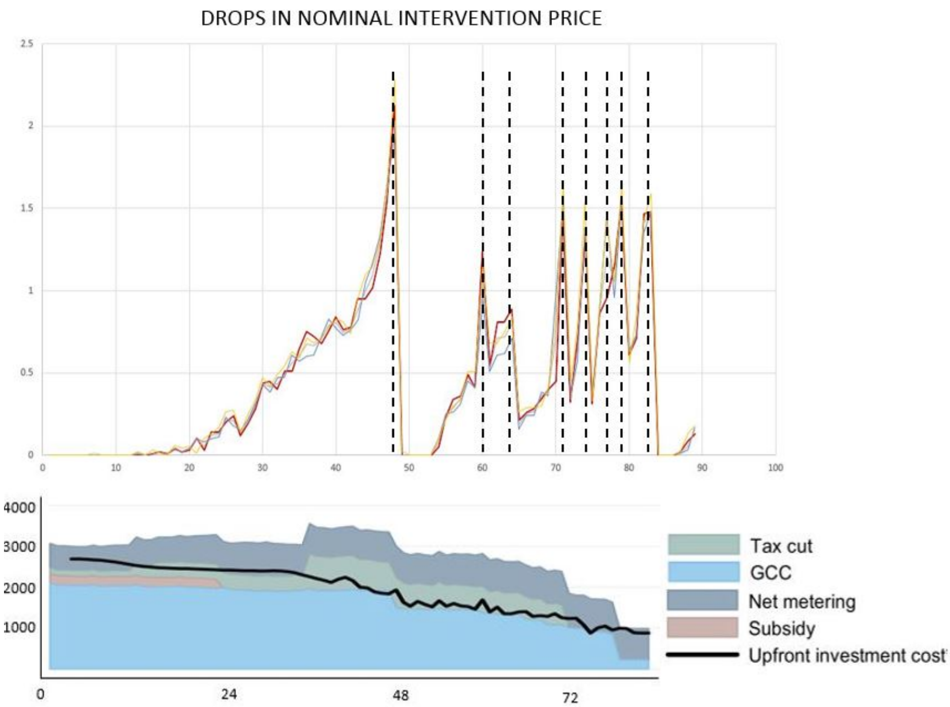

Figure 5.1: Above: Drops in Nominal GCC Price over Time (Model) , Below: Costs and Benefits of a 4 kW PV (Reality) (De Groote and Verboven [2016])

Another remarkable similarity is the exponential increase in acquired solar panels. In the model used in this thesis the effect of neighbours is taken into account. The consequences are simple; whenever a household installs solar panels, it will have a convincing effect on the other households without solar panels. In chapter 3, which is dedicated to the explanation of the model, we already stated that adding one installation within 0.5 miles of adopting households in the year prior to the adoption increased the number of installations in a block group by 0.44 PV systems on average (Graziano and Gillingham [2015]). To conclude, we explain that at the start neighbours only have a small influence in the complete simulation because of the large unavailability of households with solar panels. As the simulation progresses, the usage of solar panels will be more wide-spread leading to a larger amount of neighbours and therefore a larger influence on the simulation results.

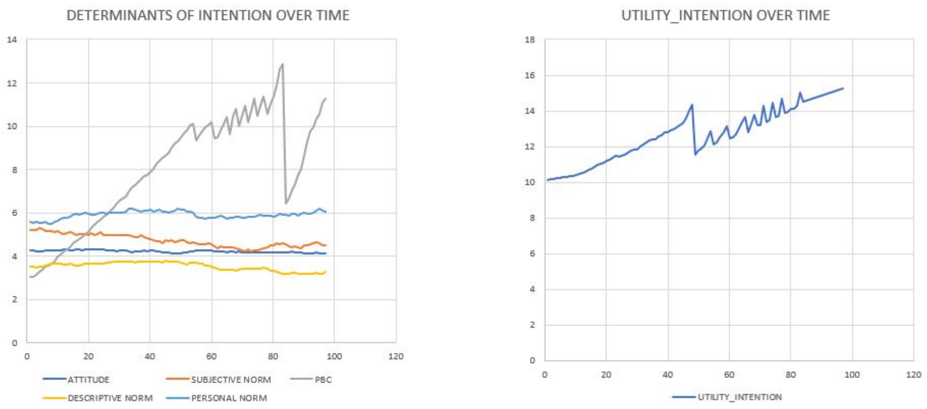

Figure 5.2: Value of the determinants of Intention and Utility_Intention

Lastly, The technology advancements ensure, both in the simulation and reality, a decreasing upfront investment cost of solar panels. As depicted in Section 3.5 data from the NREL is used to estimate how the technology develops. As a result, the affordability of solar panels becomes 1.25 percent cheaper every month. This partly explains the increasing amount of adopting households.

