Residential PV Adoption:

Exploration on Communication Channels' Influence through Consumers' Psychological Decision Making

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Exploration on Communication Channels' Influence through Consumers' Psychological Decision Making

by

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to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Thursday September 27, 2018 at 10:00 AM.

Student number:	4326210	
Project duration:	August 1, 2017 – September 30, 2018	
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Abstract

This thesis researches the influence of various communication channels, considering the psychological aspect of consumers, to the adoption process of residential PV system, using agent-based modeling case study in the Netherlands. Agent-based model is used to explore how PV adoption dynamic behavior emerges as the result of information transfer between individuals on a new technology. Diffusion of innovation theory is used as the basic framework on how the usage of new technology can spread and theory of planned behavior is utilized to get better understanding on consumer's psychological decision making process. Further discussion with a representative of power utility and interviews with 2 PV installers are done to obtain more knowledge on the system. The study shows that mass media has important role in spreading information to speed-up the adoption, more importantly in providing initial knowledge to households that have not had interest on PV yet. The role of information is further shown as there is indication that households' interest tend to increase with more knowledge available on the internet, and at the same time, leads to the increase of adoption rate. A crucial role of communication channel is to draw PV installer together with potential adopter. Finally, the adoption rate is strongly slowed down by household's basic reluctance on new technology and lower income level.

Acknowledgements

As I finally finish my Master Thesis, my journey as a Master student in TU Delft is finally over. The whole process has been very complex, just like the problem discussed in this thesis. I would like to give my fullest gratitude to all people that has helped me throughout the process of this thesis.

For my parents, that has always supported me at any condition and allows me to finish my Master study, and for my brother that keeps reminding me of home with his visit once in a while to the Netherlands.

For Auke, that has helped me with a lot of stuff throughout the project and keep being supportive. For Igor and Martijn, that have helped to redirect my research at the second half of the work, and for Andrea who has constantly given feedback and 'research-thinking' on my work.

For the two PV installer companies that has helped me to obtain information for this thesis.
For Diones Supriana that has helped organizing meetings and various other appointments in the project.
For Leonie Boortman, who has helped to kick start my thesis again in the middle of the process and to help me with a lot of the administration matters.
For Esther Park Lee, who has introduced me to Auke for the first place.
For Miss Linda Kamp, that has helped me in doing the Energy & Society track.
For Zofia Lukszo and Gerdien de Vries that have spared their time to help with the early part of my thesis.

For Thomas Litaay and Danica Antonia that have become my best friends.
For my fellow classmates that has helped me throughout my studies, especially Nga Phung, Hemant Sharma, Hao Ge, Dwi Sasetyaningtyas, Gerry Julian, Bas Buise and Mark Sassenburg.
For Tante Gail, Om Yongki, and Don Bosco community that became part of my life during my early time in the Netherlands.
For my badminton mates, that have helped me to refresh my mind with our intense badminton games.
For my friends from the church in Delft, for PPI Delft, for KMK, and for me workmates in restaurant.

And finally, to the Almighty God who allows me to have this experience and for the chance to meet these people.

Delft University of Technology — S. Maximillian
August 15, 2018

Contents

Chapter 1

Introduction

Following the transition towards low carbon economy, various technology to produce or consume power with better energy efficiency or lower carbon emission have been developed. Photovoltaic (PV) system is an example of technology which its number of utilization in residential area have increased significantly in the past few years. High penetration of PV, on the other hand, poses a threat to power utility, both technically and financially. Technically, residential PV system increases the complexity in power flow control system (Iwai et al., 2014), and financially, due to the decrease of power demand (Castaneda, Franco, and Dyner, 2017).

The Netherlands has been experiencing significant increase of residential PV system installation in the past 10 years (Bakker, Maat, and van Wee, 2014). While preserving the agenda to increase renewable energy share in its total energy utilization, it is also in the Dutch government's interest to have a **stable rate of adoption** in order to allow power utility to adjust its strategy. This study aims to provide more insight on the innovation diffusion process of residential PV system in the Netherlands through agent-based modeling as the modeling framework.

1.1 Residential PV Adoption as a Complex Problem

Diffusion of Innovation
The adoption of an innovation, such as PV system, does not occur spontaneously. It might take years after its first appearance for an innovation to be widely adopted. The process on how information on this innovation is spread around and communicated through certain channels over time in a social system is referred to as **diffusion of innovation**. In this process, the communication concerns with a new idea, to increase the knowledge of other consumers on the idea. When the new idea is being adopted widely, social change occurs. (Rogers, 2002)

According to Rogers (2002), "*rate of adoption is the relative speed with which an innovation is adopted by members of a social system*". Most diffusion process has an s-shaped adoption curve. Rate of adoption influences the slope of the adoption curve and it varies for each innovation (see Figure 1.1). Even when for the same innovation, it may also be different in different social system condition. There are multiple aspects that influence the rate of adoption in a complex manner. This also applies in the adoption of residential PV system.

Determinant Factor on Residential PV Adoption
Much research has been done on the determinant factors for household to adopt PV system through empirical socio-economic data. Groote, Pepermans, and Verboven (2016) used very detail data from 220,464 installations in Belgium, including the size of the power installed. Dharshing (2017) looked at the spatial patterns of PV adoption and measured regional spillover effects between neighboring counties to observe any geographic clustering behavior in the diffusion process. Rode and Weber (2016) utilized set of spatio-temporal data from German's household to observe localized imitation role in PV adoption. Schaffer and Brun, including the size of the installed capacity. Sommerfeld, Buys, and Vine (2017) observed the interplay between some demographic variables and quantifies their influence to the uptake in south-east of Queensland, Australia. Balta-Ozkan, Yildirim, and Connor (2015) also used set of data from the UK, including household demand for electricity, to

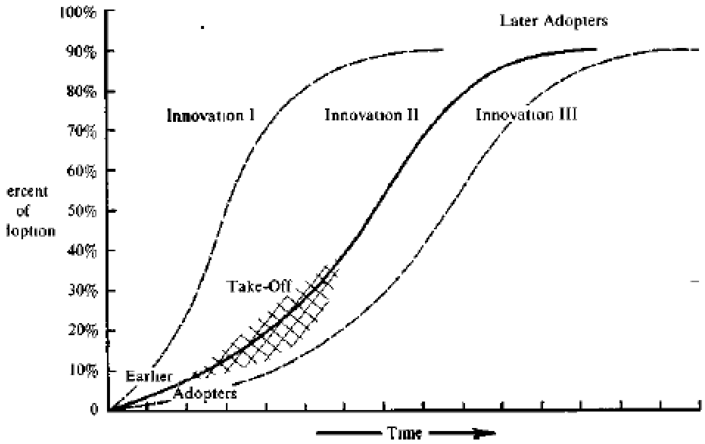


Figure 1.1: Adoption Curves of Different Innovation (Rogers, 2002)

see the adoption pattern for regional scale. The result from these studies generally agrees that demographic condition of household, such as age, income, house ownership, electricity demand or even population density, does affect PV adoption. Income factor may correlates with the electricity demand and house ownership, while localized imitation and spillover effect found to have essential role in the technology's diffusion process, indicating the important roles of communication channels.

While there are numerous factors that influence households, financial aspect is an important factor. Vasseur and Kemp (2015) deployed questionnaire in the Netherlands and found that the cost of a PV system is an important aspect to adopt or not to adopt. Fleiß, Hatzl, Seebauer, and Posch (2017) and Rai, Reeves, and Margolis (2016) also found similar result in Austria and the USA respectively, whereas Schaffer and Brun (2015) also showed the minute role of the environmental aspect for household in considering to adopt PV.

Even though each household has its own decision making process, as pointed out in another study done by Vasseur and Kemp (2015) after looking to the demographic of the Netherlands' households, the influence of social relationship should not be neglected. Snape (2016) used temporal data from the UK to show how the s-curve of innovation diffusion does not occur smoothly, implying the influence of external factors on the decision making process. This diversity in adopters' behavior and their decision-making process must then be taken into account when trying to explore PV adoption.

Noll, Dawes, and Rai (2014) observed the role of solar community organizations (SCO) in peer effects, showing that SCO should be carefully discussed as its social interactions are able to inform and influence consumer effectively when there is high trust between the agents. Karakaya, Hidalgo, and Nuur (2015) explored the motives to adopt PV systems at grid parity via a case study in the Southern Germany. It was discovered that communication between local solar companies and adopters is a key factor to minimize the complexity of the technology. Palm (2016) and Palm (2017) interviewed and surveyed Swedish PV adopters to find that peer effects and local promotion leads to high diffusion rate, which the diffusion process mainly occurs through existing relationships, rather than between neighbors that did not already know each other.

Influence of PV Adoption to the Electricity Market and Power Utility

The occurrence of PV system has a feedback loop correlation with electrical price (Cai, Adlakha, Low, Martini, and Chandy, 2013). With the incorporation of renewable technologies to the power system, power utilities experience decrease of revenue and are forced to raise their prices. In this scenario, it further benefits the adoption of PV by household and is argued to result on a vicious cycle that leads to the death of the utilities. This is called as the 'death spiral'. (Costello and Hemphill, 2014; Felder and Athawale, 2014)

While the topic of 'death spiral' has been discussed intensively in the past few years, there are several different arguments on the importance of rooftop PV in causing death spiral. various studies point out that it is unlikely for distributed PV to cause death spiral by itself. The magnitude of rate changes due to rooftop PV adoption is not that severe to alter the market (Satchwell, Mills, and Barbose, 2015). Both a system dynamic model developed by Laws, Epps, Peterson, Laser, and Wanjiru (2017) and an agent based model (ABM) developed by Muaafa et al. (2017) indicate that death spiral is not likely to happen solely because of rooftop PV. On the other hand, a system dynamic model developed by Castaneda, Jimenez, Zapata, Franco, and Dyner (2017) with case study in Colombia shows that death spiral occurs when rooftop PV installed is greater than 2 kW. Despite of the discrepancies, all of them agrees that death spiral may still occur under the right condition and attention must be given on the rate of adoption to allow power utility to adapt to the new condition, especially through energy policy.

Forecasting PV Adoption
Further understanding on the adoption rate of PV in the future can be done through modeling and forecasting. Laws et al. (2017) presents a system dynamic model that predicts the adoption rate of residential PV and used to investigate the influence to electricity retail price. Guidolin and Mortarino (2010) proposed an innovation diffusion framework based on Bass models to forecast PV national development pattern. This framework managed to show several stages of diffusion and that incentive measure does not always help the diffusion. Islam and Meade (2013) has attempted to measure household level preferences for panels through discrete choice experiments. Karakaya (2013) tried to implement finite element method in forecasting the diffusion of PV systems in southern Germany. Iwai et al. (2014) observed both PV and EV diffusion in Toyonaka, Japan, and the potential to decrease electrical load and peak of electrical load assuming smart charging scenario.

Camargo and Dorner (2016) went one-step ahead to evaluate how the presence of small-scale energy storage (ES) system contributes to the potential of PV adoption in a municipality, with high detail of technical analysis. The research incorporated household roof-top design, different types of irradiance, and shadowing effect of hills or mountains. It was found that low implementation of ES improves energy utilization, variability, and reliability, while higher implementation does not lead to further significant improvement. Sekitou, Tanaka, and Managi (2017) also observed the benefit of adding ES to complement PV system at household with the decrease of electricity demand.

Palmer, Sorda, and Madlener (2015) used ABM to simulate the effect of support scheme change on the Italian PV adoption. The households were initially divided into subgroups according to the locations. They were then distinguished further into 5 classes of age, 6 types of household, and 5 levels of highest education. Rai and Robinson (2015) built another ABM utilizing behavioral science, i.e. by applying the Theory of Planned Behavior (TPB) as the base of the decision making process, and payback period of the investment as the main factor in considering the decision. The model incorporated shadowing effect from its surrounding as a factor for household in predicting expected power output and profit of PV installation, besides financial resource, home value, and the simplified version of peers influence. The model was validated with empirical data of PV adoption in Austin, Texas, with the result provide strong support for the predictive capability of the model. This result, together with Rai and Beck (2017), indicate that the incorporation of behavioral science are effective to bridge the gap between ABM and the actual behavioral change at large scale. The model was also implemented in Robinson and Rai (2015) to determine the spatio-temporal patterns of PV adoption.

1.2 Knowledge Gap and Scoping

As it has been shown multiple times, PV adoption and diffusion of innovation in general is influenced by both communication channel (either through neighbors or local communities) and the psychological aspect of decision making of each household. However, to the best of the author's knowledge, there is yet any study to **explore the influence of various communication channels, together with household's decision making, to the adoption curve of residential PV system, especially through ABM**.

This thesis addresses the mentioned knowledge gap, and is done as part of a bigger project conducted by ZEnMo (with Auke Hoekstra as the project leader), which is currently conducting research to explore the impact of the appearance and utilization of renewable energy to the power network balance using ABM. The project of ZEnMo utilizes GIS & Agent-based Model Architecture (GAMA) software to implement the model and the Netherlands is used as a case study. As this thesis is part of the project, GAMA software will be used as the platform in which the model is implemented and that the case study is done for the Netherlands.

There are numerous factors that could be researched in this study. However, the model focuses on the role of communication channel and individual decision making in influencing residential PV rate of adoption. Thus the influence of some other factors, such as the dynamic of electricity price, is not looked at thoroughly.

This thesis provides two contributions to the literature. Firstly, it provides an agent-based model for diffusion of innovation process which incorporate communication channels and psychological aspect with high level of detail. Secondly the outcome of this thesis provides further insight on the roles of communication channels and psychological decision making in DOI process of PV system based on agent-based modeling.

1.3 Research Design

1.3.1 Research Question

Based on the knowledge gap and the scoping of the thesis, the following research question is presented:
How does the adoption curve of residential PV system be influenced by consumer's decision making psychology and various communication channels?

Furthermore, this research question is broken down into several sub-research questions which are answered throughout this thesis. These sub-research questions are:

1. How does Dutch residential PV adoption system look like from the consumer's behavior and social structure perspective?
2. How is Dutch residential PV adoption modeled into an ABM incorporating the installed-PV peak power?
3. What are the influence of various communication channels and consumer's decision making to the adoption curve of residential PV according to ABM?
4. How well does the ABM represent the actual system?

1.3.2 Research Approach

The approach used to answer the research question is based from the complex adaptive system (CAS) perspective and agent based model framework. This thesis is divided into five steps: literature review, conceptualization, formalization, analysis, and results and evaluation. (van Dam, Nikolic, and Lukszo, 2013)

The first step, literature review, relates on the first research question. The integrated framework proposed by Wolske, Stern, and Dietz (2017) is used in this thesis to implement DOI and TPB from the household's perspective. More information on TPB, DOI, and PV adoption system is gathered mainly through desk research. Two interviews with local PV installer companies are also used to gain further understanding on the behavior of local PV company and household. In this thesis, the two local PV installers will be referred as Installer-1 and Installer-2 to maintain confidentiality, as asked by the installers.

Conceptualization and formalization step help to answer the second sub-question. The model conceptualization into ABM is built based on the result of first sub-question. Firstly, the model is translated into a data structure which is recognizable by GAMA software. The main simulation is done in GAMA software version 1.7.1, as it is the software used by ZEnMo. MATLAB is also used to produce solar data irradiance. The process is followed by model verification.

Model calibration is done with the help of empirical data from the *klimaatmonitor.nl* database of PV adoption from 2008 until 2015. Furthermore, the calibrated model is used to explore the influence of the subjected factors to the adoption curve. Data analysis is done with RStudio software. The outcome of this analysis helps to answer the third sub-question. The result is further discussed and evaluated to the existing knowledge of residential PV adoption to answer the final sub-question.

1.4 Thesis Outline

This thesis starts with the elaboration of the theories used to in this thesis, both as the framework for the problem and the framework of the modeling tools that is used (ABM). Then chapter 3 discusses the finding on the Dutch residential PV adoption system based on literature review and interviews.

Chapter 4 shows how the system can be conceptualized to be used in ABM, while chapter 5 describes the formalization of the model into the GAMA software, including verification of the model.

Chapter 6 explains the experiment design necessary to answer the research question and chapter 7 provide the result of the analyzed data from the experiments. Then, chapter 8 discusses the validity and applicability of the model to the real world. Finally, chapter 9 conclude this thesis by providing the answer to the main research question, and by giving further recommendation based on the conclusion.

Chapter 2

Theoretical Background

This chapter elaborates some concept and background theories that are utilized in this thesis. Firstly, diffusion of innovation is elaborated on in section 2.1, as it is the framework that describes on how PV adoption occurs. Section 2.2 discusses theory of planned behavior as the framework that explains consumer's behavior in purchasing PV. Then, section 2.3 explains the concept of complex adaptive system and why diffusion of innovation is considered as a complex adaptive system. Finally, agent-based modeling is described, which includes the reason to utilize ABM.

2.1 Diffusion of Innovation

In diffusion of innovation, information, knowledge, and uncertainty play essential roles. Diffusion can be considered as a special type of communication which the message being delivered actually brings knowledge regarding an innovation, or, by Rogers (2002), was referred to as new idea. This 'newness' aspect results on consumer's uncertainty on the new idea and the uncertainty can be reduced by the acquisition of information through any communication channel. The more information obtained by an individual regarding the innovation, the better the knowledge of that individual on the innovation.

As mentioned before in section 1.1, each innovation has different rate of adoption. An innovation's rate of adoption can be explained through 5 characteristics: relative advantage, complexity, compatibility, trialibility and observability. Relative advantage is the degree to which the innovation is perceived as better than or having any kind of advantage from the preceding idea. This can further be broken down into various different aspects, such as performance or aesthetic. Complexity refers to the difficulty level of the innovation to be understood and used. Then, compatibility concerns whether the innovation match with past experiences, needs and existing values or not. Trialibility refers to the possibility of the innovation to be tried or be experimented with and observability refers to the degree to which the innovation can easily be found by the individual. These variables are strong predictor for the rate of adoption of an innovation. The work of Ostlund (1974) shows their high predictive capability, more so than personal characteristic variables such as venturesomeness, cosmopolitanism, etc.. The same finding was also found by Labay and Kinnear (1981).

During a diffusion process, consumers go through different stages starting from obtaining first knowledge until forming a final decision on implementing the innovation, and confirming this decision. This process is referred to as the **innovation-decision** process. It consists of 5 stages: knowledge, persuasion, decision, implementation, and confirmation (see Figure 3.3). At the beginning, one becomes aware of an innovation and gain some knowledge on the presence of that innovation and how it functions. Then the individual start to form certain attitude, either favorable or unfavorable, towards the innovation at the persuasion stage. At this stage, he or she seeks further information about the innovation actively. At the decision stage, the individual takes part in activities that ends with adoption or rejection of the innovation. The implementation stage refers to the time when the individual has adopted the innovation and is using it. Finally the confirmation stage occurs for some time after adoption or rejection where the individual is convinced with the decision to adopter or to reject. Rogers, 2002

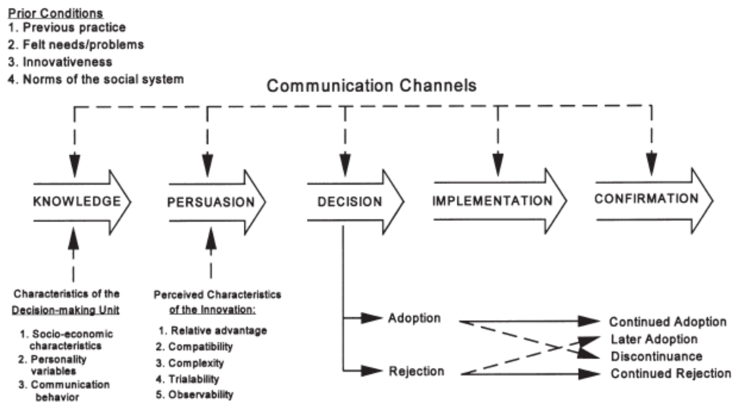


Figure 2.1: Innovation-Decision Process (Rogers, 2002)

Rogers (2002) also categorizes individual into several adopter categories depending on their timing of adoption. The first to adopt the innovation are classified as innovators. They are then followed by early adopters, early majority, late majority, and the last are laggards (see Figure 2.2). Franceschinis et al. (2017) investigated households' preferences toward different heating system in Veneto, Italy and found that the percentage spread is, by large, in accordance with Rogers'; 26.9% are associated either with innovator or early adopters, 29.1% are with laggards, and 44% are associated with early and late majority.

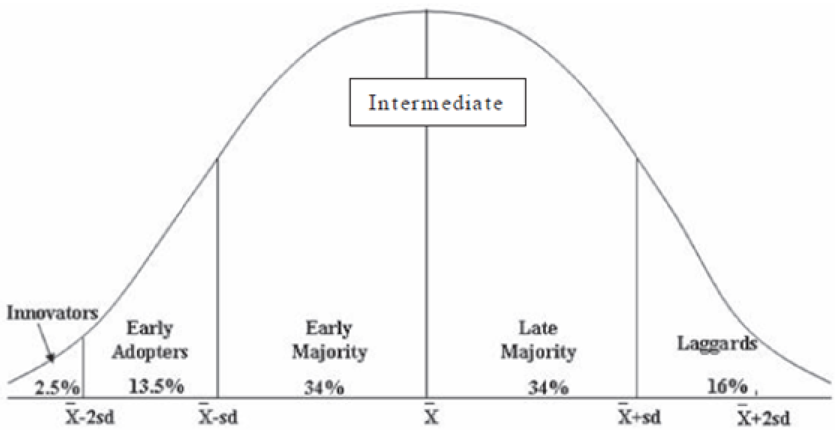


Figure 2.2: Adopter Categorization (Rogers, 2002)

Communication channels are essential in becoming a mean to transfer information from an entity that has the information to another entity which has not had that information yet. Communication channel can be differentiated into interpersonal and mass media. Within the adoption-decision process, the two types of channel play important role at different stages; mass media channels are generally more important at the knowledge stage while interpersonal channels becomes more important at the persuasion stage. Furthermore, the effect of each channels are also different for different adopter categories, for instance, early adopters are usually more easily influenced by mass media than later adopters. Rogers, 2002

Diffusion of innovation occurs within a social system and brings about some social change. Rogers (2002) defined a social system as "*a set of interrelated units that are engaged in joint problem solving to accomplish a common goal*". All types of entity can be part of a social system; this includes individuals, organizations or a group of people. The structure of a system heavily influence diffusion process. For example, the role of mass media and interpersonal channels in a city in the Netherlands may be different with what occurs in a village in Bangladesh, as mentioned by Rogers (2002).