Although large segments of the complete model correspond to the reality a few differences still exist. By observing Figure 2.5 one can distinguish three dissimilarities with the real world. The primary aspect is the increasing difference between the adoption rate of the model and the one of the real world. In addition, the adoption rate is not fluctuating as much as it is supposed to when comparing to the reality. Thirdly, determinants have, especially at the end of each simulation, a too low impact on the resulting behaviour leading to a too low fluctuation in solar adoption rate. The main reason is twofold again. On the one hand, the modeled affordability is higher than the sense of affordability in real life. Taking into account that affordability is the only determinant of the perceived behavioural control and the determinant of intention itself has the highest influence on the behavioural intention, an excessive affordability can have great impact on the result. As the simulation slowly ends, the affordability takes over resulting in the negligence of other beliefs and determinants of intention. On the other hand, the impact of several interventions is inadequately modeled. The main argument herefore is a lack of detailed analyses treating the impact of different interventions. To overcome this gap, we utilized an estimation provided by an industry expert, but a better refinement of this value would improve this thesis by a great extent. The possibility of improving this value is elaborated upon in Chapter 7.

Finally, differences between the reality and the model exist because of the uncertain impact of interventions. Now, interventions in the model only have direct influences upon one determinant of intention. This relationship is derived out of common sense, but is not the only relationship that exists. For example, we use Mark with his skeptical mindset again. He is pessimistic about solar panels, but his friends and family are positive about the new technology. It could be possible that when subsidies are introduced, not only Mark's sense of affordability, but also his attitude changes by a large extent.

As mentioned earlier in this chapter, this validation section mainly focused on validating the model in its completeness. In Chapter 3, a first subdivision into smaller parts facilitated the validation of multiple micro-systems. However, the interactions among them is evenly important. We discussed how beliefs influence the adoption rate and we addressed the major errors in the model. By completing this chapter we build the structure upon we can answer sub-question four: *"What interventions are best introduced to maximize the households' solar panel adoption rate?"*. More regarding this matter is demonstrated in the following two chapters.

6

Experiments and Results

In this chapter we will describe the executed experiment revolving around the fourth sub-question: *"What interventions are best introduced to maximize the households' solar panel adoption rate?"*. Our first objective is to show that our model is not only helpful to understand the solar panel adoption rate, but can also be used to explore the future adoption rate whenever green certificates, subsidies or tax cuts are set in place. In the next section we first analyze our model and delineate how it can be used to gain insights in the exploration of the solar panel adoption rate. In section 6.2, we indicate the design of the experiment including a small description of the variable parameters. Thereafter, we dive into the experiment itself in section 6.3. We clarify the effect of interventions followed by a short economical comparison to determine the most desirable intervention on a price quality basis. Our second objective entails gaining more insight in how we can generalize the outcome to a wider scope. We include the usage of boundaries to indicate to what extent the model can be used for other purposes. We will contribute to our second objective by discussing the relevance of our results in the next chapter.

6.1. Model Pre-Analysis

Before diving into the experiment, we would like to analyze our model first to gain insight in the dynamic behaviour it encapsulates and in addition, define how computer simulations can aid in understanding the model.

Just like all other agent-based models does the model of this thesis depends on individual agents having interconnected behaviours. In other words, whenever one agent decides to execute a certain behaviour, the behaviour of other, in this case surrounding, agents are influenced. Agents interact with each other whenever one of them decides to acquire solar panels whereas the others remain using conventional energy. Due to the interaction between agents the idea of 'affordability' changes leading to a re-evaluation of solar panels by the agents without solar panels. This means that whenever an agent acquires solar panels, it exerts an influence on its neighbours changing their behaviours which can eventually lead to a domino effect of change. Additionally, predicting the decision behaviour of individual agents is demanding (and sometimes even problematic) when we intervene in its context. For example, whenever the government decides to introduce green certificates, new opportunities arise and an increasing amount of households will adopt solar panels. The outcome differs although the same agents are used within the model itself. To clarify, it is difficult to analytically predict the behaviour of agents due to their interrelation with each other and the influence of multiple variables and interventions. Simulations can serve as a good aiding tool to gain more insight into the model itself by capturing and apprehending the way agents in a world change.

A plurality of sources exists that deal with the adoption of solar panels in the past, however during the complete period of this research not a single source was found that explored the future adoption rate using agent-based modelling. In the following experiment we will thus study two relevant matters: the adoption rate of solar panels whenever no interventions are set in place and the effect of interventions on the future solar adoption movement. We have done an exploratory experiment in combination with a short evaluation on the value for money of all interventions.

6.2. Experimental Set-Up

Before starting the actual experiment it is useful to sketch its set-up. A first glimpse upon the design of the experiment is given which both includes the most important parameters and modeling decisions that will affect its outcome. The most relevant choices are depicted below:

- The experiment will be executed in a 20x20 world where 500 individual agents interact with each other. The main reason for this choice is the consistency with the model constructed in chapter 3. Using 500 individuals in a model is the perfect balance between necessary simulation time and correct usage of the data.

- The National Renewable Energy Laboratory (NREL) performed a meta-analysis of studies that examined the lifespan of solar panels and the degradation that occurs annually. The results were congruent and showed that solar panels annually degrade around 0.8 percent (Jordan and Kurtz [2012]). To stay above the 85 percent efficiency limit the model runs simulations for only 204 ticks, which in reality correlates to 17 years. Important to notice here is that the set limit is not a generally agreed value and multiple solar panels exist with a longer lifespan. However, as we want to account for all types of solar panels the limit is set on 204 ticks.

- Every governmental intervention is modeled as a change in affordability or a lowering of the utility value of intentional behaviour. The model scales depending on the effect interventions have on individuals.

- The effect neighbours have on individuals is included identically in the experiment and the model of Chapter 3. In the latter, we stated that individuals are 144 percent more inclined to buy solar panels whenever their neighbours have them.

6.3. Experiment

We present an experiment that simulates the effect of three governmental interventions targeting ones beliefs and behaviour on the adoption of solar panels. Although a large variety exist on how the government can aid households in their acquisition of solar panels, only three are further elaborated upon: green certificates, subsidies and tax cuts. We present these three as they (1) expose interesting insights in how the government can maximize their effect on households and the adoption rate of solar panels, (2) show unexpected outcomes that can be explained by using the model and (3) already have been cited in Chapter 3.

Our experiment combines information on three smaller simulations devoted to only one individual intervention. The model first uses identical data from tick 0 until tick 96 whereafter interventions cause the adoption rates to differ. Note that the first part of the model is a representation of the reality where interventions have been inserted already and therefore only the second part shows changes. The three governmental interventions under consideration are introduced for different time lengths based on their relative cost to make the comparison as fair as possible. From De Groote and Verboven [2016] & IEA [2016] we found that introducing green current certificates and tax cuts cost 1.681 EUR/year and 2.630 EUR/year for the government respectively. In addition, households require on average 330 EUR/MWh whenever subsidies are included. This amounts to 1.619 EUR/year and makes subsidies therefore the cheapest option. To assure a fair juxtaposition, we model the subsidy for the solar panel's complete lifetime of 17 years. The green current certificates and the tax cuts are modeled for a shorter time period of 9 years and 2 months and 5 years and 10 months respectively as they are more expensive to have in place.

We take several insights from these simulations and try to find an answer on the question whether interventions are worth the money and which one is the most effective in terms of price and quality. Aside of the experiment itself, a small analysis is executed to determine the effectiveness and price of the interventions.

Important to comprehend before discussing the result of the experiment is the definition of intervening. In this dissertation we identify governmental interventions as actions taken by the government to positively influence a certain execution. Whenever no interventions are inserted, the government does absolutely nothing and lets the citizens do their own thing. Specifically for this model, having no governmental interventions in place means that the government withholds itself from helping households by any means. The interventions still available in the present would therefore also be removed.