While diffusion of innovation describes elaborately on how information spreads and the process in which consumers go through over time, the elaboration only slightly discusses the consumers' psychological aspect on decision making to adopt or to reject the innovation. In Rogers (2002), it is stated that most consumers will adopt an innovation after trying it first or after having confirmation from its peer that has tried it, especially when the innovation cannot firstly be tried beforehand. Theory of planned behavior is a theoretical framework that may be used to fill this psychological aspect of consumers' decision making.

2.2 Theory of Planned Behavior

Theory of Planned Behavior (proposed by Ajzen (1991)) is meant to predict human behavior in certain context with the assumption of rational decision making. The theory was initially developed in the fields related to advertising and public relations. It has been used to explain consumers' behavior towards green technology, including decision to purchase and adopt PV system. Jager (2006), Korcaj, Hahnel, and Spada (2015), and Yadav and Pathak (2016) explored consumers' motives to buy PV using TPB in the city of Groningen in the Netherlands, Germany, and India, respectively. Moreover, agent-based models built by Rai and Robinson (2015), Rai and Beck (2017), Robinson and Rai (2015) uses TPB to model households' decision making in adopting PV system.

The theory argues that the intention to do certain behavior can be a good predictor to expect whether the individual actually does the behavior or not. The stronger the intention, the more likely the behavior to be done. This intention is, in turn, determined by the individual's attitude, subjective norm (SN), and perceived behavioral control (PBC). This three aspects are commonly combined in a unidimensional construct (i.e. $\Sigma b_i e_i$, $\Sigma nb_j mc_j$, $\Sigma cb_k pf_k$) (see Figure 2.3) Taylor and Todd, 1995.

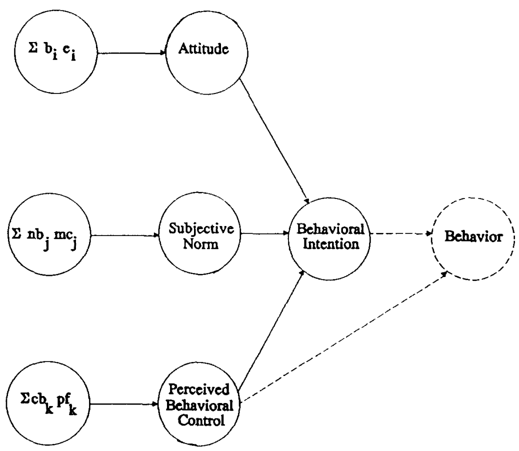


Figure 2.3: Theory of Planned Behavior (Taylor & Todd, 1995)

Individual's attitude towards a behavior is formed from certain beliefs held by that individual towards the outcome of that behavior, and compared it to the outcome of another behaviors. There may be multiple beliefs which correlate with a certain behavior. Based from the individual's beliefs, positive or negative attitude regarding the behavior may be formed.

The second aspect which influence intention, i.e. SN, concerns with social pressure. It consists of two different norms . The first one refers to the behavior that its peers will do given the same option and condition. The second refers to the perceived response given by them. People will always try to follow the norm; it depends on the importancy of the peers to them though.

The last aspect, PBC, indicates perception on the possibility to execute the behavior. It represents the limited control had by the individual to perform the behavior. There are two aspects of PBC: facilitating conditions and self efficacy. Facilitating conditions stand for access to the resources needed to carry out the behavior; this includes time, money and other type of resources required. Self-efficacy, on the other hand, means the perceived ability of that individual to do it. The higher the perceived possibility to carry out the behavior, the higher the PBC, and the larger the intention is (Ajzen, 1991; Taylor and Todd, 1995).

The theory of planned behavior argues that intention can only manifest into behavior if the individual perceived that he or she has enough control to do the behavior. In other word, besides intention, PBC also have influence to the final behavior. Here, PBC represents the individual's actual control over the behavior. Ajzen (1991) stated that '*to the extend that a person has the required opportunities and resources, and intends to perform the behavior, he or she should succeed in doing so*'.

2.3 Complex Adaptive System

System, as described by Ryan (2008), "*[...] is a representation of an entity as a complex whole open to feedback from its environment*". A system can further be elaborated as (1) an idealization; (2) is organized; (3) has multiple components that are (4) interdependent; (5) has emergent properties; (6) has a boundary; (7) is enduring; (8) effects and is affected by its environment; (9) exhibits feedback; and (10) has non-trivial behavior.

Then, socio-technical system is a system where technical artifacts (e.g. road, pipeline, factory) and actor entities (e.g. employee, company, ministry, government) coexist. Within the system, they are interconnected with each other (Kay, 2002). PV adoption, and diffusion of innovation in general, is a socio-technical system, where PV technologies, power utilities, consumer, and other actors and technologies are present and interrelated to each other. Socio-technical system itself, is a class of complex adaptive system (Kay, 2002).

Adaptation, in biology, is the ability of an organism to alter its structure in order to fit better in its surrounding. The alteration that occurs must be an improvement and is a response to stimuli from its environment. This improvement must also be constant ot, at least, periodically constant over (van Dam et al., 2013). Thus, adaptive refers to the property of an organism for being able to do improvement as a response of a certain constant stimuli from its environment.

In the most basic term, complex means "not simple". The meaning of complex is not completely established. More importantly, it is observer dependence; complex and simple can happen at the same time. However, usually, the simpler the structure of a system, the more complex its functionality is. When a system, is broken down, the sub-system is commonly more simpler in structure, but is more complex in function. Complicated, is a special type of complex, i.e. where all parts move together precisely forming a complete one unit.

Adaptive system, most commonly is complex due to the interrelations between its sub-system. The most basic property of complex adaptive system is chaotic behavior, where "*complex behaviour,19 arising in deterministic, non-linear dynamic systems, when relatively simple processes or rules are repeatedly applied*". Two major displays of chaotic system are having a characteristic structure and is sensitive to the initial conditions van Dam et al. (2013).

A complex adaptive system must behave with a certain emergent property. This emergent behavior, however, is unpredictable. The system usually always goes to certain attractors, or goes away from repellers. The mechanism of what causes emergent behavior is difficult to be examined and understood. (van Dam et al., 2013)

2.4 Agent-Based Modeling

Agent-based modeling is a method to examine emergent properties from a bottom-up perspective through the interaction of 'things' or 'entities', instead of a particular thing or a whole set of things. In agent-based modeling, there is no certain objective to be achieved. It merely describes an entity and together with its interaction to its surrounding. This entity, in agent-based model, is often actualized in an agent as the smallest element of ABM. (van Dam et al., 2013)

In ABM, agent is located in a certain environment and has certain states and rules in which it follows to decide on certain action to be done on its surrounding or on itself. Moreover, it also receives inputs from its surroundings which may or may not alter some of its states (see Figure 3.1) (Jennings, 2000). This states are a set of internal parameters of the agent which gives information on the current condition of the agent. Rules is the internal model mechanism of an agent that uses states to alter or preserve states (van Dam et al., 2013). For instance, in this thesis, Theory of Planned Behavior is used to build the rules of an agent (household). The accumulation of all agents in a model, their states, rules, actions, and interactions results on a certain emergent property of the modeled system.

The environment in which agents are located in, also has certain aspects which can be inputted by the modeler, or by the emergent property of the model. The environment provides structure to the agents to interact. Some of the most common structures are soup and scale-free network. A unique aspect of the environment is time. In ABM, time goes in a discrete manner by a tick (or cycle in GAMA) for each time unit, instead of continuously as what happens in the actual world. This create difference in the sense that everything happens parallel in the real world, while the model goes sequentially.(van Dam et al., 2013)

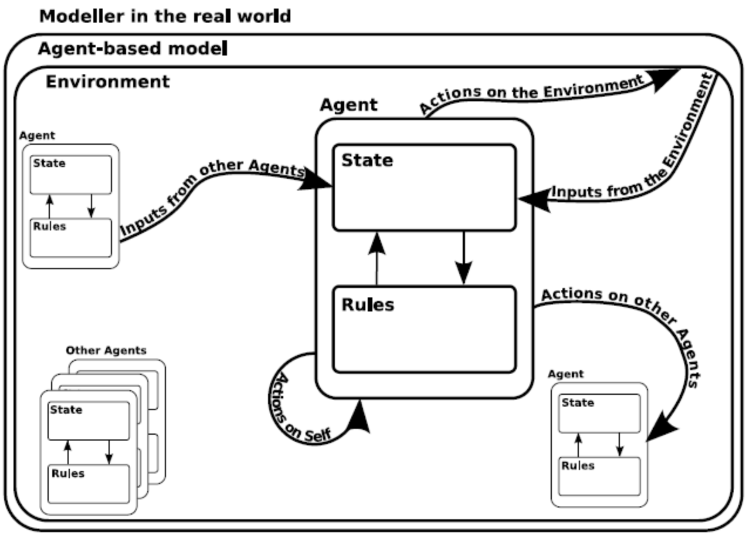


Figure 2.4: Structure of an agent-based model (van Dam, Nikolic, & Lukszo, 2013)

In modeling CAS, the model must also be a CAS. Modeling the real world, however, is not a trivial task. Simplification is necessary to be done by the modeler, but it must be done appropriately according to the main objective, in such a way that the model have enough accuracy as well as complexity to be able to obtain insight based from the complex behavior of the model. It still has to be emphasized that even this result is already a 'wrong' result because the model is only an interpretation of the real world made by the modeler.

Agent-based modeling is the most suitable for modeling a complex adaptive system. The framework of ABM allows the modeler to create complexity through the dynamics between agents and the environment. It also requires minimum level of knowledge on the overall level of the model, but can already be built and understood as long as the mechanism of the individual agents are known. At the same time, the environment can observe a particular property occurs as the result of the model that, that is the emergent property. The construction of ABM make possible for the modeler to observe emergent properties from a bottom-up perspective of a world with complex structures and dynamics. (van Dam et al., 2013; Borshchev and Filippov, 2004)

Chapter 3

The World of PV Adoption in the Netherlands

After the description of DOI, TPB, CAS, and ABM in the previous chapter, this chapter follows up with the elaboration on how the system of Dutch residential PV adoption looks like. This chapter also gives the answer to the first sub-question. The first and second section elaborate the general overview on PV market development as well as the implemented policies in the Netherlands. The next section discusses PV system technology as the main technology that is being assessed in this thesis. Section 3.3 elaborates in detail the decision making process of resident, as a consumer in regards of PV system, to adopt or to reject PV. It is followed by an explanation on the communication channels that are present in and possibly influence the system. Finally, the last section concludes the chapter by answering the first sub-research question, regarding consumer's behavior and social structure perspective of PV adoption.

3.1 PV Market and Policies

PV system in general has started to be installed in the Netherlands since the end of 1990s. The number grew for several years until 2003 and after several years of slow growth, significant increase occurred after 2010 (W. G. van Sark, Muizebelt, Cace, de Vries, and de Rijk, 2014). Specifically for small consumers (network of $< 3 \times 80$ Ampere), up until 2010 the increase of installed power annually was merely 13% and it reached the value of 91% after 2010 (PWC, 2016). According to *Productie Installatie Register* (PIR), in total, 1.32 GWp (GW-peak) of PV system had been installed in the Netherlands by the end of 2015 (S. Magazine, n.d.). As a late-comer in the renewable energy sector, the adoption rate of PV has taken a steady development and is expected to keep growing until 2023 (P. Magazine, 2017).

One of the main factor that helps to kick-start PV adoption is the implemented policy. Since 2004 up until now, *salderingsregeling*, which from now on will be referred as net metering, is implemented. Net metering scheme allows PV owner to either directly use the produced electricity, or to deliver it to the grid only to use it at later time. For each kWh of power being produced, the produced power decreased the owner's electricity bill by 1 kWh. This implies that under net metering, power produced by PV system is priced as high as the retail price of electricity. (Commission, 2015)

Net metering applies to systems up to 15 kWp with grid connected three phase electrical system below 80 A (Ampere). To be able to participate in the net metering scheme and being 'compensated' by power utility, resident must register its PV system on PIR (RVO, n.d.). Initially, the amount of power that can be 'compensated' was limited to 3000 kWh per year. This was increased to 5000 kWh in 2011, before in the end the limit was lifted in 2011. The limit at the moment is, thus, the total power consumed by the owner. Also, the compensation was initially implemented only for the delivery part of the electricity tariff before it included *energiebelasting* (energy tax) in 2008. (PWC, 2016).

Besides net metering, there is another policy implemented for any type of technology related to sustainable energy. *Milieukwaliteit van de Elektriciteitsproductie* (MEP) was implemented until 2008, until it was replaced by *Stimuleringsregeling Duurzame Energie* (SDE). Both are a type of feed-in premium (FiP), where subsidy is given for every energy produced by the technology. The amount of subsidy is technology specific; it basically is determined according to the electricity cost produced by the technology, measured against the average cost of electricity from all type of renewable energy technology, as well the overall average electricity cost. SDE was fastly changed into SDE+ in 2010. However, all of these policies are meant for system larger than 15 kWp (Londo, Matton, Usmani, van Klaveren, and Tigchelaar, 2017; ZonnePannelen.net, n.d.-b), i.e. more for organizations rather than individual households.

Since 2017, another policy was discussed as a proposal to replace the current net metering policy and it was recently reported by PV Magazine (2018) that the Netherlands' Ministry of Economic Affairs and Climate Change plans to implement *terugleversubsidie* (return subsidy). This scheme is perceived to help regulating the adoption rate of PV in general and prevent any turbulence on the adoption. In the scheme, consumer would still has to pay for the delivery cost for self produced and consumed electricity. It is planned to be set to leads to payback period of around 7 years. For part of electricity that is delivered back to the grid, it will be compensated in another scheme which would be determined by power utility. Furthermore, power cap may also be included for the amount of electricity that is fed to the grid. Depending on the pricing system set by power utility, this scheme may also promote self-consumption (Londo et al., 2017; P. Magazine, n.d.).

3.2 PV System

PV system consists of the PV module itself and the other components, which the whole is called as balance of system (BOS). BOS comprises of cabling, inverters, module controller, and some other electronic devices. The performance of a PV system is highly determined by PV module's performance. In general, PV module's efficiency lies around 12% up until 21%, depending on the type of module and the atmosphere temperature. At the high temperature condition of around 40 ^{o}C, PV modules efficiency might drop up to 2%-3% from the already low efficiency. On the other hand, the efficiency of BOS is around 90% (Smets, Jäger, Isabella, van Swaaij, and Zeman, 2016).

In the Dutch market, there are 2 types of modules that are dominating the market. These are poly-crystalline Silicon (poly-cSi) and mono-crystalline Silicon (mono-cSi) (W. van Sark and Schoen, 2016). Mono-cSi has a better efficiency of around 17% while poly-cSi's is only about 14%. This efficiency difference also correlates with the price, in which mono-cSi usually costs around 670 E per panel and poly-cSi costs around 600 E per panel (ZonnePannelen.net, n.d.-a; Smets et al., 2016).

Traditionally, the cost of PV system was dominated by the high cost of PV module. This changes in the past two decades and the fraction of PV module cost has decreased from 60% to 40% since the 1990 (Strupeit and Neij, 2017) with the remaining comes from soft costs (labor, cabling, and etc.). By February 2016, the average price of PV modules in the Netherlands had already reached 1.05 Euro/kWh (W. van Sark and Schoen, 2016). The total hardware cost is about 75% of the total PV system's cost (ZonnePannelen.net, n.d.-a) while further studies show that annual PV module price decrease is about 97%. Moreover, the technology for these type of PV has been mature enough and is not likely to grow significantly anymore. The decrease on its price, mainly occurs due to the economies of scale effect globally (Mayer, Philipps, Hussein, Schlegl, and Senkpiel, 2015).

In installing a PV system, ground-coverage-ratio (GCR) is a parameter that indicates on how much the system cover the total area of the surface. According to both Installer-1 and Installer-2, the common maximum GCR to be implemented on a roof is around 0.85 due to safety reasons. Furthermore, a PV system has a life time of about 25 until 30 years. After this duration, PV performance drops and should be replaced by a new system.

The total power production from a PV system for a year can either be calculated with or without the incorporation of the specific house's orientation (east, south, etc.). According to both Installer-1 and Installer-2, majority of information available on Dutch websites, as well as what is provided by installers to their client at the beginning of the discussion, is based on the calculation that does not take into account any house orientation. In this method, all house is assumed to face South and that the annual power production is simply calculated as a fraction of the total installed power (of about 85%). This calculation leads to the idea that payback period for all houses is about 7 years in the period of 2015-2018 (van der Wilt, n.d.). The other method requires more rigorous calculation, which the technical detail is shown in Appendix **??**.

3.3 Consumers' Innovation-Decision Process

The decision making process of how consumer purchases rooftop PV system can be explained through TPB and DOI. While DOI provides useful framework to aspects of diffusion and innovation-adoption process, Rogers (2002) did not mention much on the mechanism of how attitude and adoption/rejection decision is formed. On the other hand, TPB provides framework on how attitude, subjective norm, and perceived behavioral control leads to behavior. In the case of PV adoption, the implementation of TPB into the first first 3 stages of innovation-adoption may explain the psychological mechanism for consumer to adopt PV system.

The main process follows the innovation-decision process proposed by Rogers (2002) which consists of the knowledge, persuasion, decision, implementation, and confirmation stages. One major obstacle for PV system is its lack of trialibility, which is an important attributes of DOI. With the technology also requires long-term commitment, the implementation stage for adopting PV needs a long-term commitment. Thus the process in PV adoption mainly focuses on the first three stages, even though implementation and confirmation do take place around the time when PV system reached the end of its life and requires replacement.

3.3.1 Accidental Information

Rogers (2002) described 3 types of knowledge: awareness, how-to, and principles knowledge. The acquisition of these knowledge is closely related with needs. Rogers (2002) defined need as "a state of dissatisfaction or frustration that occurs when one's desires outweigh one's actualities; in other words, when 'wants' outrun 'gets'. There are abundant types of need, the following are some which relate to PV adoption: the need to solve climate change issue, the need to be the same with one's peers, the need to be more independent in term of electricity supply, the need to 'be' an environmentally sensitive person, and the need of having more saving or less expenditure (Jager, 2006; Kaplan, 1999).

There are several types of knowledges. Awareness knowledge refers to someone's awareness of the presence of an innovation. In knowledge stage, the acquisition of awareness knowledge is argued as an unintended process as someone cannot look for 'the' specific innovation when someone does not know its presence. How-to knowledge is the knowledge on how the innovation can be utilized while principle knowledge refers to the underlying principle on how the innovation works or contributes to another matter (Rogers, 2002). However, consumer may also obtain awareness knowledge by seeking information which is started from certain other need (e.g. someone reads about PV through an encyclopedia because of the need to find solution to climate change).

The knowledge stage of DOI still continues after awareness knowledge is obtained. It is replaced by persuasion stage when consumer actively searches for how-to and principle knowledges. The transition process between knowledge and persuasion stages may not be smooth though and the precise moment on when that occurs is also not clear. Consumer may forget about the innovation and not looking for information anymore (Rogers, 2002). This may happen when consumer's need is not very urgent, and it thus lacks in motivation compared to the effort that has to be exerted in order to find relevant information. Further elaborated, the degree of motivation to find more information regarding an innovation, that originates from any kind of need, determines the stage in which the consumer is in since there is no specific definition of 'active' which can differentiate between active and inactive in looking for information. Naturally, one's motivation may also diminish after some time when it is not 'nurtured'.

In the case of PV, motivation to adopt PV can be categorized into 3: instrumental, environmental, and symbolic. Instrumental refers to motivation because of the utility obtained by owning PV, environmental motivation comes from one's concern on the environment, and symbolic refers to motivation caused by the effect of owning PV to one's identity and social status. (Noppers, Keizer, Milovanovic, and Steg, 2016). It is only natural for these motivations to be closely related or influenced by the knowledge of from that aspect. For instance, one might has instrumental motivation because he or she has certain knowledge on PV potential to support self independency from the grid.

3.3.2 Intention Creation

In TPB, actual behavior is preceded by intention which again, preceded by attitude as one of its influencer. Korcaj et al. (2015) also pointed to this gap between intention and behavior. It also aligns with DOI which states that "discrepancy between favorable attitudes and actual adoption is frequently found" (Rogers, 2002). Kaplan (1999), in his research on adoption of PV system by energy utility, addressed the persuasion stage to be represented by the forming of interest through knowledge, motivation, and several other variables. Motivations was found to be important in determining interest, partially due to its strong influence on knowledge; motivations drive consumer to search for more information.

The term interest implies that the knowledge-seeking behavior is done with 'affective investment' to obtain it (Kaplan, 1999). Consumers are willing to invest cognitive effort and this manifests from certain motivation. The study uses behavioral intention of TPB as a measure of interest because interest provides linkage to the actual behavior (to purchase PV system) (Kaplan, 1999), and thus, interest is associated with intention at the rest of this report.

Besides interest, consumers also have what is called as liking (Sung, Vanman, Hartley, and Phau, 2016). Liking represents the feeling that comes from familiarity with the current situation. As DOI has mentioned, uncertainty is the condition where consumers feel that they do not know the technology well, thus uncertainty and liking is closely related, if not identical. Uncertainty and liking, in other words, are the representation of consumers' reluctance to change due to the uncertainty nature of a new technology.

If motivation is the driver to obtain more information, knowledge allows consumer to have perception on the attributes of innovation, both positive and negative attributes (Faiers and Neame, 2006; Yadav and Pathak, 2016). This gives further consent for intention to occur, even if the consumer has not yet had a lot of knowledge. Attributes (associated with attitude in PB) have been reported by numerous studies to influence intention positively (Chen and Hung, 2016; Paul, Modi, and Patel, 2016; Yadav and Pathak, 2016).

When the attributes are not positive enough, the consumer is not convinced yet with its 'intention' on PV and is in dissonance, i.e. a state when an individual's mind is in 'disequilibrium' (Rogers, 2002). When the attributes' positive value overcomes certain threshold value, the intention materializes. Nonetheless, not all knowledge must be acquired by consumer before the intention to adopt is materialized. Roberts (1997), as mentioned by Kaplan (1999), said that adoption may not be preceded by principle knowledge; even though, good decision making can be promoted with more knowledge.