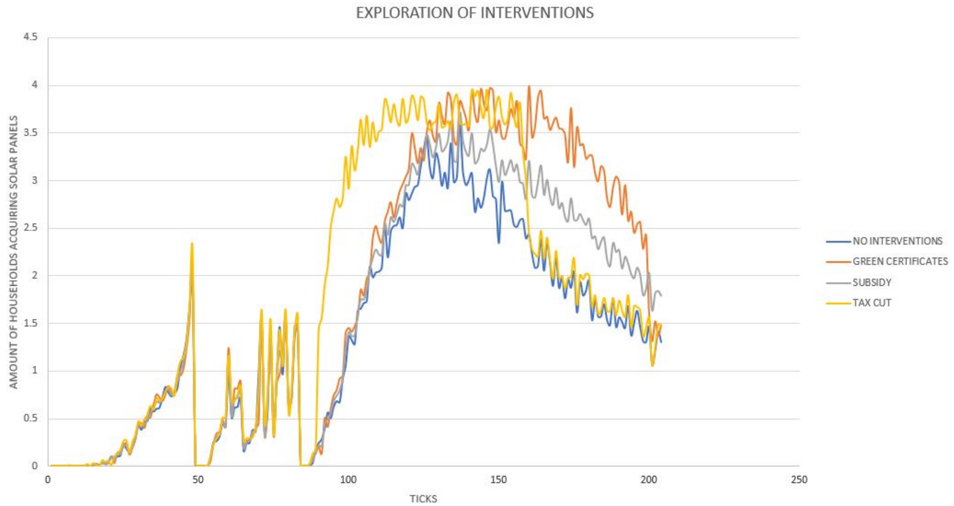

Figure 6.1: Exploration of Interventions (Y-Axis represents the average of the households that acquired solar panels

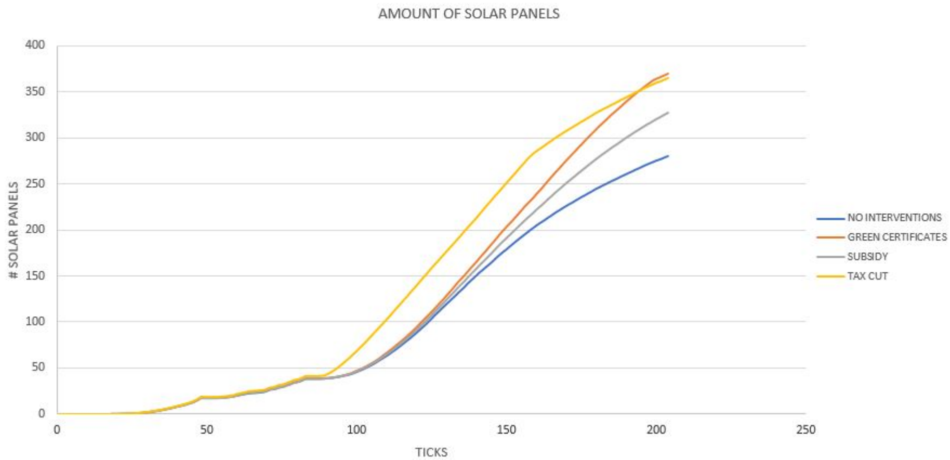

Figure 6.2: Amount of Households with Solar Panels in the Model

6.3.1. Usage of Subsidies

The experiment conducted consists of two parts (as was stated before). First, just like in the model, a graph is made representing the solar adoption rate from 2006 (tick 0) up until the present (tick 90) with the actual interventions set in place. Second, the interventions are removed and only subsidies of 10 percent were used in the exploration phase which starts at tick 90 until tick 204.

Specifically, subsidies have an effect on the affordability of buying solar panels. As a result the belief including the affordability increased by 10 percent whenever subsidies were inserted. Interestingly enough the slope of the adoption rate whenever subsidies were included is only a little bit steeper than the one without subsidy inserted. The main reason herefore is the slow rate at which information about subsidies is transferred in comparison with tax cuts (De Groote and Verboven [2016]). In other words, the influence of increasing one belief is lower as it has a lower impact than increasing a determinant of intention, behavioural intention or behaviour directly. As a result of subsidies, the amount of agents in the model adopting solar panels increased by 47 agents leading to a total sum of 327 agents. This corresponds to a total increment of 253.000 households and an adoption of solar panels of 1.77 million households in its totality in reality.

6.3.2. Usage of Green Current Certificates

The second intervention the Belgian government can use to promote solar panel adoption is called green current certificates. A more elaborated description is given in Chapter 2. For now, it is important to understand that this intervention is investigated in the experiment in a similar way as subsidies; first, the real interventions are used to model the present whereafter only green certificates are applied to model the future. As stated earlier, green certificates are modeled for 9 years and 2 months more (110 ticks) so that the cost of introducing green current certificates equals the cost of introducing normal subsidies for the whole life span of the solar panels (which results in 9.5 years or 114 ticks).

In the model used for the simulations green certificates result in a 18 percent increase in affordability. This increment influences the agents' affordability and therefore perceived behavioural control again resulting in a positive change towards a world with solar panels. To conclude, the effect of installing green certificates is considerable. On average, the amount of households that adopted solar panels increased from 280 to 365 which is an increment of 85 households. If we only focus on the simulation itself, one can result that the usage of green certificates will have, together with tax cuts, the biggest impact on the future solar adoption rate.

6.3.3. Usage of Tax Cuts

The last intervention treated in this simulation is tax cut. Just as green current certificates is tax cut modeled for a shorter amount of time due to the higher cost of the intervention. We opted for a tax cut of 5 years and 10 months where the VAT price reduced from 21 to 6 percent (which is represented in the model by a 200 percent increase in intention). One must keep in mind that tax cuts are generally interventions that have difficulties predicting its macroeconomic effect on a long-term basis because the outcome is largely dependent on how taxpayers use their additional income and how the government adjusts to its reduced income.

The effect of inserting a tax cut is different from the previous interventions. Whenever the interventions is inserted, a large amount of households directly switch to solar panels. Tax cuts give an extra push to adopt solar panels, but whenever they are no longer used the solar adoption curve almost matches the one where no interventions are included. The main reasoning exists in the way tax cuts are modeled as being an influence on intentional behaviour directly. The outcome demonstrates that the introduction of a tax cut positively influences the adoption of solar panels by 30 percent. In other words, whenever a tax cut of 5 years and 10 months is introduced, an increase of 85 households in the model can be noticed. In reality the increment equals to 459.000 households making the total amount of households with solar panels equal to 1.97 million.

Table 6.1: Effect of Interventions

	# HOUSES WITH PV (MODEL)	# HOUSES WITH PV (REALITY)	INCREASE
NO INTERVENTIONS	280	1514538	/
SUBSIDY	327	1767123	17 %
GCC	370	1995408	32 %
TAX CUT	365	1973549	30 %

6

6.3.4. Policy Implication

Our findings demonstrate that whenever the government wants to achieve the highest adoption rate possible it must include green certificates. However, green certificates do not show an evenly steep increment of purchased solar panels as tax cuts do. This raises questions whether the government could not have achieved a higher level of adoption by combining tax cuts with green certificates. The following paragraphs dive into the advantages of using green certificates while the possibility of combining GCC's with tax cuts is subsequently elaborated upon.

De Groote and Verboven [2016] indicates that the government could have reached a similar amount of solar panel adopters when an upfront subsidy is introduced. In total, when summing the individual green certificate costs, the price equals 3.77 billion Euros . Whenever the government decided on giving an upfront subsidy, the program would have been only 2 billion Euros. Hence, the government could have achieved identical adoption rates at only 53.3 percent of costs of the program using green current certificates, amounting to a total saving of 1.77 billion Euros. If one extrapolates this value in terms of savings per household and takes into account that the above mentioned values do only take solar panels into account that have been acquired up until now, one finds that almost 700 Euros can be saved whenever upfront subsidy is used (De Groote and Verboven [2016]). Subsequently, introducing upfront subsidies result in a low value for money and must be withhold in the future.

The same can be said about tax cuts. This intervention type reduces the tax obligations of taxpayers who meet specific criteria. From the perspective of the taxpayers lower taxes seem desirable, and there are arguable advantages of the intervention, but tax cuts also lower the amount of money the government receives which can be used to do good and necessary things in society (just as subsidies and GCC's). The main difference between this intervention and the others however is that tax cuts pose difficulties on predicting the future macroeconomic behaviour. In addition, tax revenues are used by honest governments to pay their debts. When less revenues are available to repay their debts, their cost of borrowing can increase as well. The main reason is the high interest rates on larger balances. Reducing taxes can therefore increase the amount of debt taxpayers have to repay without the government receiving any added benefit (Ingram [2011]).

In conclusion, governments have the ability to select upon their preferred type of intervention. If the government's intention is to increase the amount of solar panel adoptions independent of the effect of the interventions, combining green certificates with a tax cut would probably be the optimal solution. However, due to time constraints, a combination of multiple interventions has not been executed resulting in this conclusions without 100 percent confidence. Whenever only one intervention can be used, green current certificates are the most appropriate one (with highest value for money). In other words, governments must find the right balance between how much they want to invest and how many households acquire solar panels before the optimal intervention can be selected.