Most likely, persuasion stage has a certain time limit; it is possible that consumer does not find any relevant information at all. On the other hand, consumer may also have already had enough knowledge, but the attributes following to intention is not strong enough. At this condition, the consumer can lose motivation and decide to not adopt (reject) PV due to the excessive effort necessary. They may lose drive to look for further information and stop looking for it, even though they notice the need for PV. A study done by Vasseur and Kemp (2015) indicated that rejecters are lack of information on the subsidy system and less familiar with the cost of PV. It may indicate that the need to find information is concealed by the effort that must be exerted.

3.3.3 Perceived Attributes of PV System

Perceived attributes can be decomposed into numerous factors. Wolske et al. (2017) integrated many factors from 3 different theories (the Planned Behavior Theory, the Diffusion of Innovation Theory, and the Value-Belief-Norm Theory) specifically for PV system. The study hypothesizes that interest in PV is most directly affected by certain perception on PV, which are perception of benefits and risks of PV, of social support, and PBC. They are, furthermore, affected by personal dispositions (consumer's internal factors based on values) and external influences. Figure 2.3 shows the complete framework. From DOI perspective, internal factors (which are influenced by individual's values) may be associated with the influence of an adopter's category towards the innovation's attributes. External influences mainly refers to the effectiveness of communication for this innovation.

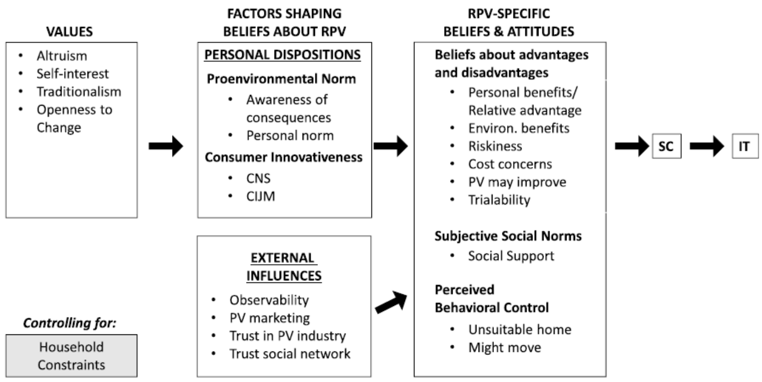


Figure 3.1: Influences in Predicting Interest to Purchase PV System (WolskeEtAl,2017)

Personal benefits, which is comparable to relative advantage in DOI, can further be decomposed into different aspect. The study of Faiers and Neame (2006) showed that payback period, investment cost, aesthetics (visual aspect), environmental, and operational knowledge (such as failure possibility) are the interesting factors to be looked at in PV adoption. Korcaj et al. (2015) showed that financial benefit, power independency, and social status are the most important factors, followed by environmental and investment cost. Sommerfeld et al. (2017) did questionnaire in Australia and found that financial aspect was the most influential factor while environmental reason was rarely mentioned.

Yadav and Pathak (2016), Paul et al. (2016), and Chen and Hung (2016) proposed extension for TPB framework by adding several other factors such as social impression, environmental consciousness, environmental ethics, environmental concerns, and environmental knowledge. These factors may be considered as knowledge of environmental aspect, belief (internal factors), and social status, when fitted in Wolske's framework. In this study, attitude, SN, and PBC are decomposed/deconstructed into different attributes to better represent consumer adoption behavior.

Based from the literature and further confirmation from both Installer-1 and Installer-2, 7 aspects of PV keeps reappearing. These are financial benefit (payback period), environmental benefit, power independency, aesthetics, social status, investment cost, and operational and maintenance (O&M) knowledge. The first four correspond to attitude and the last two correspond to PBC while social status represents SN.

3.3.4 Behavior Hindrance

Intention does not necessarily result on behavior as PBC also has influence on it. Study on this specific area for PV system is still very rare, in fact, there is yet any as far as the author knowledge. Based on the interview with the two installers, 3 PBC factors occurs as the most common reasons that their customers mentioned; these are the knowledge of an installer, effort needed to manage the administration, and investment costs. Some PV installer offers help to manage consumer in handling the administration. This factor is included based on the work of Jager (2006) and Korcaj et al. (2015) which show how bureaucracy may become a hindrance and that there is discrepancy between 'willing to install PV' and 'willing to install PV in the near future', indicating effort barrier to adopt PV.

3.3.5 Re-Evaluation

In Rogers(2002), not only consumers that adopter that can evaluate the implementation of the technology. Rejecter may also reevaluate his or her decision when rejecting PV. After some time has passed, it is possible for them to have better perception and to finally adopt PV.

3.4 Communication Channels

As Roger's DOI suggests, mass media and interpersonal relationship are the two types of communication channel. Television's advertisements, emails, and newspapers are examples of mass media that may transfer information. These channels have larger role to increase awereness knowledge during consumer's knowledge stage. At the current Information Age, internet allows everybody to obtain information in a very fast manner. During persuasion stage, it is very likely that consumer will do some research through internet.

Peers, including neighbors, colleagues, relatives can introduce someone to PV system, as well as to give better understanding on how actually the system works. Palm (2016, 2017) studied PV adoption behavior in Sweden and found that consumers' gain confirmation on whether the technology works as intended or not from their close peers such as friends and family members instead of their neighbors. This means that personal connection has more roles during persuasion stage while neighbors have obvious influence during knowledge stage only by installing a system on his or her roof. However, there are of course negative influence by spreading the weaknesses of PV through this channel.

Regarding connection, the network of connection between households is an important aspect of the social structure when discussing emergent pattern. The network of connection formed can be modeled through the scale-free network (see Figure 3.2). The network has more extreme values than random network. In social network, there are a lot of people that has tiny role in the society and has small number of connection. On the other hand, there are some people (e.g. politicians or artists) who have a lot of connection and may give a lot of influence to his or her connection (Wilensky, 2005), referred as opinion leader by Rogers (2002). These opinion leader may help or hinder PV adoption significantly depending on their action.(van Dam et al., 2013)

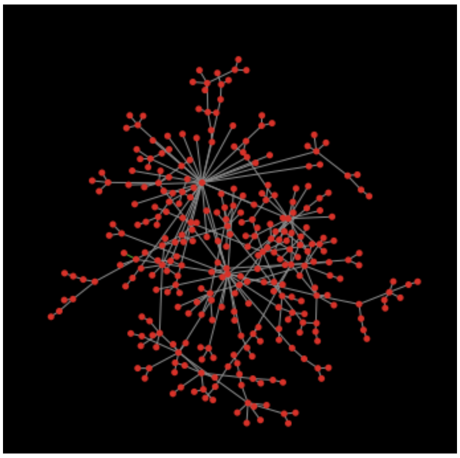


Figure 3.2: Scale-Free Network Generated in NetLogo (Wilensky, 2005)

One other communication channel based from the interview with Installer-1 is PV installers themselves. PV installers often provide service for consumer who wants to know more about PV, thus becoming a source of information for consumer during its persuasion stage. On the other hand, PV installer usually does not do any promotion at all. They basically uses mouth-to-mouth and their website as the media for which consumer can contact them.

Lastly, in the Netherlands, there are communities which give extra concern on renewable energy. These groups are called as local energy initiatives. They are formed by a group of citizens who have their own sustainable energy provision at local level. The activities of these groups are rather diverse, sometimes they can help stimulating energy savings and sometimes they organizes collective PV system purchasing. These groups might at some point help spreading the knowledge on PV system, or even increase social influence (subjective norm). (Timmerman, 2017)

3.5 Sub-conclusion

This section elaborates the world of PV adoption in the Netherlands and provides answer to the first sub-question: *How does Dutch residential PV adoption system look like from the consumer's behavior and social structure perspective?*

Consumer goes trough a process called as innovation-decision, in which consumer gains knowledge on PV system during the knowledge stage. When having enough motivation, he or she goes to the persuasion stage to look actively for knowledge. With enough intention, consideration to purchase PV occurs and the decision depends on whether the consumers' can purchase it or not. Once become a rejecter, consumer may reconsider the product again.

Along the way, different aspect of knowledges and motivation influences how consumer's act. The most important motivations are instrumental, environmental, and symbolic. The most important knowledges are knowledge on autarky, environmental, social, aesthetic, O&M, investment cost, and payback period. Interest leads to intention, and together with liking, investment cost and effort necessary, consumers may adopt or reject PV.

The technology of both poly-cSi and mono-cSI PV modules have matured enough so that any price decrease of the hardware most probably comes from the increase of adoption globally. The cost of PV system has had higher fraction of the soft cost in the past few years due to the decrease of PV module's price. PV system also has the life time of 25 until 30 years.

During the decision making (innovation-decision) process, various information flows to the consumer. Mass media and peers (neighbors and close connections) play important role in the knowledge stage to give awareness knowledge before motivation occurs. Close connections, PV installer, and self-seeking on internet plays more important roles during persuasion stage and decision stage. The social network, in such a dynamic system, can determine the outcome of the model. Figure 3.3 shows the innovation-decision process with the relevant social and technological influences.

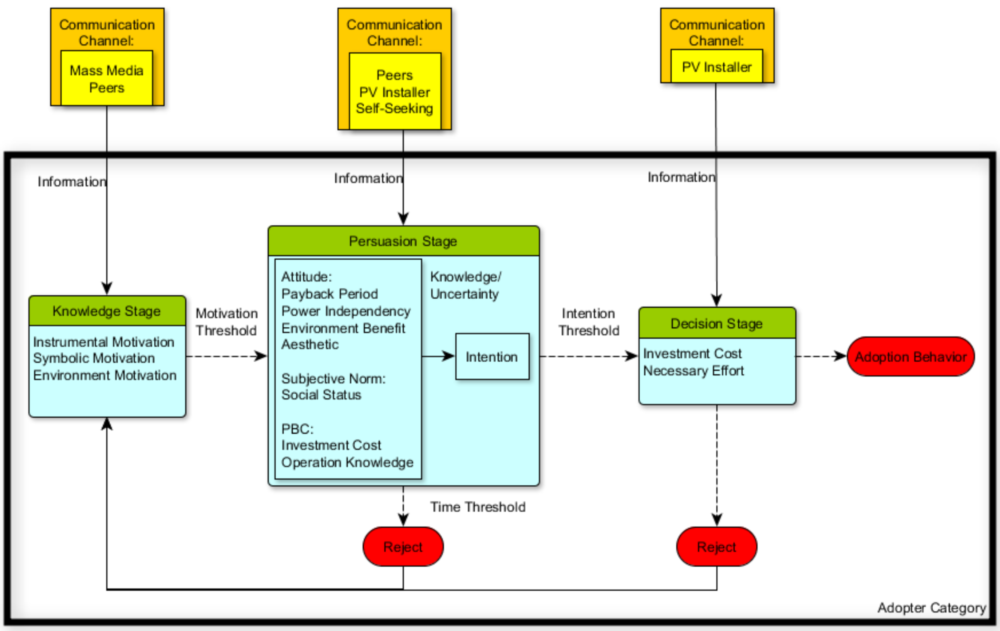


Figure 3.3: Innovation-Decision Process of Consumers in Adoption PV System

Chapter 4

Conceptual Model

This chapter decomposes and conceptualized the world of residential PV adoption into a model. The first section discusses the world concept at macro level, including the emergent patterns and problem owner. Section 4.2 describes the important agents, while section 4.3 elaborates important object (technology) within the world. It is then followed by the interactions between agents, as well as the environment that influences the system. At the end an overview of the model is shown. This chapter, together with 5, provide the answer to the second sub-research question.

4.1 Problem Description

As mentioned in chapter 1, the main problem is the lack of insight on the influence of communication channels to adoption rate, incorporating household's decision making process.

Emergent Patterns
As has been elaborated in section 2, the adoption of PV occurs as the result of information transfer through communication channels, as well as each household's decision making. However, the process may not be smooth, as found by Snape (2016). It is not trivial to pinpoint the crucial factor or moment which influences the outcome due to the complex nature of the system PV adoption is the emergent pattern observed in this model.

Problem Owner
There are two main problem owners for this model. The first problem owner is power utility who must prepare themselves towards the shift of power demand in the future and the second problem owner is the government of the Netherlands. The two actors are very closely related regarding this problem.

Power utilities are important stakeholder in the electricity sector. When residual power load shifts, not only power utilities are made difficult to tackle the technical challenges (mostly for power operators), but they are also exposed to the possible decrease of revenue because of the occurrence residential PV as power source. When the amount of installed PV increases rapidly, it may result on bankruptcy of several power utilities, or that power utilities may increase electricity tariff to make up their losses (Castaneda, Jimenez, et al., 2017). On the other hand, power utility has almost no control regarding the adoption rate, instead the government has more power due to its authority to adjust policy.

It is of the government's interest and task to help power utilities during PV adoption in facing significant drop of revenue while maintain the adoption in a healthy rate. One way to do it is to change the electricity pricing policy into a scheme that is more utility-friendly. Another way to control the rate of adoption is by regulating the information and the communication channels.

In this thesis, the author acts as a modeler to help power utility and government have better insight on how information and communication channels influence adoption rate through household's decision making.

4.2 Actors and Agents

There are several important actors that are taking part in this system: household residents, PV installers, government, power utilities, and local solar communities. Particularly for ABM, household residents and PV installer, is of interest to be modeled as a specific agent, while government mainly influences the other agents by changing pricing scheme policy independent of what the other agents do. Government may also help to promote PV system through mass media.

4.2.1 Household

In this model, household resident is assumed and is represented as a single household agent. Each household has a house as its living place and its own income level. The power consumption of a household is determined based on its income. All households have their own knowledges, interests, and liking which determine their behavior and decision regarding PV. Particularly, there are 5 different stages of households' perspective towards PV, with each having their own behavior. These stages are non adopter, early rejecter, potential adopter, knowledgeable rejecter, and adopter. A household may change category when certain requirements are met.

The main behavior of these households is that each of them always try to socialize with one of its connection every week, except for potential adopter because potential adopter focuses on finding knowledge on PV or to find an installer to purchase one. At the beginning of each cycle, these households evaluate whether they want to socialize or not. During socialization, household may influence the other household by sharing positive or negative perspective towards PV.

Knowledges, Interest, and Liking
Households have 6 different knowledges: (1) autarky knowledge (i.e. knowledge on the possibility of PV to provide self sustaining power system to the household, (2) environmental knowledge, (i.e. knowledge on the capability to support environmental cause by purchasing PV), (3) social knowledge (i.e. knowledge on what one's connections' perspective is towards PV, (4) operation-maintenance knowledge, (5) payback period knowledge, and (6) investment cost knowledge.

These 6 knowledges determine each household's interest. Besides that, each household also has an uncertainty level on PV which determines the household's liking. Liking is also influenced by peers confirmation during socialization, either positively or negatively. Finally, it also increases during interaction with PV installer if the installer does not provide help in the administration process of the PV. When interest exceeds liking, a household has the intention to purchase PV. The complex interaction between knowledges will be discussed further in section 4.4.1.

Non Adopter
Household is categorized as non adopter when it has never had any interest on PV. During socialization, non adopter may be influenced positively by adopter or influenced negatively by a rejecter. Non adopter may gain knowledge on PV system either from any promotion through the media, or through socialization. When either one of its autarky knowledge, environmental knowledge, or social knowledge surpasses certain threshold-to-be-interested-enough on PV, non adopter becomes potential adopter and has certain motivation depending on the knowledge that surpasses the threshold. However, it may also become an early rejecter when it has too high uncertainty.

Early Rejecter and Knowledgeable Rejecter
Household who decide to not adopt PV but has never actively looked for information about it is categorized as early rejecter, while households who have actively looked for information before rejecting PV is categorized as knowledgeable rejecter. Early rejecter and knowledgeable rejecter may influence non adopter negatively during socialization. Specifically for early rejecter, it may also be influenced negatively by another early rejecter or knowledgeable rejecter. Early rejecter becomes a potential adopter when it has motivation and has been influenced by some of its connection that has become an adopter, thus help convincing the early rejecter. For knowledgeable rejecter, it becomes a potential adopter again when it has had some positive socialization with adopter.

Adopter
Adopter refers to household who has purchased PV. Adopter may influence all other category positively. When become an adopter, household remembers the installer that it purchased PV from but it might lose the installer's contact over time.

Potential Adopter
Potential adopter refers to households that looks actively for information on PV, either through its own connection, self research through internet, or by asking an installer directly. It always starts by asking its connection through socialization, as the most trustworthy source, followed by doing internet research. However, potential adopter will not try to ask an adopter that it knows to have less knowledge than itself. It only consults an installer after some times have passed, but it has to have considerably high interest to be willing to make contact with an installer. If potential adopter's interest stays low for some time after becoming a potential adopter, it becomes a knowledgeable rejecter.

Potential adopter who either wants to purchase PV or to have consultation on PV, will try to ask for any contact, once again, through its connection as the starting point. When it fails, potential adopter looks for a contact from internet. If there is no installer found after some time, potential adopter becomes a knowledgeable rejecter. Furthermore, if the consultation fails (interest does not exceed liking), potential adopter also becomes a knowledgeable rejecter. When potential adopter has already had intention to purchase PV, i.e. when its interest exceeds its liking (will be discussed in the next part), it will have a negotiation with PV installer on the size and cost of the supposedly to be installed PV.

4.2.2 PV Installer

While there are numerous PV installer in the Netherlands, 4 PV installers is used in this model. Two installers provide service to help with administration process of PV while the other two do not. Then each one of the two are either a small or a large company, resulting in 4 'different' PV installers. Small and large PV installer has different soft cost per kWp PV installed, due to different time spent on man power to install the PV. For PV installed with more than 10 modules, the tariff per module decreases due to economies of scale effect. Every year, PV module price decreases, and thus, installer must also update its price for every year.

When a household ask for the price of PV for its house (negotiation with a potential adopter), installer does a detail calculation for the PV size, power production, investment cost, and payback period. By default, large installer usually proposes for its client to have the largest size of PV system, i.e. to cover the whole rooftop with PV modules. Small installer starts by proposing a size that leads to the household to have zero net power consumption annually. Some potential adopter directly asks to have a size that results on zero net power. This process is based on the result of the interview with the installers.

4.3 Object

PV system and house are the most prominent object in this model.

4.3.1 PV System

Only one type of PV module is considered in this model, as the difference between mono- and poly-cSi are not that significant. PV system can be owned by either a household or an installer. The one which is owned by an installer helps to calculate investment cost, power production, and payback period for the installer's client.

4.3.2 House

House building which is owned by household has a certain roof orientation (North, Southwest, etc.), roof tilt angle, roof surface area, and roof type (gable, hip-pyramid, and flat). Surface area determines the maximum amount of PV module that can be installed. Normally, maximum about 85% of the total surface can be used for PV system. Tilt angle, together with orientation, influence PV system power production when installed on the rooftop. Roof type naturally affects the available surface and orientation.

4.4 Interactions

4.4.1 Assessing Interest and Liking

Each knowledges, except for social knowledge, solely represent the amount of knowledge possessed by the household; it does not represent how the household perceives PV from that aspect. Therefore, the higher the knowledge level does not always result on greater interest towards PV, especially in the case of environmental and autarky knowledge. Specifically for social knowledge, it is influenced by both connection and neighbors, represent the knowledge that others have started using PV, and the knowledge has positive relationship with interest.

Except for social knowledge, each knowledge level is separated into three, with the so called lower and upper threshold. When the knowledge is below the lower threshold, household has never considered PV from that aspect of knowledge and above that, the household have already had some knowledge, and thus a perspective on PV. For instance, for O&M knowledge, household has never considered that PV requires some knowledge to be operated and there are some cost required to maintain its operation. The upper threshold concretizes the separation when household start to change perception on PV because it understands PV fairly well on the specific knowledge.

For autarky and environmental knowledge, value below the upper threshold means that household totally believes that purchasing PV system can provide power-independency from power grid or can help climate change significantly. With the value higher than upper threshold, household has more understanding on the complexity of autarky and environment effect and becomes somewhat more sceptical. For the other knowledges, barring social knowledge, knowledge value being below the upper threshold means that household has negative perception on PV (e.g. high investment cost or difficult and costly O&M), while being above the upper threshold means that household might has become more positive as it understands more on PV. A detail calculation to determine payback period and investment cost (which uses varying house orientation) is only done by installer when it is in a negotiation (section 4.4.4). Other than negotiation, the value obtained on investment cost and payback period with the knowledge value higher than the upper threshold are the investment cost and payback period of the standard size needed to have zero net power, that is 12 PV modules.

The relationship used to determine interest requires certain weight and the perceived attributes of the household's knowledges. This will further be discussed in section 5.2.2 and Appendix C.

Liking is mainly formed from the household's uncertainty. This however increases when potential adopter is dealing with a PV installer that does not provide help with administration of the PV system.

4.4.2 Socialization

During a socialization between adopter and potential adopter, transfer of information on PV occurs for certain from adopter to potential adopter. Potential adopter knowledges increases if the potential adopter's specific knowledge is considerably lower than the adopter's specific knowledge. Potential adopter will not ask for information from someone who is known to has less knowledge than the potential adopter itself.

When adopter or rejecter socialize with someone else, it may influence the partner. Social knowledge is always affected when the influence happens, either positively (by adopter) or negatively (by rejecter). If the adopter has never influenced the other household before, the other household remembers the adopter as someone to refer to in the future when trying find more information on PV. When positive influence happens, the adopter's partner's knowledge may increase if it has less knowledge on that aspect than the adopter. Furthermore, the uncertainty of the influenced household decreases due to a 'confirmation' effect of the adopter. Similarly, negatively influencing socialization increases the uncertainty, even though the household does not gain any knowledge.

4.4.3 Consultation

When potential adopter consults an installer for information, it asks for information in two steps. After the first step, potential adopter assess its interest before deciding on whether to purchase, or to ask for more information. The second step have lower knowledge increase for the potential adopter. If the interest exceeds liking after the two steps, potential adopter and installer will negotiate on the final deal.

4.4.4 Negotiation and Proposal

When potential adopter negotiates with a small installer, the installer ask for the household's annual power consumption and creates a proposal for a PV size which is enough to cover all of the household's annual consumption (zero net power). The household assesses its interest and liking according to the cost and payback period proposed by the installer, and determine its budget to install PV system based on its interest, liking, and income. If the investment cost is considerably different than the household's budget, installer proposes another size according to the budget. However, PV installer will not install the system if the number of module is lower than 4, thus this becomes the minimum price to afford PV system.