7
Discussion and Further Work

In the previous chapters we have demonstrated how we used the theory of planned behaviour in combination with agent-based modelling to explain the past and explore the future solar adoption rate. In this chapter we look at the broader picture and look for an answer on the question: *"Is the model relevant and can it be used by the government for a more general application?"*. In the continuation of this chapter we first elaborate upon the interesting insights the model has given us and how the model contributes to a better decision-making process of solar adoption interventions. Secondly, we define how the government & science can benefit from the model. Thereafter we indicate how the model fits within the context of governmental promotion and to what extent the model can be used in other areas. Finally, we elaborate upon the limitations of this dissertation and suggest plausible ways to increase its exactitude in conjunction with a small enumeration of possible topics that can be executed in further studies.

Before starting this chapter, it is necessary to clarify that results from agent-based models can rarely be translated one-to-one to the real world. The main reason why this model is not a perfect reflection of the reality is the lack of quantitative numbers indicating the importance of all beliefs (Mercuur [2015]). As the purpose of this thesis is to create a model that displays the real solar adoption rate in the best possible way, we could execute extensive studies to find more exact data. However, even then, the outcome of this model, and all other agent-based models, must be confirmed by all means.

7.1. Interpretation of Results

As was previously stated, we initiate this section by discussing the outcomes of the model in addition to giving descriptions for meeting or not meeting the prior expectations. Furthermore, we delineate how the results fit within the framework driven in the first chapters of this dissertation and clarify how the findings provide new or different insights into what was already known. We finalize this section by stating the model's added value to different governments and science in general.

7.1.1. Validity of Research Design

As many agent-based models has the one constructed in this dissertation different interesting results. The key finding of the experiment is the difference between tax cuts, upfront subsidies and GCC's. If one only looks at the near future, one would indicate that the Belgian government benefits the most by selecting tax cuts as its main intervention. However, the effect of green current certificates is bigger if we look at the long-term impact. Interestingly enough is that within one governmental term two things can happen. On the one hand, the government can decide to invest in interventions which have a high short-term impact. In this case Belgian society clearly sees the effect directly, however the price to introduce tax cuts is higher than the 2 other interventions. On the other hand, the government can decide to invest in a higher future impact. Politically it is advantageous to implement tax cuts to see the impact at the end of the governmental term and therefore not to lose voters. In the latter case, no real difference can be seen for multiple years between having and not having subsidies or GCC's introduced.

Furthermore, it is interesting to see that the results match our expectations and that the effect of neighbours, technology advancements and interventions all have a positive effect on the amount of acquired solar panels. In the model and validation chapter of this dissertation, we demonstrated that the effect of neighbours is the smallest (with only 4 extra households acquiring solar panels in 100 ticks). Technology advancements and interventions however have more influence on the decision-making behaviour of households which together caused between 50 and 75 households to adopt solar panels.

7.1.2. Added Value of the Model

To Belgium & Other Countries:

The results of this dissertation looks interesting and could lead be of added value for the government. Not only did the model give us interesting insights, but it also proved to be trustworthy enough to be used in subsequent research. First of all, we can conclude that, even with the theory of planned behaviour being a well-used theory in the renewable energy, this dissertation is one of the first dissertations combining agent-based modelling with the acquisition of solar panels and is the primary one treating both the solar panel adoption rate of Belgian households and the effect of interventions on the solar adoption behaviour. In Chapter 3, we investigated the determinants of intention and beliefs and found out that both 'attitude' and 'perceived behavioural control' have the biggest impact on the decision-making process of adopting solar panels. The government must therefore not only aid financially (with as result lowering the perceived behavioural control), but also promote the beliefs that directly influence the attitude. A good example is to educate households and reassure them that solar panels are advantageous in the longer term.

If we zoom out and look at the model from a more holistic point of view, we suggest that the design can be a first aid or explanatory tool to understand the effect of governmental interventions on the buying behaviour of Belgian households. The model already encompasses interventions that are variable in price, thus making it easier for the government to perceive the effect of the inserted intervention. In other words, the government has the possibility to use the model to test a large amount of different interventions (varying GCC prices, higher and lower subsidies, varying tax cuts). Whenever a specific simulated intervention fulfills the need of the government, a subsequent analysis must be executed that serves as a verification for the outcome of the simulation. In the future, when the government understands the value of the model, it can invest in questionnaires executed by data analysts to obtain more accurate data about the adoption of solar panels in Belgium. When this information is set in place, the Belgian government can start using the model as the main tool on which the choice of intervention is based upon.

The government benefits the most from the created model if it is not only able to predict the acquisition rate of solar panels, but can be used in other areas as well. Logically, expansions of the model can be the outcome of two possibilities. On the one hand, the model can be expanded so that other countries can make use of it and on the other hand, the model can be generalized making it possible to use it in other businesses. The former possibility is to generalize the application area of the model. It is not advisable to extend the model to domains outside the adoption of renewable energy. The main reason is the big differences that exist in making choices between different industries. First and foremost, do beliefs themselves change significantly whenever new industries are touched upon. In addition, the relationships differ between beliefs and determinants of intention, determinants of intention and behavioural intention and lastly behavioural intention and behaviour. However, using the created model within the area of renewable energy in Belgium is perfectly possible. Important to understand is that although some weights of beliefs change, the majority will remain identical making it possible to tweak the unknown variables as is done in this dissertation. For example, whenever the government decides to use this agent-based model to apprehend the acquisition of small scale wind turbines by households and understand which intervention best suits their needs certain beliefs will change. One of them will be 'beauty' which will probably be have a bigger impact than it did in the case of acquiring solar panels. By executing a questionnaire or by tweaking the model to correspond to real data, one will find the new importance of 'beauty'.

The expansion towards other countries is treated second. Whenever any other country wants to use the model (which was tailor-made for Belgium), a study must be performed that elaborates upon the differences in behaviour between the chosen country and Belgium. This need exists because Belgian households expose other behaviour and prioritize other beliefs and determinants of intention.

To Science:
Science benefits from the model for two reasons. On the one hand, the constructed model serves as an additional tool towards a more renewable future as it can clarify the impact of governmental interventions and help in their selection of choosing the most promising one. On the other hand, we can assure that both solar panels and batteries will become more efficient in the future leading to a higher solar adoption rate. This knowledge has been gathered throughout the writer's years of studying sustainable energy technology at the University of Technology in Delft. Whenever more households start adopting solar panels, governments can decide to decrease the amount of interventions. Our model can be used to better illustrate the effect of this action; the variation of the interventional impact.

7.2. Limitations of the Research

Evenly important as presenting the added value of this dissertation is addressing its limitations. In the process of creating a model a large amount of assumptions needed to be made due to a lack of data, knowledge and due to time constraints. A few are worth mentioning as it limits the usage possibilities of the model. Firstly, we narrowed our scope to households having the possibility to decide whether or not to acquire solar panels. In others words, only detached, semi-detached and terraced houses that were bought by households were modeled. However, 24.5 percent of Belgian households rent their house and 1 out of 3 Belgian households currently live in an apartment having no decision on the adoption of solar panels. As a result, in reality, certain people can make the decision of adopting solar panels for a large number of houses whereas others have no decision power at all. Secondly, the model uses a random function to allocate houses in the imaginary world. In reality however some houses are located in cities and some at the countryside. Logically, houses positioned in cities have more neighbours and therefore have a larger chance to be positively affected to buy solar panels. We limit ourselves mainly due to the pragmatic reason that no single city and/or countryside is the same and therefore no universal data is available. Thirdly, agents within the model can only positively influence each other. However, in a minority of cases solar panel adopters will have bad experiences with the new technology and will prevent others from buying it. Again, a lack of specific data was at the basis of this limitation. Fourthly, the experiment neglected the inequality of Belgian households' wealth. For certain families buying a solar panel is a big investment needing a large amount of time to think about whether it is profitable to apply or not whereas for others it is a small amount of money. Lastly, there has been no shortage of criticism towards the theory of planned behaviour. It is mostly limited due to its exclusive focus on rational reasoning, while unconscious influences such as emotions are excluded. In addition, we can only experiment with interventions we now the result off. Introducing interventions with unknown effects is impossible to implement in the model as we tweak our beliefs and importances depending on this data.

7.3. Recommendation for Further Research

If we purely reflect upon the approach taken, we can state that the process of retrieving usable information was a road with multiple hurdles. During the complete dissertation many assumptions needed to be made in order to clarify our research question and to find a suitable approach to tackle the problem. The way this dissertation dealt with decision-making was positive as every decision is subjected to a small description of why it was made and what effect it has. However, paired with every assumption comes an area that can be further researched. The key recommendation for further research is therefore twofold. First, the selected modeling techniques must be further elaborated upon. Not only is a detailed survey regarding the Belgian households' acquisition rate of solar panels an important asset to improve the outcome, but also the weights of the different beliefs and determinants of intentions must be further investigated upon. Second, multiple different modeling and decision-making theories exist which are not researched. To assure that both agent-based modeling and the theory of planned behaviour are optimal techniques we have to explore all other techniques as well.