Large installer does a calculation for a fully covered rooftop and proposes the corresponding size as its first proposal. Then, potential adopter assesses its interest and available budget based on the proposal. Again, if the investment cost is considerably different than the budget, another proposal according to the budget is created. However, potential adopter which has had negotiation before (means already knows that maximum coverage does not lead to maximum profit), directly asks for the size that results on zero net power instead of maximum coverage.

The detail calculation of the payback period requires deeper analysis on power production. Installer observes the orientation and tilt angle of its client's roof, and based on that, the amount of irradiance received by the surface every hour in a day, averaged for each month in a year, is determined. Based on this, PV and BOS efficiency, as well as the total surface area covered, the power production for a year is obtained. Then, depending on the year, the total annual saving is determined from power production and retail electricity price. After considering the O&M cost, payback period is estimated.

4.5 Environment

There are several other factors that influence agents in doing their activities. Some of these factors are promotion through mass media (including internet), changes in PV modules' price and retail electricity price, possible changes of PV technology (the occurrence of BIPV or thin film solar cell to the market), the appearance of energy storage, and changes on pricing scheme. Promotion through mass media, which is also influenced by government, is considered as environment because government is not included as an agent. Not all factors are included in the model due to time limitation and because it is not the focus of this thesis. The included factors are mass media promotion, changes in PV module's price, and electricity price.

Every year, each household's autarky knowledge and environmental knowledge increase due to promotion done through mass media either by government or local solar communities. It is also assumed that discoverability of installers on internet is determined through the adoption percentage emerged from the system for each specific year.

PV module price is assumed to decrease by 97% annually following the estimation done by Mayer et al. (2015). Payback period calculaton has different percentage for the period before 2008, where only the delivery tariff was reimbursed with net metering. Furthermore, the maximum power limit that can be reimbursed is changed in 2011 into the household's power consumption after previously being a constant value of 5000 kWh.

4.6 Overview of the Model

PV adoption happens as the result of information diffusion through communication channels, becomes an emergent pattern. This, however, leads to a new problem. The problem is owned by both power utility and the national government, and the problem is on the increase of residential PV system installation which leads to decrease of power demand, and eventually power utilities' revenue.

Important actors in the system are households, PV installers, and local energy initiatives. Local energy initiatives, together with government, does promote renewable energy technology, including PV, through mass media. Households goes through an innovation-decision process to adopt PV, passing through different stages: non adopter, potential adopter, adopter, early rejecter, and knowledgeable rejecter. PV installer helps to spread knowledge when household want to get more knowledge on PV, and help in deciding the suitable PV size to be installed.

There are 2 objects that has influence on the system, that is the PV system and houses building. Naturally, PV system requires certain amount of spending to be installed. House's roof orientation, surface area, and tilt angle influences power production of the installed PV, further affects the payback period for the installed PV.

In deciding to adopt or to reject, a household makes decision based on its interest and liking. Its interest is determined from the knowledge that the household has: these knowledges are autarky, environmental, O&M, social, investment cost, and payback period. These knowledge can comes from mass media, through socialization between households, from the internet, or directly from installer.

There are several external variables that influences the social system, such as electricity price and PV modules price. PV modules price obviously affects the investment cost of the system, while electricity price influence the system's payback period.

Figure 4.1 shows the model structure of the system, especially the role of the actors.

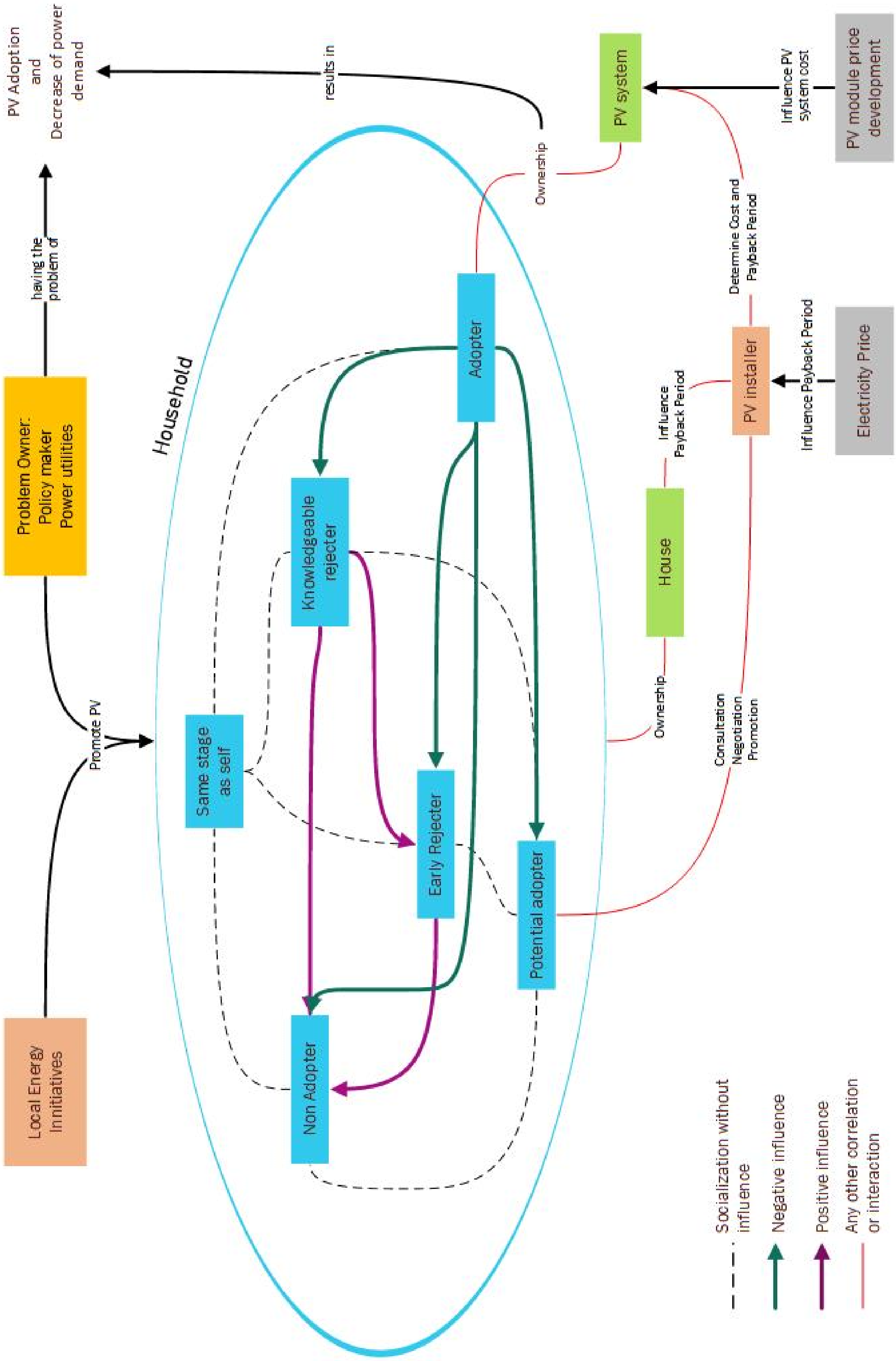


Figure 4.1: Conceptualized Structure of the Actors' Role in the System

Chapter 5

Model Implementation

After the model has been conceptualized, it must be transformed into a structure that is understandable for GAMA, the software used in this study. This chapter elaborates the formalization of the model concept until the implementation to the software, starting by the data structure used in the model (section 5.1), then followed by the general narrative/storyline of the model in the data structure form (section 5.2). Section 5.3 explains the implementation of the model into the software as a code. When the model and the code has been put into the software, it still needs to be verified to make sure that the built model is correct (section 5.4). This chapter, together with chapter 4, provide the answer to the second sub-research question.

5.1 Data Structure

The model concept must be translated into data structures that can be understood by GAMA. The complete list of states of all agents, objects, and the world (or global, as it is referred to in GAMA) is available in Appendix B. There are 6 types of data structures implemented: string (characters), float (decimal numbers), integer (whole numbers), agent (including object), list (container of several data, in any type of structure), and matrix (container for numbers which can be used for calculation). Majority of the states are structured as float, in the value between 0 and 1. In this section, some of the non-obvious and important states are elaborated according to the agents, while the complete list of the states is available in Appendix B. Starting from here, the states are written in *italic* font.

5.1.1 Households

General States
Household's *stage* is put as string, which might be filled as "Non Adopter", "Early Re", "Potential Ad", "Knowled Re", and "Adopter" to indicates the household's category towards adopting PV; 're', 'knowled', and 'ad' are shortening of rejecter, knowledgeable, and adopter respectively. *AnnualPowerConsumption* and *Income* are structured as integer in the unit of kWh and Euro respectively.

SocializingState is structured as string with possible value of "not socializing", "socializing", and "looking for partner/adopter". Household also has *AdopterConnection*, which is a list of the household's *Connection* that it specifically knows to have become an adopter, and *Blacklist*, that is a list of *Connection* that the initial household knows to have less knowledge than itself. When looking for information, household does not ask member of Blacklist again.

Knowledges and Perceived Values
All knowledges are structured as float on a scale from 0.00 to 1.00. This scale measures the level of knowledge owned by the household; 0.00 represents no knowledge at all, while 1.00 represents a knowledge level where someone knows a lot on the subject, almost reaching the same level as an 'knowledgeable person' on the field. For instance, for *AutarkyKnowl* (knowl as shortening of knowledge), the value of 1.00 shows that the agent can explain that PV might not always be able to create independent self-sufficient power system due to solar fluctuation and there are more

complexities with energy storage present. It is the assumption that all households can acquire this knowledge independent of its intelligence.

For *SocialPressure*, the higher the value shows that the household is aware that there are people around itself that has adopt PV. During the action socialization, *SocializationPress*, which is also measured in float between 0.00 and 1.00, increases or decreases for certain value. *SocializationPress* was supposed to be combined with the percentage of *Neighbors* that has become adopter, in order to measure the value of *SocialPressure*, thus including both influence from its *Neighbors* and *Connection*. This is modified in such a way that *Neighbors* impact is not included due to software bugs which will be discussed further in section 5.4. In this modified version, partically *SocialPressuse* is equal to *SocializationPress* and only incorporates socialization impact.

In calculating interest, the influencing value depends on the knowledge level, as well as *LowerThreshold* and *UpperThreshold*, where both are global state structured as float. For knowledges below the *LowerThreshold* all values are structured as string filled with "nothing", represents the absence of perception by household on PV based from that aspect. Below *UpperThreshold*, values for autarky and environmental knowledge are seen as positive, while values for the other knowledges are seen as negative. These positive and negative value will be discussed further in section 5.1.5. The values for knowledge level above *UpperThreshold* vary considerably between knowledges. An exception occurs for *SocialPressure*, where the perceived value is always the same with its contained knowledge value. All perceived values are structured as float in the range of 0.0 and 10.0 and are collected in *PerceivedValues* as a list to contain the values. More on this matter will be discussed in section 5.2.2 and in Appendix C.

Motivation, Liking, and Interest
Motivation is structured as integer with the value varies between 0 until 3; 0 represents never has interest, while 1, 2, and 3 represents instrumental, social, and environmental motivation respectively. *FutureUncertainty* is structured as float between 0.00 and 1.00, as well as *UncertaintyLimit*, which determines that non adopter becomes early rejecter or not. *InstruLimit*, *SocialLimit*, and *EnviroLimit* are the threshold limit for each knowledge to obtain the corresponding *Motivation*, thus are structured as float. *Liking* is a function of *FutureUncertainty*, thus it is structured as float in the range of 0.0 and 10.0, similar to *Interest*.

Potential Adopter States
ResearchState shows what the potential adopter is doing at that moment. It is structured as integer where: 1 represents asking connections, 2 represents looking for an installer contact on internet, 3 represents consultation with installer, and 4 represents negotiation on a deal. *Reason* shows the reason of a certain household to have rejected PV previously even after becoming a potential adopter. The structure is string with "Investment Cost" means the reason is due to the high investment cost and "Others" means any other type of reasons. *attempt* is structured as string of "1st", "2nd", or "multiple" to shows the number of attempt for household to find knowledge on or to purchase PV (become potential adopter).

As a Rejecter
RejecterConnectionCount is structured as integer and shows how many times it has been influenced by an adopter since becoming a rejecter.

5.1.2 PV Installer

PV installer has a state named as *Scale* and it shows the size of the company. It is a string with the possibility to be filled by "large" or "small". *WorkHourCost*, structured in float, shows the soft cost of installing a system in Euro/Wp. *AdministrationService* (integer) represents whether the installer help household to register its PV on PIR (value of 1) or not (value of 0).

5.1.3 PV System

PV system has *Price* refers to the actual price (Euro/Wp) in float. Then, *WattPeak*, *SurfaceArea*, and *PVEfficiency* are all structured as float representing Watt peak, surface area, and efficiency of the PV module (per module). *PowerProduction* of PV system is structured as a 1x288 matrix, representing the system's hourly power production in Wh for a whole year, averaged for each month. A system must has an *Owner*, that is either an installer or a household.

5.1.4 People

As the *Owner* of a system can consists of different agent, both PV installer and household are categorized as one type of 'parent agent', people. This agent has 4 states. *OwnedPV* and *ProductSold* refer to PV system agent for household and installer, respectively. *Client* shows the household that is being in contact with an installer and *ProposedTotalArea* is the area proposed by an installer when a household has intention to purchase a system. All of these states have to be accessed by PV system through its *Owner*, which means these states have to be accessible for both agents.

5.1.5 Global

The number of global parameters that are incorporated is very high, partially because almost all numeric value that is inputted to any agents are extracted back to global to give the overview of any parameter used in the model. This includes, among others, *BOSEfficiency*, *OMRatio*, *MaxGCR*, and *PVPrice*. These are parameters used calculating PV system costs, i.e. efficiency of BOS, ratio of O&M cost to the investment cost, maximum ground.

UpperThreshold and *LowerThreshold* are the threshold knowledge on when a household changes perception on PV; they also acts as the knowledge level of when household become interested on PV and have motivation to find more information. *AuxiliaryWeight*, *SocialWeight*, and *MainWeight* are the weight given to the household's knowledges when assessing its interest. *InitialFutureUncertainty* acts as the initial tendency for household to reject change, in this case PV system. All of them are structured as float. Respectively, *TimeLimit* and *MakeDecisionTimeLimit* are the time limit for being a potential adopter and the time limit to wait until it finally decide on whether to look for any installer or to reject PV. These two states are structured as integer. All of these states are representation of internal states of households which the 'value' in reality is rather arbitraty, but at the same time is difficult to be changed.

To calculate the exposure level of installer, *PromotionFactor*, PV adoption rate, and *SmallLargePromotionRatio* are used. *PromotionFactor* is, in a way, a measure of installer's traceability and activeness in promotion.

Majority of global states that acts as environment for the agents are structured as float. *AverageIncome* represents the average income level in the Netherlands. *PanelPriceDecrease* shows the annual decrease of PV panel. *BudgetIncomefraction* is a representation of how much of a household's income are allocated for spending; it is an economic states. *UnintenKnowlIncrease* and *ResearchKnowlIncrease* are the maximum level of knowledge increase occurs unintentionally (for non adopter and early rejecter) or intentionally when researching internet (for potential adopter). These two states represents the available information and degree of knowledge gain by household.

Both *UnintenKnowlIncrease* and *ResearchKnowlIncrease* can be further differentiated according to each communication channel into *UnintenKnowlIncreaseConnect*, *UnintenKnowlIncreaseMedia*, *ResearchKnowlIncreaseSelf*, *ResearchKnowlIncreaseInstaller*, and *ResearchKnowlIncreaseConnection*. In the calibration process (section 6.3), *UnintenKnowlIncrease* states are combined together as 1 parameter.

5.2 Model Narrative

The general narrative of the model is elaborated in the following subsections. This narrative is also summarized in a pseudo-code format, which is available in Appendix D. From now on, the actions are written in **bold** font. Furthermore, some new actions are created either due to the software mechanism (**main_activities**) or code duplication (**ask_new_proposal**, **rejecter_become_potential_ad**, and **become_rejecter**).

5.2.1 Annual Changes

Every year, *price* of PV module decreases. Following this, PV installers update their tariff (*PriceList*) for various size of PV system and their *MinimumPrice* of PV system to be installed in **calculate_installing_cost** action. Then, the probability for households to find an installer through internet (*FindLargeInstaller* and *FindSmallInstaller*) is updated according to adoption rate (equation 5.1) with the maximum value of 100. Furthermore, adopter has a chance to lose its *Contact* by certain probability (*ProbLosingContact*). Other stages of household gain some *AutarkyKnowl*, *EnvironmentalKnowl*, *InvCostKnowl*, and *PayPeriodKnowl* for the maximum value of *UnintenKnowlIncreaseMedia*.

$$\begin{aligned} FindLargeInstaller &= AdoptionRate \times PromotionFactor \\ FindSmallInstaller &= SmallLargePromotionRatio \times FindLargeInstaller \end{aligned} \tag{5.1}$$

5.2.2 Weekly Changes: Households

Socialization Decision and Main Activities
At the beginning of the week each household, except for potential adopter, assesses whether they want to spend their time by having a **socialization** with one of its connection or not. At the same time, potential adopters that do not want to ask an installer (*ResearchState* = 1) try to look for an adopter from one of its *AdopterConnection*. Each household that plans to do socialization, changes its *SocializingState* into "looking for partner/adopter". Only after everybody have finished this step, household starts to actively do their **main_activities**.

For households who intents to do **socialization**, they either do the action **looking_for_partner** (non potential adopter) or **looking_for_adopter** (potential adopter) at the 'same' time. Potential adopter who does not intent to socialize, either does the action **finding_installer_on_internet** (when ResearchState = 2), **consulting_installer** (when ResearchState = 3), or action **evaluating_interest_liking** after doing **internet_research** (when ResearchState = 1).

For households who plan to do **socialization** and do find a socialization *Partner* (thus having *SocializingState* = "socializing"), they will socialize together. Potential adopter who plans to socialize but do not find a partner will do **internet_research** by its own. Every time a potential adopter has just finished socializing or doing internet research, it updates its *Interest* and *Liking* by doing **assess_interest**, and **evaluating_interest_liking** to decide on what to do next if its *TimeAsPotentialAd* is already longer than *MakeDecisionTimeLimit*.

For potential adopter who was doing **consulting_installer**, it has 2 sessions in which each session allows it to obtain some information on all knowledges over PV. The first session gives more information than the second session with the first session increases knowledge as much as *ResearchKnowlIncreaseInstaller*, and the second session is for any random value below the first one. After each session, it does **assess_interest**. If after the two sessions, potential adopter's *Interest* still does not exceed *Liking*, it does **become_rejecter**.

Potential adopter who does **finding_installer_on_internet**, might not find any installer, depending on *FindLargeInstaller* and *FindSmallInstaller*. After this, potential adopter compares its *Interest* and *Liking* to either do **negotiation_deal** or **become_rejecter**.

After finishing all **main_activities**, all households always do **behavior**.

Finding a Socialization Partner
Households who do **looking_for_partner** (non potential adopter), ask any of its *Connection* to socialize. If the other household also has *SocializingState* = "looking for partner/adopter", they will each changes their *SocializingState* into "socializing" and become each other's *Partner*. Each household has 3 attempts to ask one of its *Connection*. After 3 attempts without success, household changes its *SocializingState* into "not socializing".

For potential adopter who is looking for a *Partner*, it starts by assess its *AdopterConnection*. Any household who is part of *Blacklist* are ignored for **socialization**. Potential adopter always starts by asking the most recent adopter that influences itself positively. Similar to the other categories of household, potential adopter also has 3 chance to find a *Partner*. Those who do not find a *Partner*, do **internet_research**. During **internet_research**, each knowledge might increase for any value below *ResearchKnowlIncreaseSelf*.

Socialization
When potential adopter socializes with an adopter to ask for information, it may either gain some knowledge or add the adopter into its *Blacklist* if apparently all of the adopter's knowledges are lower than the potential adopter's knowledges. For each knowledge, potential adopter will either gain knowledge as much as *ResearchKnowlIncrease* or the knowledge become the same value as the adopter's, depending on the difference for that knowledge between the 2 households.

During **socialization** between non adopter or early rejecter with any rejecter, there is some probability as much as *InfluencingProb* that negative influence may happen. When negative influence happens, the influenced experiences a decrease of *SocializationPress* by *SocialFactorChange* and an increase of *FutureUncertainty* by *UncertaintyChange*.

For the **socialization** between an adopter with non adopter, early rejecter, or knowledgeable rejecter, positive influence may happen. If the household who is influenced is either non adopter or early rejecter, its *AutarkyKnowl*, *EnvironmentalKnowl*, *PayPeriodKnowl* and *InvCostKnowl* increases if the adopter's knowledge is higher than its *Partner*'s knowledge. For any rejecter, its *RejecterConnectionCount* increases by 1; it will become potential adopter again after it reaches the value of *ConnectionLimit*. Moreover, their *SocializationPress* also increases and its *FutureUncertainty* decreases if the adopter is not in *AdopterConnection* yet (never been influenced by this adopter).

Assessing Interest and Liking
The value of *Interest* is determined by weight and perceived value, which is further determined by knowledge level. Each knowledge which has the knowledge level higher than *LowerThreshold*, receives a weight and a perceived value. Payback period and investment cost knowledge have the largest weight (*MainWeight*), followed by social knowledge with *SocialWeight*, and the rest with *AuxiliaryWeight*. For knowledge that does not have weight or perceived value, it is ignored in the assessment. Each weight is further normalized by the total available weight to make it into the fraction of 1.

When the knowledge level of investment cost and payback period are higher than *UpperThreshold*, their perceived value are determined by asking an *InstallerContact* to **creating_proposed_system** if **assess_interest** is done as part of **negotiating_deal** (*ResearchState* = 4). If **assess_interest** is not called from those actions, the perceived values will either be based on the standard size of PV that leads to 'zero net power' (when knowledge $\geq$ *UpperThreshold*) or *NegativeViewValue* (when knowledge $<$ *UpperThreshold*). Moreover, if the potential adopter has a house with *Orientation* to the North (> 270 or < 90), the payback period value will be 0 when *Vendor* does not do the calculation.

Liking is found by multiplying *FutureUncertainty* by 10. It is further added by *AdministrationEffort* if potential adopter is either **consulting_installer** or **negotiating_deal** with an installer that does not give *AdministrationService*$(= 0)$. More elaboration on the combination of the knowledge level and perceived value is available in Appendix C

Evaluating Interest and Liking, and Negotiation
This action mainly occurs as the result that potential adopter has made up a certain perspective towards PV and willing to take further action, after doing **internet_research**, **socialization**, or even after doing nothing.

If any of the potential adopter's *Interest* does not exceed the *ContactingThreshold* of *Liking*, potential adopter will do *become_rejecter* if it has *TimeAsPotentialAd* longer than *MakeDecisionTimeLimit*. Besides that, potential adopter tries to find an installer contact in order to **consulting_installer** (when *Interest* exceeds *ContactingThreshold*) or **negotiating_deal** (interest exceeds

Liking), changing *ResearchState* into 3 and 4 respectively. These potential adopter ask the maximum of 3 of its *AdopterConnection* for *InstallerContact*. If potential adopter does not have any *AdopterConnection*,or if it does not find any *InstallerContact* even after asking around, it will do **finding_installer_on_internet** and its *ResearchState* becomes 2.

When **negotiation_deal** is called from **evaluating_interest_liking**, the action is directly executed at the same cycle. It is different with **finding_installer_on_internet** and **consulting_installer** which is done at the next cycle.

In *negotiating_deal*, potential adopter is explained about PV such that its *PayPeriodKnowl* and *InvCostKnowl* becomes equal to *UpperThreshold* (understands well). The installer do **creating_proposed_system** to determine PV *InvestmentCost* and *PaybackPeriod*, which is later used for potential adopter to **assess_interest**. The system size proposed by a "large" *Scale* installer, or if the potential adopter has never done *negotiating_deal* before, is the maximum amount possible to be installed. Besides that, it is going to be the size required for potential adopter to have zero net power, except if the limit of roof area to be used has been reached.

The household determine its budget based on its *Income*, *Interest*, *Liking*, and *BudgetIncomeFraction*, as shown in equation 5.2. When the budget is higher than the *InstallerContact MinimumPrice*, a PV system agent is created as the *OwnedPV* of the household. When the *AvailableBudget* does not exceed it, potential adopter do **become_rejecter**. If the initial proposal of the *InvestmentCost* is too high or too low (i.e. when the difference is more than the cost of 1 module, the size is adjusted according to the *AvailableBudget*. When it is finished, potential adopter becomes an adopter.

$$Budget = Income \times BudgetIncomeFraction \times \frac{Interest}{Liking} \tag{5.2}$$

Common Behavior
Firstly, all households update their *SocialPressure* every cycle. Non adopter and early rejecter always assess their *SocialPressure*, *AutarkyKnowl*, and *EnvironmentalKnowl* on whether any one of them has exceeded *InstruLimit*, *SocialLimit*, or *EnviroLimit*. Once *Motivation* occurs, non adopter becomes a potential adopter. Early rejecter, however, only becomes potential adopter when it also already has *ConnectionRemains* as *ConnectionLimit*. This potential adopter has the *ResearchState* of 1 and *attempt* "1st". Non adopter might also become an early rejecter if its *FutureUncertainty* exceeds *UncertaintyLimit*.

Potential adopter increases its *TimeAsPotentialAd* by 1 and do **become_rejecter** when it reaches *TimeLimit*. Furthermore, knowledgeable rejecter also becomes a potential adopter when its *ConnectionRemains* is already equal to 3. The *attempt* becomes either "2nd" or "multiple".

5.2.3 Called Action: PV Installer

The action **creating_proposed_system** is done by PV installer only when there is a demand from household during **negotiating_deal**.

In the action, installer can propose different *ProposedSize* and *InvestmentCost* depending on the negotiation, either to suits its *client AvailableBudget* or *AnnualPowerConsumption*, or even the maximum *ObservedHouse RooftopArea*. Once the *ProposedSize* is determined, another action done by the *ProductSold* PV system is executed, **calculate_power_production**.

This action mainly consists of technical calculation and decision. For instance, to decide on the amount of PV modules for each rooftop slopes depending on different *RooftopType* and *Orientation*, or to calculate the power produced by a system based on the received *IrradianceX*, *BOSEfficiency*, *PVEfficiency*, and some other variables. The complete mechanism is available in Appendix F.

After having the *AnnualPowerGenerated*, *AnnualSaving* for the *Client* can simply be calculated by multiplying the reimbursed power with *RetailElectricityPrice*, and another fraction factor to represent percentage of energy tax and SDE from the full tariff (specifically for net metering policy before 2008). The reimbursed power is limited to 5000 kWh until 2011, and is set to be limited to the annual power consumption of the household after 2011.

$$AnnualSaving = TotalAnnualEnergyProduction \times RetailElectricityPrice \quad (5.3)$$

5.3 Software Implementation

The model is programmed in GAMA using an actual neighborhood GIS map which is available in ZEnMo database. The selection is based on the income level of the households, available of valid data for calibration purpose (with the help of brief googlemaps observation), and building type (appartment, *rijteshuis*, or ground bounded house). There are 9 GIS database available in ZEnMo, however, many of them mainly consists of areas with appartments and low income level, where PV adoption does not commonly occurs (yet) due to the cost and roof unavailability. Based on these factors, the area of Bosweide in the Hague is chosen as the most suitable area with its high income level, available database, and ground bounded houses. Another interesting candidate is the area of (part of) Alteveer-Cranevelt and Schuytgraaf, both in Arnhem, but they lack of in valid database.

In implementing the model to the software, an initial condition of the world is created. Houses' *RooftopType*, *Orientation*, and *RooftopTilt* are set, 4 PV installers are created with different *Scale* and *AdministrationService*, and household are created as many as *NumberOfResidents*. In ZEnMo model, agent resident is used as the default agent to represent household, thus in the model code, it is written as resident while in actuallity it should be household.

Households are assigned certain *Income*, and, based on it, as well as *AverageAnnualPowerConsumption*, their *AnnualPowerConsumption* is determined. Any motivation limit is determined randomly from either *LowerThreshold* and *UpperThreshold*, for non-adopter while *UncertaintyLimit* determined as *UpperThreshold* and *MidThreshold* for all household. Households that already have *Motivation*, have its knowledge determined according to the *Motivation*.

An important aspect of this initialization step is the determination of the social network among the households. The household's *Connection* is determined in a way to represent the scale-free network. The code to recreate the network is built according to the Preferential Attachment model available in NetLogo library. A random household is chosen as the first one to have a connection.

5.4 Model Verification

The verification is done mainly through unit testing, i.e. a technique to test a small part of the code. A predefined input is executed by the code, and the output is compared to the expected output. In this verification process, unit testing is done step by step from the beginning of the codes, starting by the world creation, to the initial agents creation and assigned states, then to the reflexes and actions in each cycle (tick). In total there are around 80 different tests with about 50 bugs found.

An important finding from unit testing is that apparently some function in GAMA do not work correctly. These are functions related to associating nearby agents in certain distance from the caller agent. The command was supposed to be used to determine the *Neighbors* of the households. Some commands that can be used for this are **at_distance** and **agents_at_distance**. Even when the distance of 0 was put in, there are still some agents found, excluding the caller agent (see Figure 5.1). Because of this, the state of *Neighbors* is omitted from the model, and any rules and interactions related with it are adjusted. An important effect of this persisting bug is the absence of neighbors influence to expose PV-system to non-adopter.

GAMA also has certain issue in the function ***sum*** to calculate the sum of a certain matrix or list. This is found in the calculation of payback period. The outcome of the sum results on a value smaller than the actual result smaller by a factor of about 10. Thus, in the model, the equation is multiplied 10 to make up the difference. There are still some difference than the actual value by around 0.1 decimals (only for one data points), but it is assumed that all of the difference is negligible. Figure 5.2 shows how the sum result is different between a calculation in GAMA and in Excel.

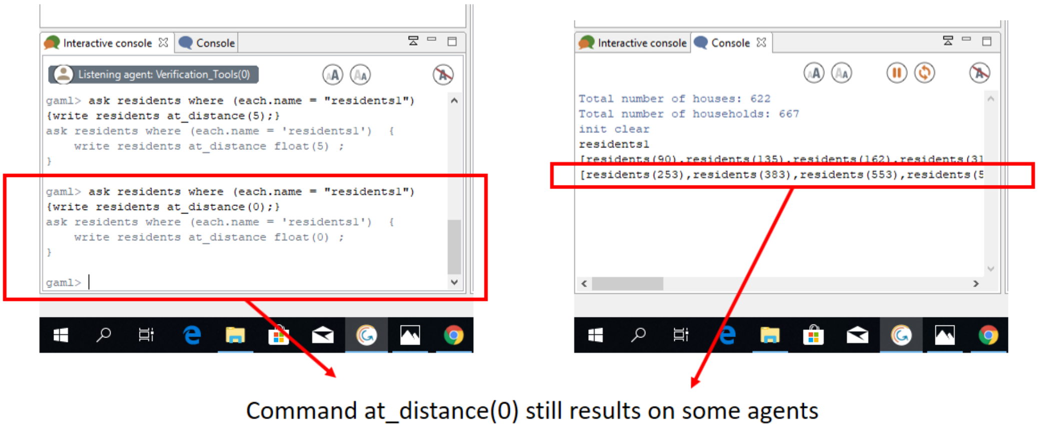


Figure 5.1: Bug in the Function **at_distance** within GAMA

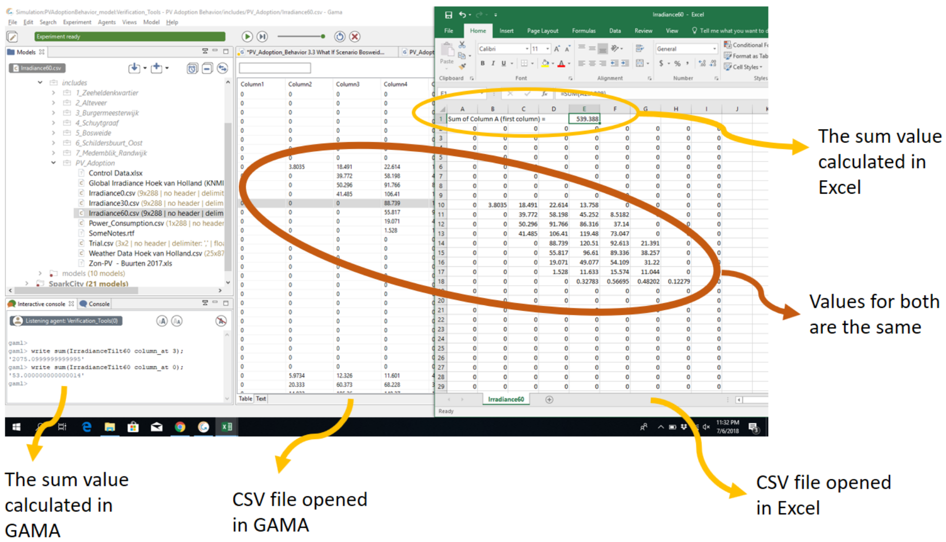


Figure 5.2: Bug in the Function **sum** within GAMA

Appendix E shows the complete tests done and the related bugs found during unit testing.

Chapter 6

Exploration and Experimentation

In this chapter, the model parameters are calibrated and the experiments are designed in order to have proper data which can give beneficial insight on the main problem. The aim of the experimentation is explained in the first section. The second section elaborates the model parameters, and possible parameter space, and their possible influence to the outcome of the experiment. Section 6.3 describes on how calibration of some parameters are done, such that further exploration in the experimentation with the parameters that are of main interest for the problem can provide comprehensible result. The experimentation itself is described in section 6.4.

6.1 Initial Hypothesis

The main hypothesis of this model is to 'replicate' real world behavior of residential PV adoption. For this type of hypothesis, the hypothesis is falsified when the regularity is not replicated (van Dam et al., 2013). For this model, it is when there is no PV adoption occurs. The main insight that can be understood from the model is on the influence of different communication channels to the adoption curve of residential PV through households' decision making at different stages of innovation-decision process.

Based on the hypothesis, *NumberOfInstalledPV* and *AdoptionPercentageProgress* are important parameters. Furthermore, there are other output parameters that may give insight, but there is no global states that represent them. Thus, new global states are created to represent these parameters. Also, it is essential to record the progress of the output parameters over time. These parameters are:

- *InstalledPVProgress*, i.e. cumulative number of adopted PV,
- *PaybackPeriodProgress*, i.e. annual average of installed payback period,
- *ProgressRejecterEarlyCount*, i.e. annual number of early rejecter,
- *ProgressRejecter1Count*, i.e. annual number of knowledgeable rejecter with 1st attempt,
- *ProgressRejecter2Count*, i.e. annual number of knowledgeable rejecter with 2nd attempt,
- *ProgressRejecterCostCount*, i.e. annual number of knowledgeable rejecter because of budget,
- *ProgressInterestLiking*, i.e. average interest-liking when potential adopter becomes rejecter not because of budget issue,
- *ProgressRejecterPP*, i.e. average payback period of rejecter,
- *RejecterUncertainty*, i.e. average uncertainty of knowledgeable rejecter which is not because of budget issue.

6.2 Parameter Space

The number of parameters in this model is humongous, mainly due to the level of detail necessary to comply with GIS map (demography aspect) and the ZEnMo project. All of the parameters can be differentiated into several categories: demography-GIS parameters, PV system parameters, psychological parameters, communication channels parameters, and economic-related parameter.

Demography-GIS parameters includes percentages of houses with certain orientation, tilt, and etc, as well as households' income. PV-system parameters includes various technical parameters of PV system, such as efficiency, kWp, surface area, and etc.. Economic-related parameters includes various prices of electricity and PV system (initial price and annual decrease rate), as well as *BudgetIncomeFraction*. The initial value of these parameters, except for *BudgetIncomeFraction*, either comes from a certain reference value, or through guestimate by the modeler based on his understanding of the concept, which comes mainly from literature. These parameters are also not included in the parameter space to be observed.

The other parameters form the parameter space to be observed in this problem because they may influence communication and psychological decision making process in the system. Moreover, a new parameter is needed before the calibration process starts, i.e. *StartYear*. The total number of parameters forming the parameter space reaches 25. Appendix B shows these parameters together with their parameter space.

6.3 Calibration

Since the experimentation requires such replication of residential PV adoption, it is necessary to find a set of parameter values which results on a reasonably similar adoption pattern as the real world. It is also to help with the large parameter space condition to reduce unwanted extreme outcome. The output data of *InstalledPVProgress* are compared to the available database for the area obtained from klimaatmonitor.nl. The database provides data for the year 2008 until 2015.

Due to the high number of parameter space available, several parameters which are presumed to have the most influence and the most sensitive to the outcome are chosen by the modeler. After some run of several combinations, the selected parameters are *UnintenKnowlIncrease* (parameter space: 0.02-0.07 with 0.01 jump) and *InitialFutureUncertainty* (parameter space: 0.25-0.45 with 0.05 jump), together with *StartYear* (parameter space: 2001-2005 with 1 jump). *UnintenKnowlIncrease* is set as a single parameter to simplify the calibration process, and also because it is enough to calibrate the parameters' value, as shown in Figure 6.1.

The historical data (black line) has a different starting value compared to the outcome of the model. This difference is understandable when considering the different categories of individual according to Roger's DOI. The obtained empirical knowledge on decision making to build the mode is most probably obtained from the dominant demography out of the households, thus the sample mainly represents how early majority and late majority (which in DOI form the 70% of the consumer) act. On the other hand, the 'first adopters' in the historical data, most probably are innovators or early adopters.

Because of the innovators and early adopters, selection for the suitable parameter values should look at the slope of the curve rather than selecting it based on the best fitness (e.g. using root-mean square). Based from Figure 6.1, 2003, 0.07, and 0.35 are chosen as the values for *StartYear*, *UnintenKnowlIncrease*, and *InitialFutureUncertainty* respectively. Further discussion on the influence of the parameters, except *StartYear*, to the adoption curve is available in the next chapter.

6.4 Experimentation

6.4.1 Experiment Time

The actual experimentation of the model is done in the time frame of 2004 until 2030. The time duration is limited to 25-30 years following the standard lifetime of a PV system, thus preventing the occurence of PV system replacement.

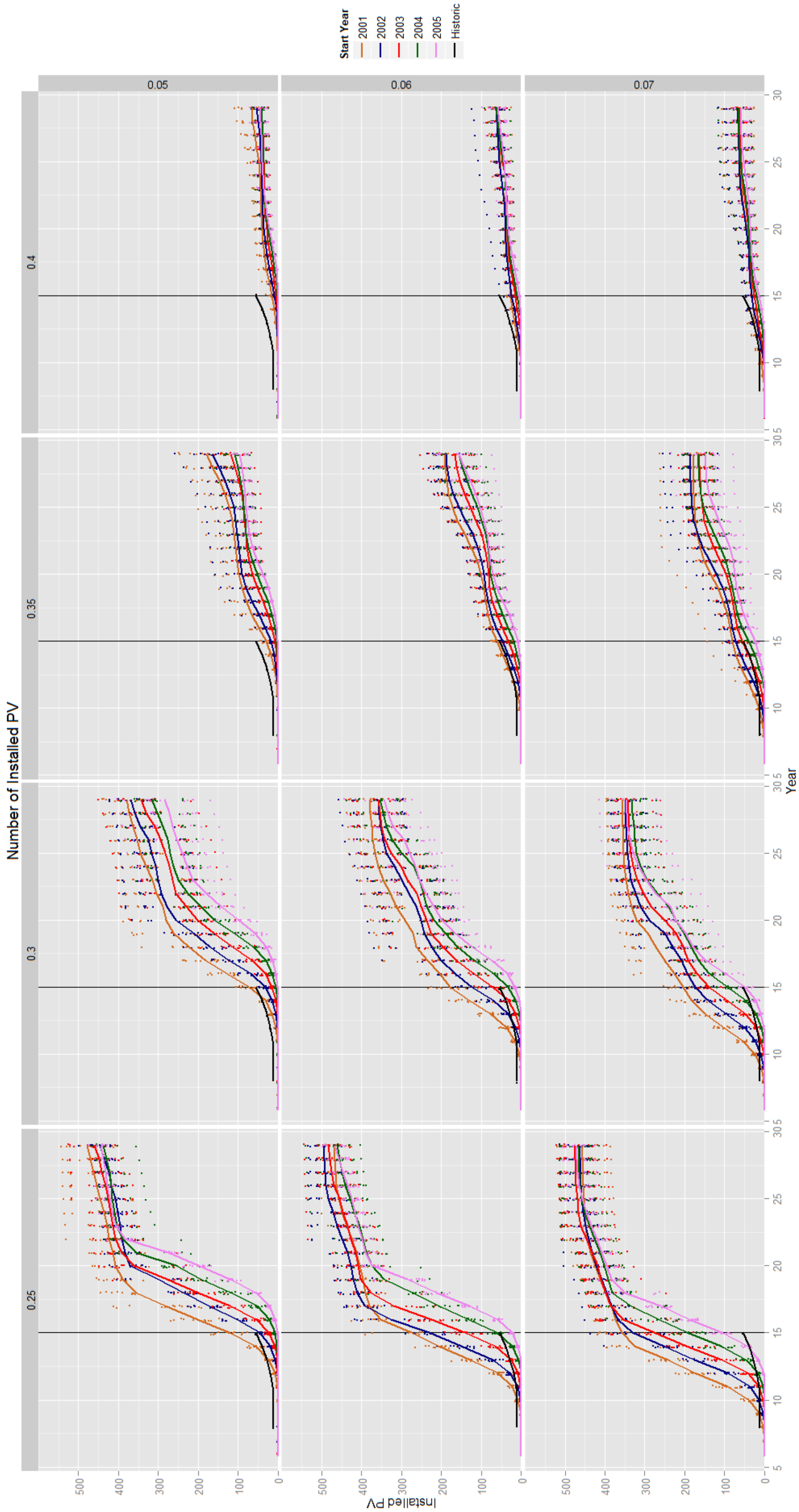


Figure 6.1: Calibration with Different Unintentional Knowledge (0.25-0.40), Initial Uncertainty (0.05-0.07), and Start Year (2001-05)

There are several changes in the model that occur at certain years. Firstly, adopter started to receive full reimburesement for its power production in the year of 2008, instead of around 25% of the whole electricity price. Then, in 2011, the maximum power limit that can be reimbursed of 5000 kWh that is implemented before that year is lifted. Since that year, the power limit depends on the amount of *AnnualPowerConsumption* of each household. In the year of 2015, certain parameters value change quite drastically. These parameters are annual PV *ModulePriceDecrease* and PV installer's soft cost tariff (*SoftCostLargeScale* and *SoftCostSmallScale*); Appendix C provides the value for these parameters.

6.4.2 Experimental Design

During experimentation, most of the communication channel and psychological parameters are explored, as well as *BudgetIncomeFraction*, but excluding *InitialFutureUncertainty* that has been explored during calibration. These 22 parameters are the parameters that the modeller has a doubt that it will not influence PV output parameters. Considering the high number of parameters, a semi-full factorial method is selected as the experiment method.

In a full factorial experimental design, all points in a multidimensional parameter space is observed one-by-one. This method requires extremely high computation process with extreme number of experiments that are required to be done (van Dam et al., 2013). As the amount of time required to execute one run is about 6 seconds, even a complete full factorial analysis with 10 parameters where each has about 5 parameter spaces requires about 2 years of computation with a healthy Intel core i7 laptop.

Another method that was considered to be used is Latin Hypercube Sampling (LHS). This method utilized certain algorithm to generate evenly distributed sample points in the multidimensional parameter space for each variables' parameter space (van Dam et al., 2013). This method, however, is abandoned due 2 reasons: (1) the modeller's lack of knowledge on analysing such stochastic data generated in a LHS set up and available time to learn it, and (2) that GAMA does not have a feature to automate such experiment with varying parameter values as in LHS. GAMA only can only do either full factorial set of experiments or experiment designs with certain optimizing property, such has hill-climbing or genetic algorithm.