In addition, it could be interesting to carry out more experiments with the existing interventions. We can model multiple interventions simultaneously or model them after each other instead of only making use of one. Aside of this, one can experiment by introducing non-governmental interventions. These types of interventions range from solar maps that indicate the profitability of solar panels for each rooftop which stimulates habitant's awareness to solar sharing. Important to notice is that the effect of non-governmental incentives is largely unknown and an elaborate empirical study is again necessary.

This experiment solely focuses on acquiring solar panels and does not give households the opportunity to install other types of renewable energy. In reality one has the option to install any type of renewable energy which certainly has effects on the total acquisition rate of solar panels. The idea is that people prefer familiarizing with one type of renewable energy first whereafter they invest in a second source probably leading to a lower amount of solar panel acquisitions due to a larger amount of options (United Nations Environment Programme [2016]).

Lastly, we recommend to incorporate the geographical location in the model to further increase its credibility. It can be advantageous to focus more on a city and region level instead of country level to get a glimpse of the differences between really dense and open neighbourhoods. Exactly pinpointing the location of the houses within the detailed models is impossible as every region is different. However, two different options exist to overcome this difficulty. One can either replicate the positioning of every house within a region and only concentrate upon one geographical location or separate the model into three smaller ones (city, village and rural area) and find the average density for every separate model. This way we can better model the effect of neighbours and account for differences in the exposure of light on the rooftops.

In sum: large differences do exist in both costs and effectiveness of interventions. Subsidies have a lower influence on the households' acquisition rate, but are way cheaper than the intervention with the highest effectiveness, green current certificates. Tax cuts however are expensive and have a lower effect on households. We therefore advise the Belgian government three things. First, the government must determine its maximum releasable budget to promote solar panels and set the target of the minimum number of transitioned households before inserting any intervention. Depending on these factors the most optimal or a combination of intervention(s) is chosen. Second, we recommend governments to make decisions based on long-term effects instead of short-term ones. Initially it looks like tax cuts have the biggest impact. However, on a long-term basis, the most households adopt solar panels by introducing green current certificates. Lastly, Bauner et al. [2013] indicates, and our model recognizes, that households not only need financial aids by introducing incentives, but also require information. We recognize that stimulation by education is still lacking although it results to large positive influences on the solar panel adoption rate.

8

Conclusion

The adoption of solar panels and the effect of interventions in Belgium remains a continuous issue complicated by methodological limitations. We therefore asked the question: *"To what extent can a model present the current PV adoption rate of households and give insights into the governmental interventions in the future?"*. We assured that this dissertation resulted in interesting outcomes by asking the following sub questions:

Which interventions affect the adoption of solar panels?

The acquisition behaviour of Belgian households is affected by a large amount of influences. One can distinct two classes of influences: interventions steered by the government and interventions without any governmental involvement. The Belgian government already initiated three types of financial, governmental interventions (namely upfront subsidies, green current certificates and tax cuts) while many organizations initiated non-governmental interventions. These type of interventions range from solar maps to lectures about solar panels.

Which theory is best suited to represent the decision-making process of households?

After researching all different options we can conclude that the theory of planned behaviour is the most appropriate tool to model the decision making behaviour process because of several reasons. First, in comparison to other techniques, TPB also focuses on the intention developing which can be seen as an additional important part of the human decision-making process. Aside of this, a clear decision-making procedure is visible. All the different important beliefs are linked to five determinants of intention and vary for every agent making it possible for every individual agent to determine its intention and thereafter its decision.

Which beliefs motivate people to acquire solar panels?

As accurate data is impossible to find, we were left with two choices. We could either execute a large-scale questionnaire or make use of meta-analyses that focus on solar panel acquisitions as well. We opted for the latter alternative as the balance between accuracy and necessary time to get a grip on usable data is herefore most favourable. We selected to use the report of Rai and Beck [2015] on the public perceptions and information gaps in solar energy in Texas as a guidance for this dissertation because both scopes perfectly complement each other and the same determinants of intention are used.

What interventions are best introduced to maximize the households' solar adoption rate?

After the model was validated, we experimented by changing the multiple interventions in the model to explore the adoption rate of solar panels in the future. Green current certificates have the highest influence on the adoption rate of solar panels, but only make a difference after approximately 4 years. The effect of upfront subsidies is lower but shows the same postponed behaviour as green current certificates. Lastly, tax cuts have a large and instant effect on the adoption rate of solar panels but are adverse for the long run as their impact is lower than that of subsidies and GCC's.

We conclude this thesis by enunciating that this study is hopefully the basis of more studies regarding the solar adoption in Belgium and hope that the Belgian government understands its task in the transition towards a sustainable future.

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