In the semi-full factorial set up, the parameters are coupled in pairs and parameter sweep is done for each pair's parameter space, commonly results in 25 combination. For each combination, 20 repetitions were done. The number 20 is selected as the multiplication of 4, which is how GAMA executes the set of experiments, and because it is seen to show enough consistency to have reliable result, mainly based on the calibration result. The selection of the pair is mainly guestimated to find combinations that would result in certain interdependency effect. An example is the coupling of *TimeLimit* and *MakeDecisionTimeLimit* which might show condition where potential adopter does not have any time to find installer in the internet as the difference between the parameters decreases. Here are the coupled parameters in the experiments:

- BudgetIncomeFraction and UncertaintyChange
- ResearchKnowlIncreaseConnection and ResearchKnowlIncreaseInstaller
- UnintenKnowlIncreaseMedia and UnintenKnowlIncreaseConnect
- LowerThreshold and UpperThreshold
- ConnectionLimit and ResearchKnowlIncreaseSelf
- SmallLargePromotionRatio and AdministrationEffort
- InfluencingProb and SocializingTendency
- PromotionFactor and ProbLosingContact
- SocialFactorChange and PowerIncomeRatio
- TimeLimit and MakeDecisionTimeLimit
- PositiveViewValue and InstallerContactingThreshold

6.4.3 Data Analysis

Data analysis is done in RStudio with the help of ggplot2 library to visualize the data.

Chapter 7

Experiment Results

In this chapter, the interesting result of the experimentation and data analysis is presented. The chapter starts with elaboration on the observed emergent pattern abd followed with results on the influence of mass media, installer, interpersonal communication, and psychological factor in section 7.2 until section 7.5. Finally, the last section provides answer to the third sub-research question.

7.1 PV Adoption as an Emergent Pattern

There are several types of patterns commonly found in the data, such as dynamic behavior, attractor change, metastable behavior, and lack of pattern. **Dynamic behavior** can be cyclical or exponential, depending on the model type. **Attractor change** may also occurs, which resulting on sudden change in the model. **Metastable behavior** is when multiple runs cluster together and **lack of pattern** happens when the data does not form any pattern and looks like noisy behavior.

The outcome of the calibration already shows the presence of s-curve, rather linear, and almost 'no-adoption' pattern, representing the dynamic behavior of the model. This also means that diffusion process does happen (under certain circumstances) and this is a further verification on the built model. The adoption curves mostly start to take-off in between 2010 and 2015 and keep increasing for about 5 years before the slope becomes flatter again. The different patterns mainly cluster together according to the parameters value without much discrepancy.

Still in between 2010 and 2015, the experiments show that there are many potential adopter becoming a knowledgeable rejecter for the first time (Figure 7.1). The curve somehow resembles the normal distribution function. These do not only indicate that majority of households become potential adopter at about the same time, but it also shows that the spread of knowledge reach households in a normal distribution fashion. It explains why an s-shape curve may occur, as the cumulative of a normal distribution results on an s-curve function.

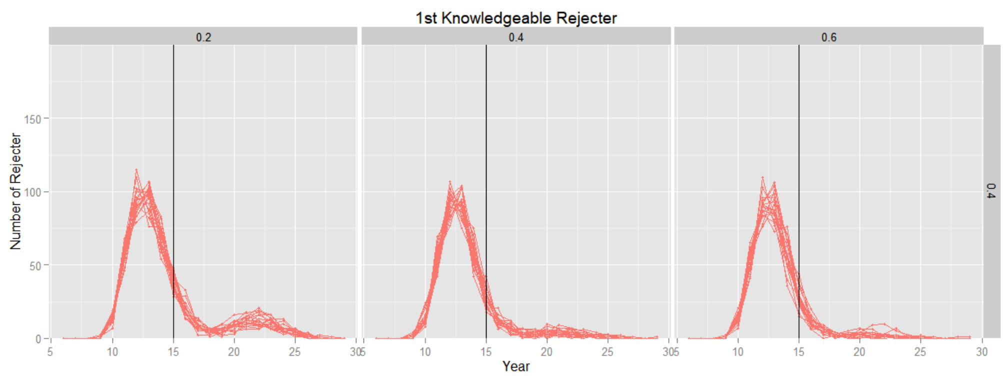


Figure 7.1: First-Attempt Knowledgeable Rejecter at *BudgetIncomeFraction*: 0.2-0.6, and *UncertaintyChange*: 0.4

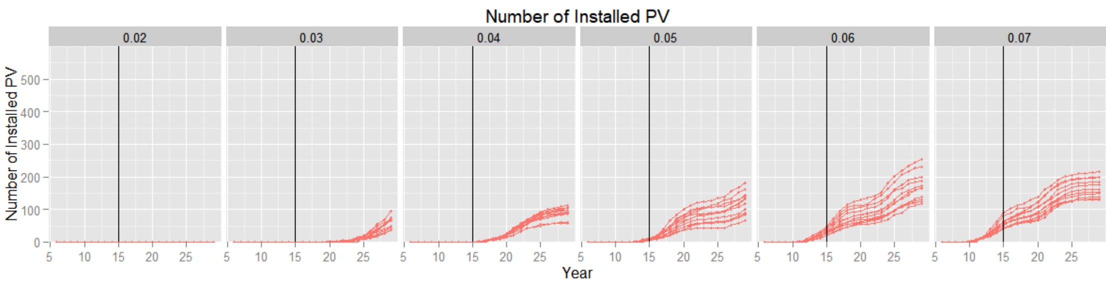
At certain parameters, there are multiple peaks of households becoming a first-attempt knowledgeable rejecter (Figure 7.1, *BudgetIncomeFraction*: 0.2). The second peak usually occurs at around 2020-22. Also, sometimes the curve has another slight increase at the same period (for instance in Figure 6.1). These sudden 'small' increase of potential adopter and second peak for first-attempt knowledgeable rejecter, most probably are the households that has the *UpperThreshold* as its motivation threshold, thus it takes a while for that household to be interested on PV.

The presence of multiple peaks and two periods of sudden increase in PV adoption shows that the phenomena of increasing PV adoption has close relation with the speed of information being transferred to promote PV to household that has not known or not interested in PV yet.

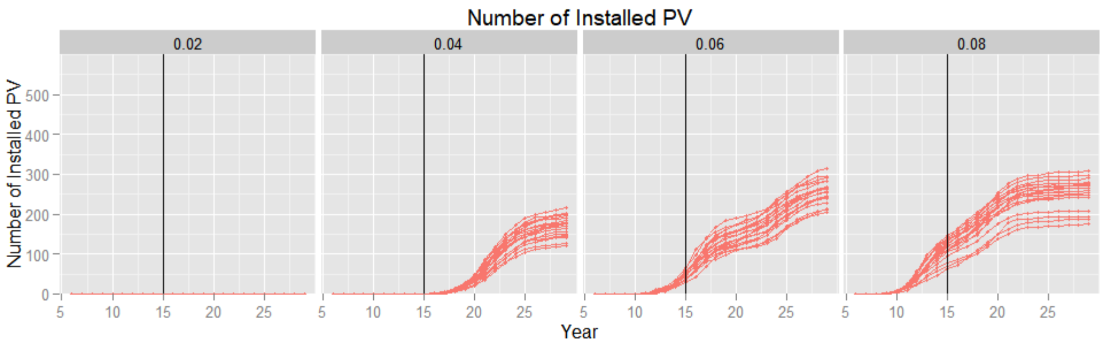
7.2 Mass Media Influences Adoption Significantly

Exploration on *UnintenKnowlIncrease* shows the importance of knowledge transfer through information spread (Figure 7.2a). The increase of information transfer, particularly through mass media (Figure 7.2), causes the kick-off of PV adoption to be earlier. However, there is no significant difference in the adoption rate during the diffusion process.

On the other hand, Figure 7.3a shows the increase of adoption rate with higher information availability on internet. Assuming that the average interest of knowledgeable rejecter is the same as adopter's when it makes a decision to reject and adopt, more information obtained from the internet also leads to higher interest (compared to liking) for the early part of the adoption process (2010-2015) as shown in Figure 7.3b. After 2015, the interest-liking ratio generally becomes more constant at 0.75 when information availability is high, while it tends to become more random with lower information availability. It is not very clear on why this occurs though, more data is necessary to understand the phenomena.

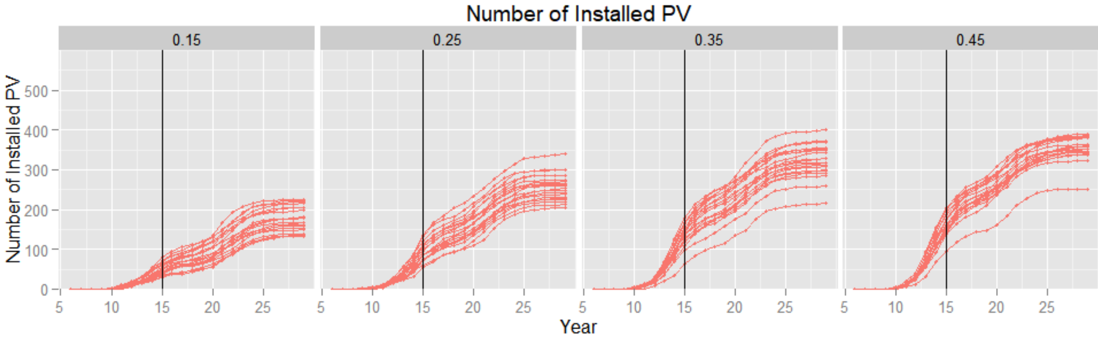


(a)

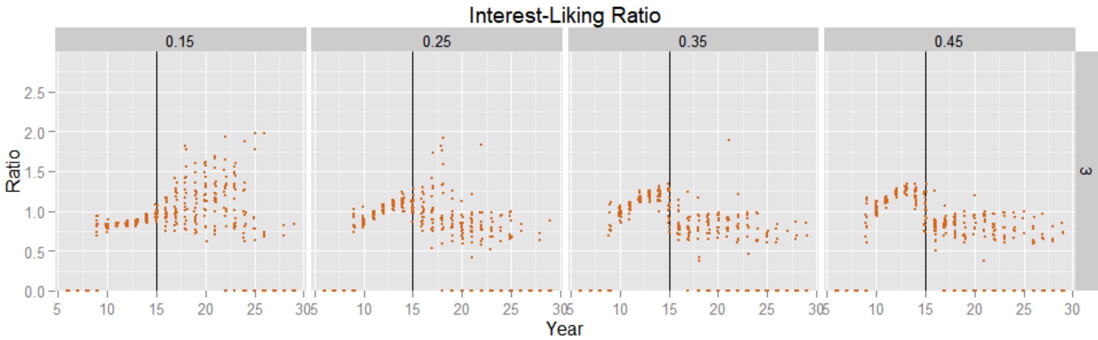


(b)

Figure 7.2: Adopted PV at *UnintenKnowlIncrease*: 0.02-0.07 (a) and *UnintenKnowlIncreaseMedia*: 0.02-0.08 (b)



(a)



(b)

Figure 7.3: Adopted PV (a) and
Interest-Liking Ratio of Knowledgeable Rejecter at *ResearchKnowlIncreaseSelf*: 0.15-0.45 (b)

7.3 Limited Role of Installer

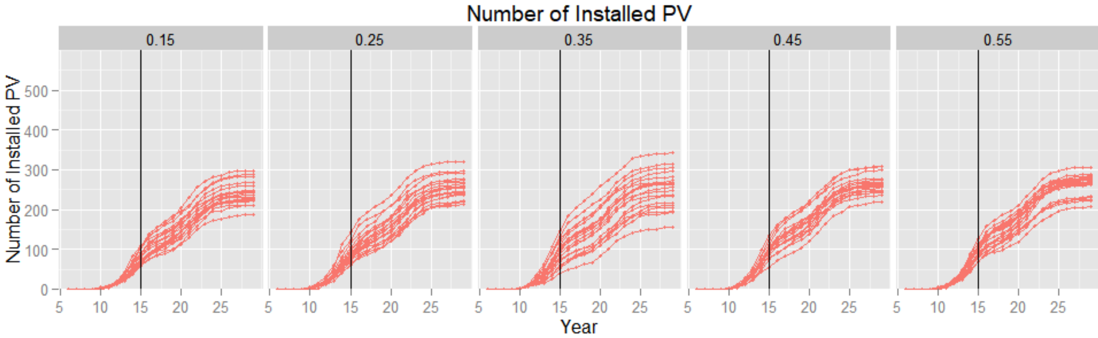
Installer has limited roles in influencing PV adoption in regards of information sharing (Figure 7.4a). There is almost negligible difference of adopted PV with varying level of knowledge shared by an installer during consultation. It is understandable though since installer will in the end provide knowledge on investment cost, payback period, and O&M before negotiation, leaving autarky and environmental knowledge to play a role by varying this parameter.

The presence of installer that does not provide help to the legal administration of PV system does not have significant negative influence to PV adoption, but the tendency is there (Figure 7.4b). This indicate that majority of potential adopter that make contact with an installer has already had high level of interest to purchase PV system.

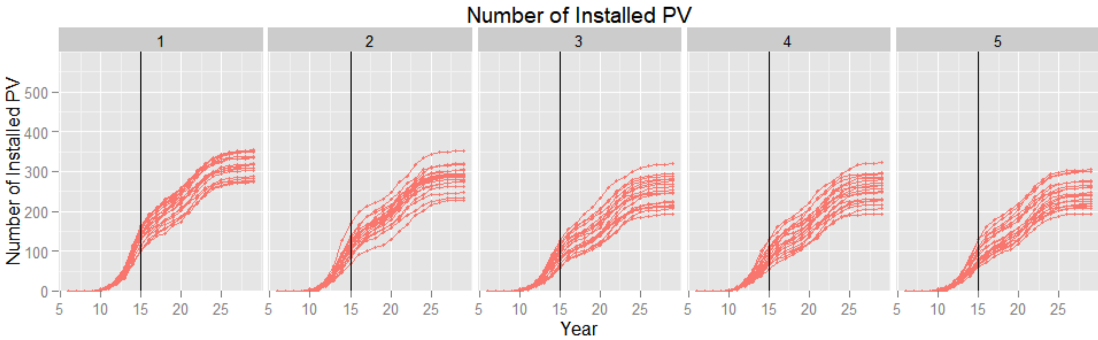
The most important role of installer is its reachability by potential adopter. The increase of promotion done by installers generally accelerates the adoption with larger adoption rate (Figure 7.4c). This is also supported with the lack of change when the tendency to share an installer's contact through peer to peer (tendency to losing the contact, more specifically) is varied (Figure 7.4d), means that potential adopter mainly finds an installer by itself through the installer's promotion.

7.4 Interpersonal Communication Channel

Varying any parameters related to interpersonal communication shows how it does not have large influence to PV adoption. None of the parameters have significant impact, starting from increasing the level of knowledge shared during socialization (both for non-adopter and potential adopter), increasing frequency of socialization, and even the importance of peers to convince a rejecter to reconsider its decision.



(a)



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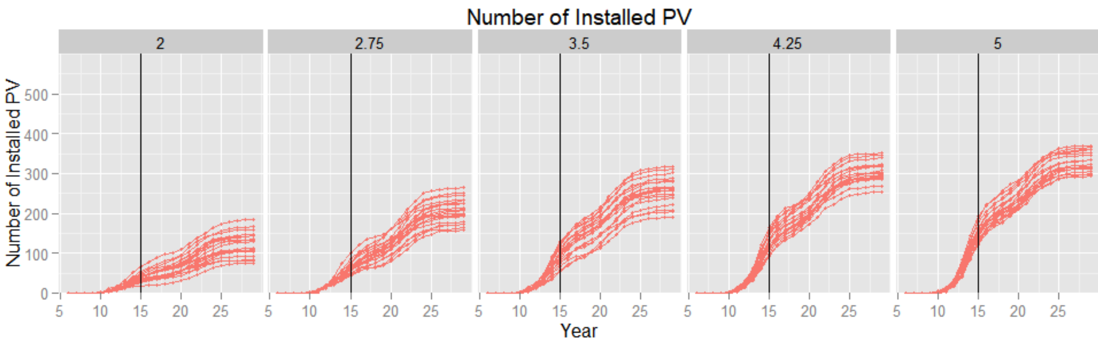

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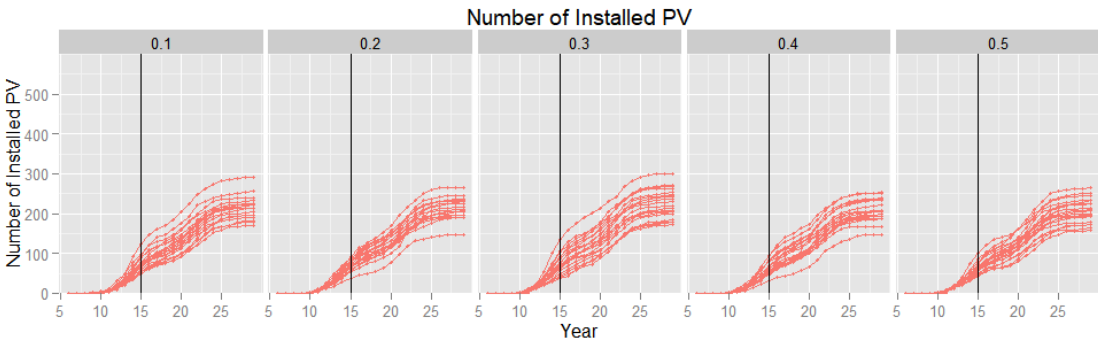
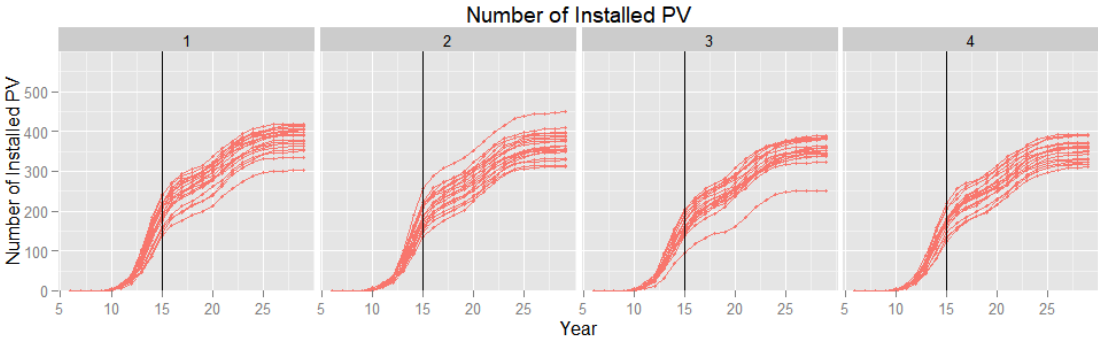


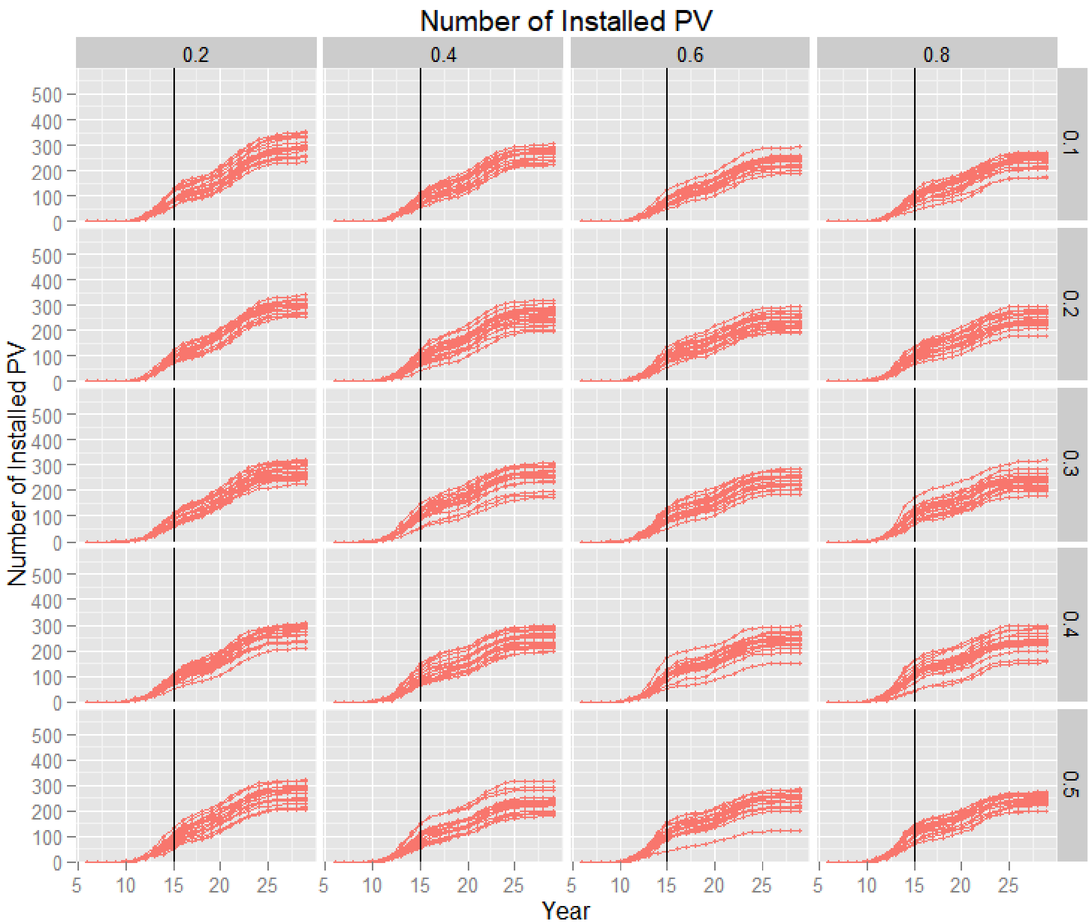
(d)

Figure 7.4: Adopted PV at *ResearchKnowlIncreaseInstaller*: 0.15-0.55 (a), *AdministrasionEffort*: 1-5 (b), *PromotionFactor*: 2-5 (c), and *ProbLosingContact*: 2-5 (d)

The experiments show that there is almost no second-attempt knowledgeable rejecter (Figure 7.6). The decrease of parameter *ConnectionLimit*, which represents the number of positive influenced that a rejecter has to experienced before becoming a potential adopter again, does not have large effect at all (Figure 7.5a). Even when the *ConnectionLimit* is set as 1, there is only small amount of second attempt knowledgeable rejecter. The finding gives indication that socialization, or more specifically positive influence during socialization, does not occurs that many.



(a)



(b)

Figure 7.5: Adopted PV at *ConnectionLimit*: 1-4 (a) and at *SocializingTendency*: 0.2-0.8 and *InfluencingProb*: 0.1-0.5 (b)

Increasing the occurrence of socialization and probability to influence others does not show any

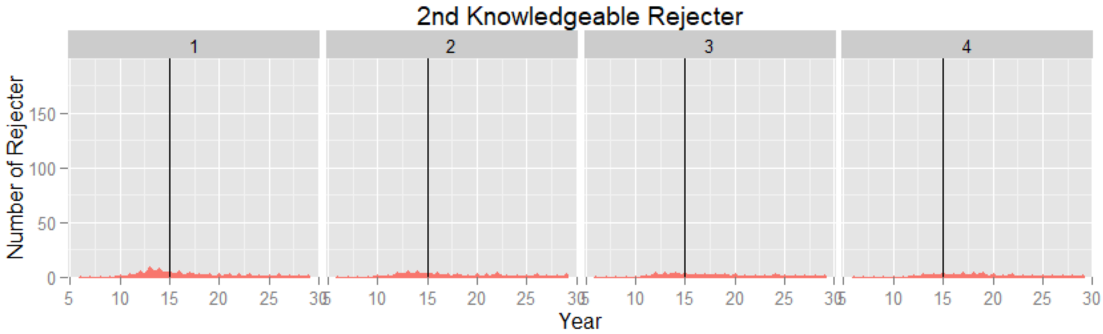
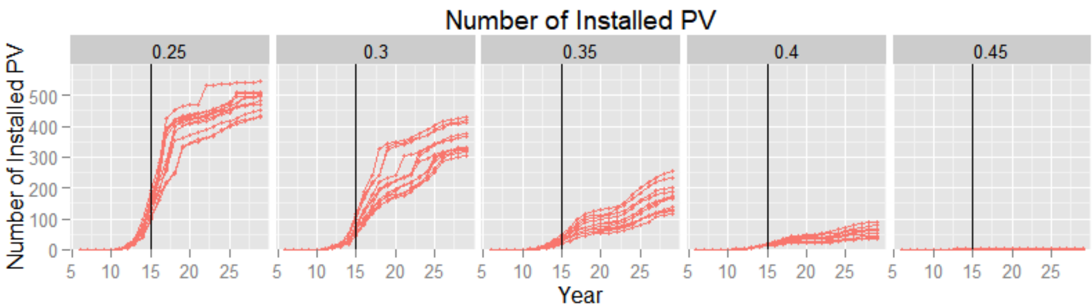


Figure 7.6: Second-Attempt Knowledgeable Rejecter at *ConnectionLimit*: 1-4

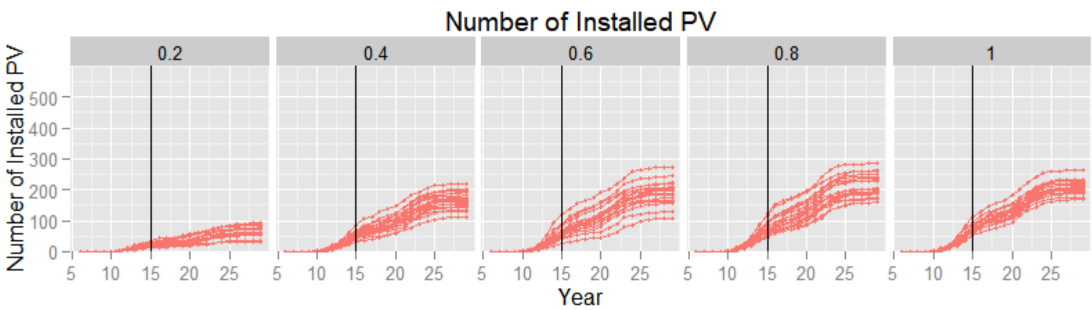
change (Figure 7.5b). This, however, is done with the *ConnectionLimit* set to rather high value, i.e. three. Thus it is possible that the amount of connection limit is still to high even with higher probability of positive influence. It becomes rather understandable that there is such small amount of positive influence and socialization when considering that in a scale-free social network; many households only have small number of connection.

7.5 Psychological Factor

Individual's reluctance to change has an important role in PV adoption, by influencing PV rate of adoption (Figure 7.7a). The higher the basic reluctance level, the lower the rate of adoption is, which is caused by the increase number of households that require higher interest to have intention. Thus, there are more household that reject PV because its interest does not exceed its liking.



(a)



(b)

Figure 7.7: Adopted PV at *InitialFutureUncertainty*: 0.25-0.45 (a) and
Adopted PV at *BudgetIncomeFraction*: 0.2-1.0 (b)

Households' decision is also influenced strongly with the tendency to spend more (as fraction of

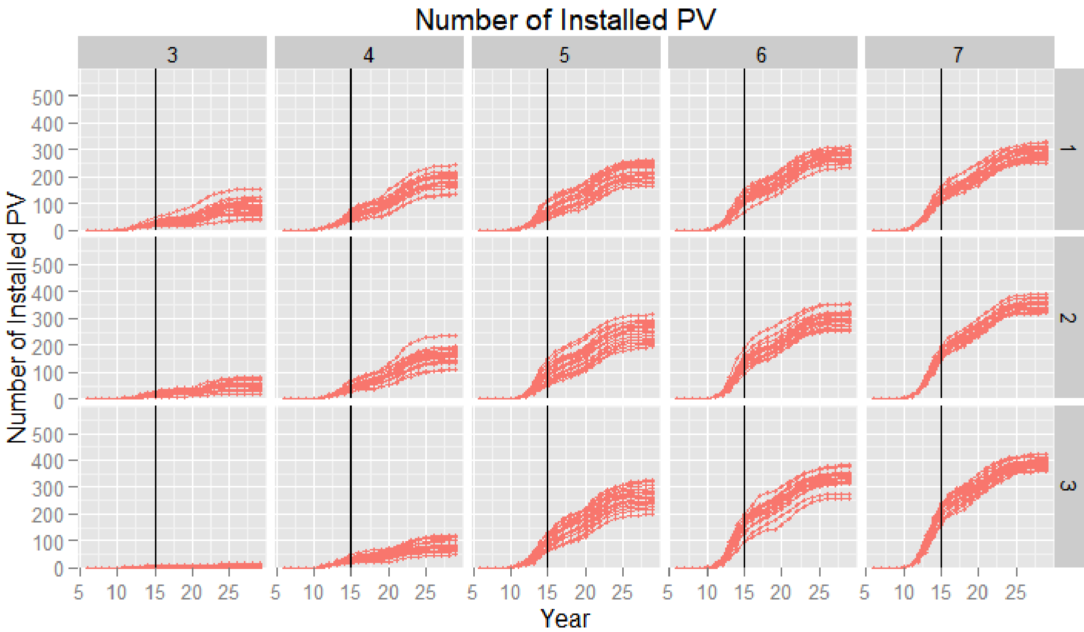


Figure 7.8: Adopted PV at *TimeLimit*: 3-6 and *MakeDecisionTimeLimit*: 1-3

income), especially for parameter (*BudgetIncomefraction)* at the value below 0.6. This has direct influence when potential adopter is faced to the ability to purchased the investment necessary to install PV. The lesser that households want to spend, the more is the number of knowledgeable rejecter that is caused solely by the expensive investment cost (Figure 7.7b). Nonetheless, the model's parameter value for this factor is rather high to say that the factor does play a role in PV adoption; the value is 1.0. Another reason is because Bosweide area mainly consists of high income households of higher than 5000 Euro monthly. By lowering *BudgetIncomeFraction*, it can also be used to represent a different population with lower level of income.

An important aspect of psychology is on the households patience in finding information about PV and before finally deciding to reject it (Figure 7.8). Rate of adoption increases when potential adopter wants to spend more time to find an adopter after considering its interest and liking (increase of *TimeLimit*), once again shows the importance of connection between potential adopter and PV installer. Adoption rate also increases with more time spent in finding information before start making judgment/evaluation on PV. This also support the idea that having more information available for households to look for it by themselves (as a potential adopter) has big influence in speeding up PV adoption. A reverse effect, however, occurs on low value of *TimeLimit*, most probably because the influence of having less time to find an installer has dominated the knowledge.

7.6 Sub-conclusion

This section tries to explain the emergent patterns based on the analyzed data obtained from the model. It also provides answer to the third sub-research question: *What are the influence of various communication channels and consumers' decision making to the adoption curve of residential PV according to ABM?*

Firstly, PV adoption as an emergent pattern does occur in the ABM under certain circumstances, commonly resulting on an s-shape or linear curve. The s-curve is easier to be spotted when there is sudden increase of large information sharing and when households' have low reluctance to install PV. The presence of the s-shape curve further verifies the PV adoption model built.

Secondly, there is a surprising result on how interpersonal communication has almost no influence to PV adoption, especially in transferring knowledge at the early phase of the adoption (before 2015). It is possible that the combination of the scale-free network, absence of neighbors, and maybe the modeling of the socialization (will be discussed in the following chapter) are the cause of this. On the other hand, mass media has a huge role in PV adoption. The more active promotion done in the media, the faster the adoption curve take-off. Furthermore, information availability to potential adopter also helps increasing adoption rate, most probably by allowing households to have better understanding (and thus higher interest) on PV.

An important aspect in the connection between PV installer and household does not occur during interactions between those two, either during consultation or negotiation. Instead it is the reachability of installer that becomes the most essential in increasing adoption rate. This is further emphasized with the importance of households' patience and willingness to spend effort to find an installer in increasing rate of adoption.

Finally, households' income and economic-psychological decision to spend part of their income also has influence in rate of adoption as some households' cannot afford to purchased a system with lower allocated budget. This, however does not occur in high income population area and most probably becomes more obvious in areas with rather smaller income level.

Chapter 8

Discussion

Having the outcome of the data analysis in the previous chapter, the next step is to evaluate the validity of the model and the outcome of the analysis. In section 8.1, the data gathering and problem process utilized to answer the first sub-question in chapter 3 are evaluated. In the next section, major discrepancies between empirical knowledge and the model after it is conceptualized and implemented are discussed. Section 8.3 discusses the result analysis and section 8.4. The final section provides an answer to the fourth sub-research question.

8.1 Knowledge Gathering and Problem Description

The whole project is started as a part of bigger project owned by ZEnMo. During the discussion with Auke Hoekstra as the project leader, the problem was clearly stated as being owned by power utility. However, after further literature review on the theories and interviews with several installers, it becomes clear that many factors that influence adoption curve as the emergent property are out of the power utilities' hand. Instead, Dutch government has much greater role in affecting these factors. Thus, it is an interesting problem where the problem owner has to influence a third party in such a way to 'share' the problem to the third party.

The decision to have interview with power installer is based on the consideration to support the applied theory (DOI and TPB) during the social process based on empirical evidence from these installers, especially on aspect that involves them such as negotiation with household. There was another attempt to have an interview with Polder PV as another source for empirical insight on PV market condition in general, but scheduling and time issue hinders the possibility to have lots of communication to get more information. Furthermore, it would be beneficial to have more insight from a government's staff, however it is deemed to be too time consuming to be done.

As it has been mentioned in chapter 2 and chapter 3, DOI and TPB have been shown to be able to provide insights on factors that influences PV adoption. As the theoretical framework that explains how new technology is being spread and adopted by consumers, DOI is suitable in elaborating PV adoption process. On the other hand, the empirical knowledges on how individuals make decision to adopt or reject PV, mainly comes from studies which does not categorize individuals following Rogers' DOI. Because of this, the understanding on psychological process of consumers is based on the majority of the population, i.e. the 'early majority' and 'late majority' consumers. The absence of 'innovators' prevents much exploration at the early state of the diffusion process.

8.2 Model Conceptualization and Implementation

The conceptualization and formalization of the model is done based on the knowledge gathered from literature and the interviewed installers, as well as from discussions with Auke Hoekstra, Igor Nikolic, and Martijn Warnier.

During model conceptualization, the discussions brought up possibilities of installer to calculate payback period without satisfying method, i.e. not detail enough with the variables. Based on interview, however, both installers claim that commonly installer would use rigorous irradiance data to calculate the system's annual power production during a negotiation. It is possible that the installers' opinion is biased towards PV installer.

The model also only considers socialization that consists of only 2 households. This might not be enough to represent information transfer through peer-to-peer and decreases the importance of interpersonal channels. This will be discussed further in section 8.3 together with the result of the experiments.

The implementation of lower threshold and upper threshold to differentiate knowledge levels and the perceived attributes is rather novel. The same goes to the method to determine a household's available budget from its interest, liking, and income. Even though they are rather novel, the modeler sees these mechanisms as the best way to represent what has been known from empirical knowledge. This comes with the assumption of 'all households have the capabilities to understand the technological aspect to some degree'.

An issue occurs during the software implementation of the model which prevents the presence of neighbors for households. This may have great influence on the role of interpersonal channel because it decreases the possibility to have someone that it can ask for information from as an adopter.

8.3 Calibration and Experimentation

When calibrated and experimented, the result clearly shows the occurrence of PV adoption, thus confirming the real world phenomena. The s-shape pattern is consistent with Rogers DOI, and the calibration with historical data supports the validity of the result even further.

In the model, influence of government and local energy initiatives are aggregated in the mass media information sharing activity. However, the scale-free network still includes these opinion leaders, represented as the agents with large number of connection. The socialization mechanism with only 2 households manages to prevent these opinion leaders to actually have large influence in increasing knowledges level. However, this also results on the lack of socialization to influence rejecter. As Rogers mentioned, interpersonal channel has larger role in influencing rejecters to become potential adopter again, rather than to share knowledge (in knowledge stage). Individual might need a confirmation on the technology by trying it first, or by having a confirmation through its peers. This might be the important aspect missing in the experimentation, mainly because of the socialization mechanism with only 2 households, the scale-free network, and the experimentation design.

Based from historical data from klimaatmonitor.nl, there was already 11 installed PV before 2010. The number does not change since 2008, which may indicate that these adopter have rather different decision-making process to purchase PV compared to the other 'rather later' adopter and probably does not manage to influence other households very much; they might be considered as innovator. While there is no innovators, the model still can replicate similar rate of adoption from historical data. This implies that in this model, the role of innovator and early rejecter to spread knowledge is not very prominent.

Experimentation on varying households' reluctance to change and spending fraction from income gives understanding in how PV adoption occurs at different demographic condition, allowing it to give insight on different areas, especially in the Netherlands. For areas with lower income and maybe more conservative (in terms of change and green technology), rate of adoption might be less. In the national scale, where there are various demographic condition, the length of the adoption curve slope might spread on longer time period than shown in this study. This model mainly shows how the slope mainly stretches for around 5 years. In the national scale of the Netherlands, it might be longer, for about 10 years. This is in accordance to P. Magazine (2017) which stated that significant PV adoption most probably will stay the same until 2023.

Furthermore, the model shows how knowledge on a technology is an important factor to increase individual's interest on the technology. This corresponds to DOI theory which says that the uncertainty on new idea can be reduced by information and the increase of knowledge (Rogers, 2002). On the other hand, it might not be the case if the innovation is, in actuality, has strong negative aspect. The increase of knowledge might actually expose its negativity. For instance, households might become rejecter instead of adopter if they become potential adopter in 2005 when PV investment cost was still very high and the payback period was bad (without considering re-evaluation).

The finding that installers role in increasing households knowledge on autarky and environmental, does not mean that installer have no role at all in sharing knowledge. The model has automatic increase of payback period, investment cost, and O&M knowledge for households during negotiation. If else, this actually further supports the argument that payback period and investment cost are the most important aspect in making a decision as has been mentioned in literature (Korcaj et al., 2015; Sommerfeld et al., 2017).

Finally, the presence of neighbors might help to share installer's contact. According to interview with Installer-1, it has large share of clients that manage to have its contact through its neighbors. Also, the incorporation of neighbors might decrease the influence of PV installer promotion.

8.4 Model Application

The model developed represents the condition in a neighborhood in the Netherlands. At the moment, in the Netherlands, there are already numerous information available on internet on PV installer. Households mainly will not have much trouble to find an installer contact. Moreover, investment cost for the system keeps decreasing and it has become quite low for the Dutch households to be purchased. In the next few years, maintaining the status quo, there are not many factors that might hinder the adoption of PV households and the prediction of stable increase of adoption until 2023 is likely to happen. Even when there is change on the electricity pricing system, as long as it maintains the payback period of PV system on around 7 years and does not create large commotion, it will not influence the adoption that much.

The calibration step manages to replicate the rate of adoption after 2010. On the other hand, the investment cost of PV system has become rather low by 2010 (W. G. van Sark et al., 2014). In the model, 2010 is the time when households only start to gain enough knowledge to become potential adopter. However, this might not be the case in other countries with considerably lower GDP per capita, such as the developing countries or the Eastern European countries, since PV module price does not change much across the world. It might be helped by the fact that soft cost forms the majority of PV installation cost, thus it is possible to have lower total cost when the standard wage for labor is rather low in the country. Such subsidy for PV installer (or other stakeholders that might help decrease the total cost).

The model might be able to show the importance of peer-to-peer communication by having lower *ConnectionLimit* and higher *SocializingTendency*, without changing the social network structure (scale-free network). Nonetheless, the implementation of scale-free network in modeling technology diffusion process should be done more carefully. Based on DOI, information transfer through mass media is different than interpersonal channel. However, nowadays, many of the opinion leaders, such as politician and artists, also use their own digital social media or doing promotion through certain organization. The difference between mass media and interpersonal communication is not very clear in scale-free network. This model only represents neighborhood activities, without much incorporation of the government or local energy initiatives. When modeling larger area, for example a province or a country, the model should be adjusted to how the influencing happens within such scale-free network. They might even have different behavior depending on their number of 'connection'.

In a system (neighborhood scale) where the network does not look like scale-free network, the role of peers to share knowledge might be larger. For instance in a rather collectivist countries such as China, Sweden, and Latin America countries. It is possible that the network allows socialization to occur more often, with larger participant, and has more information being shared (larger 'trustworthiness') than mass media. Modifying the socialization behavior might be enough to change the model. In such condition, the information of a PV installer contact through peers might have larger importance and thus, promotion of PV installer through internet might not be the most important aspect in allowing households to obtain a contact.

8.5 Sub-conclusion

As the final chapter before conclusion and recommendation, this chapter provides answer regarding the applicability of the results obtained from this model in the real world. This section answers the last sub-research question: *How well does the ABM represent the actual system?*

The model is built to have a better understanding on the adoption of residential PV for power utility. Besides of the perspective of power utility, more information was also gathered from different actors, namely PV installers and, to some extent, consumer. Combined with literature review on DOI and TPB, which are commonly used to explain technology adoption process, it leads to thorough information being gathered on the issue.

In the implementation of the model, scale-free network is used. Socialization mechanism which only includes 2 households help preventing the occurrence of double influence from opinion leaders (government or local energy initiatives) and mass media. However, it comes with the cost of low number of socialization between peer-to-peer and leads to small possibility for adopter to make rejecter re-evaluate its decision. The model manages to replicate how technology diffuses in a rather local region. The implementation for larger, scale such as national scale might require adjustment on how opinion leaders help spreading information.

The model does not incorporate the influence of neighbors due to software bug and this might have increased the importance of finding installer's contact through internet. In reality, the importance might not be as strong as shown in this thesis, especially in another country with different culture, for instance collectivist countries such as Sweden where the social network structure might be significantly different from scale-free network. More socialization between connections and neighbors are most likely to decrease the importance of internet in this matter.

Increase of knowledge does support the adoption of PV, but it is mainly because in the case study, the technology has had rather desirable attributes (investment cost and payback period). In another social system where the economical condition is not as supportive as in the Netherlands, the increase of knowledge might results on the increase of rejecters. Depending on the demography, it might not be easy to 'repair' the image of the technology had by these rejecters. It is the best to have residents gain knowledge at the right time, in this case, when PV price already become low enough and 'reimbursement' policy is profitable enough.

Furthermore, in different demographic area with different economic condition and conservatism, the adoption rate is different. For the case of the Netherlands, this demographic variation results on the adoption process might last for about 10 years, several years longer than in this model which does not have demographic variaton.

Finally, the presence of innovator is not very crucial in the take-off of adoption curve and in the spreading of the technology to rather high adoption percentage. This model does not show any diffusion process which correlates with how technology survives in its niche and how it influence the take off.

Chapter 9

Conclusion and Recommendation

This chapter consists of conclusion, which provide the answer to the main research question, and recommendation based on the conclusion and based on the research work that has been done by the author.

9.1 Conclusion

This section conclude the thesis by answering the research question based on the finding shown in the previous chapters, which give answers to the sub-research question as attempts to help providing more insight on residential PV adoption process. The main research question is: **How does the adoption curve of residential PV system be influenced by consumers' decision making psychology and various communication channels?**

The finding from literature review and the interviews show different stages of households in the process of adopting PV system: (1) knowledge stage, (2) persuasion stage, (3) decision stage, and (4) re-evaluation. Different communication channels give influence at different stages. Two types of communication channel stated by Rogers in its DOI theory (mass media and interpersonal) can further be differentiated into the role of active mass media promotion (through advertisement), available passive information (mainly the internet), peers, and PV installers themselves. Mass media and peers have major influence on the knowledge stage, that is when household has no actual motivation and interest to purchase PV. During persuasion stage, when household actively looking for information after having interest on PV, peers, PV installer, and internet play larger role. PV installer is the main communication channel during the decision stage, when households deciding on whether to adopt or to reject PV.

During the process, households make a decision based on several aspect of PV: power independency possibility (autarky), environmental benefit, social pressure, aesthetic, operation & maintenance, investment cost, and payback period. Out of all these, payback period and investment cost are the most essential. These different aspects are also dependent on the knowledge owned by household on the particular aspect, which are strongly influenced by various communication channels. Based on the framework of TPB, it is shown that these knowledges mainly affect a household's decision process in the persuasion stage, by determining the level of interest and the strength of the intention the household has. In decision stage, investment cost become a hindrance together with the amount of necessary effort that has to be spent by households, mostly to find PV installer and on the legal administration process of installing PV.

The insight from the case study shows the presence of the adoption through the s-shape curve of adopted PV, verifying the emergent pattern dynamic behavior as the result of information transfer through communication channels. Mass media plays an important role in speeding up the take-off of the adoption curve. When the spread of information forms a rather normal distribution function of influx of potential adopter, it leads to the appearance of the s-shape curve, assuming that all household has the same level of basic reluctance to change. The availability of passive information increases the steepness of the slope, which mainly due to higher knowledge, and thus having larger interest on PV.

The model manages to represent PV diffusion process to be adopted by majority of residents in a local area in the Netherlands by replicating available historical data. However, it does not show the role of innovator consumers in influencing the take-off and adoption rate of PV system. In such local area with scale-free network structure, peer-to-peer interaction does not influence PV adoption at all, at least when the socialization process is rather limited to small number of households only. In different socialization mechanism, the influence of peer-to-peer might be seen in re-convincing households that have already negative perception on PV (the rejecters). Also, the absence of neighbors due to software issue exacerbates the absence of peer-to-peer influence. It is possible that peers do have role in increasing PV rate of adoption, even though not in a very significant manner.

Opinion leaders, including politician and other public figures, have important role when they are considered to promote the technology through mass media. In a system with low degree of socialization (just like in the model), mass media plays much important role to kick-start PV system adoption. The availability of information on internet helps increasing rate of adoption when the technology does show positive attribute, for example low investment cost or high long-term profit.

Another important psychological aspect is households' patience to spend more effort and time to find more information and to find an installer's contact. This is also aligned with the importance of installers' reachability for households to make contact with them, despite of the minor influence had by installers' act to share knowledge on the autarky and environmental aspect of PV. Both has significant influence to rate of adoption. This strong correlation might be decreased a little when there are neighbors present, or at least when there is good interaction between neighboring residents to share knowledge on PV installer.

The slope of the adoption curve, i.e. the rate of adoption, is strongly influenced by the basic reluctance of households on new technology. The model uses a single value of basic reluctance value which might not be the case in the real world. when the reluctance value are randomized, the slope of the PV adoption should become less steep and the adoption would take longer time to complete. This might even be stretched further when considering population with lower income level. In the case of the Netherlands, this support the idea that significant rate of adoption will still continue at least until 2023 and changes of electricity pricing scheme might not have large influence as long as payback period stays around 7 years.

9.2 Recommendation

Based from the result of this study, there are two categories of recommendation: (1) recommendation for the problem owners and (2) recommendation for further research on the topic.

For the Actors
Most likely, the significant increase of PV in the Netherlands will still continue at least until 2023, after already having about 5 years of significant rise. As power utility is facing a problem on the rapid increase of installed PV, maintaining the adoption speed in a stable rate is essential. It is the best for the problem owner to maintain the level of promotion (through mass media) as the current condition. The central government can also try to cooperate with large local energy initiatives or provincial governments to do promotion in different areas one-at-a-time to control the adoption rate. For instance, they should focus on areas with larger income level before reaching out to more lower income level later on. PV system price is predicted to keep decreasing and it is better to have lower income residents to be exposed to the technology at the time when the price is seen as 'appropriate' to them. This will help to smoothen the adoption process by preventing the occurence of rejecter, which might not be easy to be persuaded to reconsider its decision. Local energy initiatives can provide monthly short magazine on PV (or green technology in general) to their respective targeted area without charge.

For PV installer, their exposure through internet (or maybe brochure and pamphlet) is the most essential. Many households manage to get an installer contact through internet. Even though in reality, neighbors might also play role in providing installer's contact, there still should be a way to contact them for the 'opinion leaders' in the neighborhood. Installer's contactability and availability is a necessity, even though installer might want to focus only to households' demand based from neighbor's recommendation for some time. This usually is the case for installer that wants to keep being in small scale, like one of the installer being interviewed.

For residents, there is no general preferable condition except that to have the most beneficial/profitable outcome out of the available options. The aspect that influence their perspective varies for each resident. It is best for residents to keep an eye on the development of the technology to have the most knowledge on the profitability. This, by itself is rather tricky. Firstly, time is money and spending too much time only to keep updated on the technology is not profitable and secondly, not all residents have the intelligence to understand the technological aspect completely. The most important for residents is to spend as much time as they want to on keeping an eye on the technology, while being aware that spending only such small time is the best thing to do.

For Further Research

This aspect then bring us to the second category of recommendation. Indeed, this study only covers part of the system. Further experimentation should be done on how the adoption would behave under different electricity prices, especially when the electricity pricing scheme does also change. Another exploration that would be needed is on the presence of electric vehicle, with the possibility to do smart charging in the future. The outcome of these studies altogether can help power utility and government to keep the adoption rate stable.

Further research on the role of communication channels is an interesting topic in the social behavior area. For instance on the role of neighbors in influencing individuals decision. It can be done with case study in different location, especially in places with different network structure. Further research can also be done for different type of technology. This study provides an agent-based framework to model the diffusion process with detail communication channels and psychological aspect, for technology that to be used by households in general. The main difference that should be adjusted is the attributes of the technology that influence residents' interest to the technology. When strong calibration mechanism can be implemented on the model, it can be used as a virtual lab for decision maker, or even private companies, in creating strategies for their innovation, similar to what Rai and Robinson(2015) did with PV system.

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Appendix A

Assumptions

In here are the assumptions taken in the conceptualization, formalization and implementation of the model:

1. All households act rationally; there is no innovator.
2. All behavior of different residents in a household, can be represented in a single agent.
3. All PV installers with the same scale and service to administration, can be represented as a single agent.
4. The importance of different knowledges (such as environmental) when consumer assessing its interest on PV does not change along the years.
5. Household has a preference of connection to be contacted, someone which is trusted, when asking for information.
6. Possibility for households to install building integrated PV (BIPV), which requires a small 'renovation' of the house, is assumed to not likely to happen.
7. The possibility of energy storage to appear and give possibilities for household to store power is neglected.
8. All small PV installer start to create a PV size proposal during negotiation as much as the size to have zero net power.
9. Households can acquire knowledge independent of their intelligence.
10. All large PV installer start to create a PV size proposal during negotiation as much as the rooftop can have.
11. All PV installer provide individual detail analysis on power production and payback period during negotiation.
12. Local solar communities influence is considered as part of finding information from internet and information sharing in mass media.
13. Socialization only occurs between 2 households.
14. Household will automatically has permission to install PV on its roof from its neighbors, even if they have connected rooftop
15. Scale-free network can represent the actual social structure in the real world
16. Exposure of PV installer is influenced directly by PV adoption.
17. PV system's efficiency dependency on temperature is neglected.
18. Electricity price does not change; any feed back influence of PV adoption to the electricity price is neglected.

19. PV module price decrease can be modeled in a constant change; it is independent of any turbulence of global and regional PV market status.

20. The soft cost of PV installation does not change significantly after 2015 and is assumed to not change as well before 2015 since 2002. The change occurs in 2015.

Appendix B

Software Data Structures

B.1 Actors

B.1.1 Households

States:

- stage
- Income
- Connection
- Neighbors
- AnnualPowerConsumption
- SocialPressure
- AutarkyKnowledge
- EnviroKnowledge
- OMKnowledge
- PaybackPeriodKnowledge
- InvCostKnowledge
- Interest
- Liking
- FutureUncertainty
- PaybackPeriod
- InvestmentCost
- Motivation
- SocializingState
- ResearchState
- Partner
- Contact
- TimeAsPotentialAdopter
- AdopterConnection
- Blacklist
- OwnedPV
- LivingPlace
- PerceivedAttributes
- InstruLimit
- EnviroLimit
- SocialLimit
- UncertaintyLimit
- Reason
- attempt

Actions:

- socializing_decision
- main_activities
- looking_for_partner
- looking_for_adopter
- internet_research
- assessing_interest
- finding_installer_on_internet
- consulting_installer
- socializing
- negotiating_deal
- evaluate_interest_liking
- behavior

B.1.2 PV_Installer

States:

- Client
- ProductSold
- AdministrationService
- Scale
- WorkHourCost
- PriceList
- MinimumPrice
- ProposedSize
- ProposedTotalArea

Actions:

- creating_proposed_system
- update_installation_cost

B.2 Objects

PV_System states:

- Owner
- Price
- WattPeak
- Efficiency
- PowerProduction
- TotalPeakPower
- SurfaceArea (Smets et al., 2016)

PV_System actions: calculate_power_production

House states:

- Owner
- RooftopType
- Orientation
- RooftopTilt
- SurfaceArea

B.3 Global

Variables (change over time depending on the emerging pattern from the system):

- PVPrice: 3.13 E/kWp (at the beginning) (Strupeit and Neij, 2017)
- PanelPriceDecrease: 0.885 (Strupeit and Neij, 2017) & 0.97 (after 2015) (Mayer et al., 2015)
- FindSmallInstaller
- FindLargeInstaller
- SoftCostLargeScale
- SoftCostSmallScale

Experimented/calibrated parameters with the parameter space, coupled together:

- StartYear: 2001-2005, 1 jump
- UnintenKnowlIncrease: 0.2-0.7, 0.1 jump
- InitialFutureUncertainty: 0.25-0.45, 0.05 jump
- BudgetIncomeFraction:0.2-1.0, 0.2 jump and UncertaintyChange: 0.0-0.4, 0.1 jump
- ConnectionLimit: 1-4, 1 jump and ResearchKnowlIncreaseSelf: 0.15-0.45, 0.10 jump
- InfluencingProb: 0.1-0.5, 0.1 jump and SocializingTendency: 0.2-0.8, 0.2 jump
- LowerThreshold: 0.30-0.45, 0.05 jump and UpperThreshold: 0.65-0.80, 0.05 jump
- PositiveViewValue: 7.0-9.0, 0.5 jump and InstallerContactingThreshold: 0.70-0.90, 0.05 jump
- PromotionFactor: 2.00-5.00, 0.75 jump and ProbLosingInstallerContact: 0.1-0.5, 0.1 jump
- SmallLargePromotionRatio: 0.1-0.6, 0.1 jump and AdministrationEffort: 1-5, 1 jump
- SocialFactorChange: 0.1-0.5, 0.1 jump and PowerIncomeRatio: 2.0-4.0, 0.5 jump
- TimeLimit: 3-6, 1 jump and MakeDecisionTimeLimit: 1-3, 1 jump
- UnintenKnowlIncreaseMedia and UnintenKnowlIncreaseConnect, both: 0.02-0.08, 0.02 jump
- ResearchKnowlIncreaseConnect and ResearchKnowlIncreaseInstall, both: 0.05-0.55, 0.10 jump

Constant psychological parameters:

- MidThreshold: 0.5
- MaxValue: 15.0
- InvestMaxValue: 12.0
- MainWeight: 3.0
- SocialWeight: 2.0
- AuxiliaryWeight: 1.0
- NegativeViewValue: 2.0

Validated (GIS-, economic-, and PV-related) parameters:

- RetailElectPrice: 0.188 E/kWh (Londo et al., 2017)
- Irradiance
- AverageIncome: 4100 E/month (CBS, 2007)
- NumberOfResidents: 667 (based on database given by OVERMORGEN B.V.)
- OMRatio: 1% (Smets et al., 2016)
- BOSEfficiency: 90% (Smets et al., 2016)
- PVEfficiency: 17% (Smets et al., 2016; ZonnePannelen.net, n.d.-a)
- surface area of different types of roof (based on observation through GoogleMaps)
- AverageAnnualPowerConsumption : 2900 kWh (Netherlands, n.d.; Statista, n.d.)
- various percentage of houses orientation (based on observation through GoogleMaps)
- various percentage of houses roof type (based on observation through GoogleMaps)
- various percentage of houses tilt angle (based on observation through GoogleMaps)
- various percentage of household income (based on database given by OVERMORGEN B.V.)

Appendix C

Correlation between Knowledge and Interest

The knowledges, except social knowledge, are differentiated by the lower threshold and upper threshold.

Below lower threshold: household has not enough knowledge to have perception on PV.

Between lower and upper threshold:

- Autarky knowledge: positive perception
- Environmental knowledge: positive perception
- O&M Knowledge: negative perception
- Investment cost knowledge: negative perception
- Payback period knowledge: negative perception

Above upper threshold:

- Autarky knowledge: any value from 6 to 9 out of 10
- Environmental knowledge: any value from 6 to 9 out of 10
- O&M knowledge: equal to the knowledge $\times$ 10
- Investment cost knowledge:
  - Research state is 4: investment cost calculated by installer contact
  - Research state is not 4: investment cost of standard 12 modules system (for zero net power)
- Payback period knowledge:
  - Research state is 4: payback period calculated by installer contact using house design
  - Research state is not 4: payback period of standard 12 modules system (facing South)

Appendix D

PseudoCode

```
global (

init (

import infrastructures
create houses (
set orientation
set roof_type
set tilt_angle
set roof_area
)

create PV_installer (
set scale
set administration_service
set labor_cost
create PV_system (
set ownership
)
set installer_fee
)

create household (
set income
set annual_power_consumption
set living_place
)

ask residents (
set neighbors
set connection
)

)

reflex annual_update every:year (
update probability_to_find_installer
update PV_price
update installer_fee
ask household (
if contact != nil (probability lose_contact)
update autarky_knowledge
update environmental_knowledge
```

```
update investment_cost_knowledge
update payback_period_knowledge
)
)

reflex socializing every:week (
ask household (
if stage=potential_adopter (become looking_for_partner)
else (probability to_become looking_for_partner)
)
)

)



species household (

reflex main_activities (
if looking_for_partner (
if stage!=potential_adopter (do finding_partner)
else (do finding_adopter)
)
else if stage=potential_adopter (
if research_state=1 (
do internet_research
do evaluate_decision )// else if research_state=2 (do finding_installer_on_internet)
else (do consulting_installer)
)
if is_socializing (do socialization)
do behavior
)

action finding_partner (
repeat 3_times (
select_1_connection
if the_selected_connection looking_for_partner ( do_not_repeat
is_socializing
)
)
)

action finding_adopter (
remove Blacklist from AdopterConnection find_one_AdopterConnection with looking_for_partner
if found (
set Partner
is_socializing
)
else (
not_socializing
do internet_research
do assess_interest
if some_time_has_passed (do evaluate_decision)
)
)

action socialization (
if potential_adopter_with_adopter (
if adopter_knowledge_is_lower (add to Blacklist)
```

```
else (
increase_potential_adopter_knowledge
do assess_interest
if some_time_has_passed (do evaluate_decision)
)
)
else if adopter_with_anyone_else_except_adopter (
probability influence (
increase_knowledge
if adopter_is_not_in_AdopterConnection (add to AdopterConnection)// )
)
else if rejecter_with_non_adoper_or_early_rejecter (
probability influence (negative_influence)
)
not_socializing
ask Partner (not_socializing)
)

action evaluate_decision (
if Interest¿ContactThreshold*Liking (
if no_AdopterConnection (research_state = 2)
else (
asking_contact_to_AdopterConnection
if found (
set Contact
if Interest¿Liking (do negotiating_deal)
else (research_state = 3)
)
else (
research_state = 2
)
)
)
else if some_time_has_passed (do become_rejecter)
)

action asses_interest (
if research_state=4 (
ask Contact (create_proposal_system)
)
else if payback_period_or_investment_knowledge¿uppet_threshold (
use cost and payback period for zero net power
)
)

action consultation (
repeat 2_times (
increase_knowledge
do assess_interest
if Interest¿Liking ( do negotiating_deal
do_not_repeat
)
else if second_trial (do become_rejecter)
)
)

action finding_installer_on_internet (
if found (
```

```
if Interest¿Liking (
set Contact
do negotiating_deal
)
else (research_state = 3)
)
)

action negotiating_deal (
research_state = 4
update investment_OM_and_payback_period_knowledge
do assess_interest
set budget
if budget¿Contact_minimum_price ( create PV_system (set Owner)
) else (do become_rejecter)
)

)



species PV_installer (
action create_proposal_system ( set observed_house
set rooftop_slopes
if Client_never_negotiate and scale=large (determine_size_as_maximum_area)
else if (determine_size_as_budget_or_zero_net_power)
ask PV_system (do calculate_power_production)
set reimbursed_power_limit
set reimbursed_power
set reimbursement_amount
set annual_saving
set payback_period
)
)


species PV_system (
action calculate_power_production (
set Irradiation_per_slope
set surface_area_per_slope
calculate total_power_production
)
)


species house ()
```

Appendix E

Unit Testing and Bugs

Simulation Model

Test 1 : All database files imported and resulted in matrix correctly (column and row matches well)
Bug 1 : Folder name in Windows Explorer was wrong

Test 2 : Scenario does change at the right time and the right order to be used as condition
Bug 2 : Scenario decision was based not from the variable Scenario, but the actual variable instead
Bug 3 : Scenario was still empty when starting the run and was not filled until the Scenario change

Test 3 : Neighborhood map imported and built with the right roads, houses, residents, households

Test 4 : Week and year reflexes change at the correct time

Test 5 : Run is stopped at the correct time (2041)

Test 6 : Progress data are saved well in the directory

Global Init
Test 7 : Basic rooftop Orientation determined correctly
Bug 4 : The condition to be compared with Dummy1 was classified as float instead of integer

Test 8 : RooftopType, RooftopTilt, and Orientation determined correctly

Test 9 : 4 PV_Installer created with different SystemType and Scale and ModuleIncrease
Bug 7 : PV_Installer was not created because MinimumPrice was directly determined from PriceList but PriceList was not yet determined
Bug 8 : All PV_Installer had the same attributes because it directly created 4 PV_Installer

Test 10 : PV_System created to be the ProductSold of Installer with its corresponding attributes

Test 11 : PriceList and MinimumPrice calculated correctly in calculating_installing_costs
Bug 9 : Action calculate_installing_costs did not clean up old PriceList for annual update

Test 12 : Resident's location is the same as its LivingPlace's (house) location
Bug 10 : Some residents did not have LivingPlace because a LivingPlace could only has 1 Owner

Test 13 : PowerConsumption of each residents determined correctly according to Income

Test 14 : TotalModule and EachModule calculated correctly
Bug 10 : Possible source of error if only using either floor or ceil to determine NumberOfModules

Test 15 : Number of adopter is correct and assigned attributes are suitable with the stage

Bug 12 : KnownPVType did not point to specific index at all when was being called

Test 16 : Created PV_System for each adopter has the correct attributes and NumberOfModules
Bug 13 : The value of ModuleAllocation was modified after the first loop
Bug 14 : NumberOfModules in init for the last adopter was already counting for all adopter

Test 17 : InvestmentCost and Cost of installed PV System calculated properly

Test 18 : Residents which are not adopter assign the correct attributes

Test 19 : Residents which have motivation assigned proper knowledges according to the motivation

Test 20 : Neighbors decided correctly, as well as the SocializationPressure and AdopterConnection
Bug 15 : If a resident does not have Neighbors, SocializationPressure cannot be calculated
Bug 16 : The resident itself was still included
Persistent bug : It still has Neighbors even with NeighborsDistance = 0

Test 21 : Scale-free networks build with proper distribution
Bug 17 : The first resident would always have the most connection

Global Reflexes

Test 22 : InfluencingProbDecrease determined correctly

Test 23 : Progress data of PV installed and adoption, recorded correctly

Test 24 : PV Prices and FindPVInstaller variables updated correctly

Test 25 : Residents decide to socialize or not correctly
Bug 18 : Value of SocializingTendency was not yet assigned

Test 26 : Scenario changes at the correct time and correctly
Bug 19 : The initial Scenario was already set to the Scenario after 2023

Residents Action (looking_for_partner, looking_for_adopter, internet_research, and assess_interest)

Test 27 : Residents doing action looking_for_partner change their SocializingState accordingly to whether it has socializing Partner or not

Test 28 : BlacklistFree determined correctly
Bug 20 : There was no condition for residents which do not have Blacklist
Bug 21 : No adopter was found because of case sensitive mistake on Adopter into stage earlier
Bug 22 : Neighbors was still added again even though already included in AdopterConnection
Bug 23 : Blacklist was also affected eventhough the command specified BlacklistFree
Bug 24 : Index loop should start at 0

Test 29 : Partner chosen correctly from Whitelist

Test 30 : Decision making based on the presence of a socializing Partner is correct

Test 31 : Action internet_research executes correctly

Test 32 : The assigned values for PerceivedAttributes (except payback period and investment cost) in assess_interest action are correct
Bug 25 : PowIndepKnowl was in fraction when MaxValue subtracted with it, also SocialPress

Bug 26 : PerceivedAttributes was not cleared after when a second assess_interest action happens

Test 33 : PerceivedAttributes' values for payback period and investment cost, while only having 1 KnownPVType, determined correctly

Test 34 : PerceivedAttributes' values for payback period and investment cost, while having 2 KnownPVType, determined correctly
Bug 27 : KnownPVType was not considered when deteriming PerceivedAttributes values

Test 35 : Liking and OldInterest determined correctly
Bug 28 : Some 'Potential Ad' might not have had Interest yet

Test 36 : PrematureInterest is calculated correctly in each loop
Bug 29 : The calculation was missing a multiplication factor of 10

Test 37 : Interest is calculated properly when having 1 KnownPVType
Bug 30 : There was resident which do action assess_interest but has not had KnownPVType yet
Bug 56 : Interest was not filled yet if PerceivedAttributes for InvestmentCost is 'nothing'

Test 38 : Interest is calculated properly when having 2 KnownPVType
Bug 31 : The first value(s) of Interest was not removed because of incorrect indexing

Test 39 : PreferredSystem is chosen correctly

Residents Action (finding_installer_on_internet, become_rejecter, consulting_installer, and evaluating_interest_liking)

Test 40 : Assignment of SystemFound and Vendor, and action assess_interest executes correctly
Bug 32 : FindTypeInstaller both 1 and 2 were not multiplied by PromotionFactor
Bug 33 : Vendor was assigned as list
Bug 34 : Condition when having 2 KnownPVType was using Interest instead of KnownPVType

Test 42 : Decide Vendor correctly according to SystemFound
Bug 35 : Condition for 'Potential Ad' which have 2 KnownPVType but only 1 Interest was not created

Test 43 : Decision to become_rejecter, making_purchasing_deal, do nothing or setting ResearchState to 3 are made correctly
Bug 54 : Condition for 'Potential Ad' which have 2 KnownPVType but only 1 Interest was not created

Test 45 : Action become_rejecter executes the changes correctly

Test 46 : Looping in gain_knowledge_from_installer action updates residents'Interest correctly
Bug 55 : Condition for 'Potential Ad' which have 2 KnownPVType with 1 Interest was too early
Bug 57 : Loop was done twice no matter the result in the first loop

Test 47 : Asking Vendor to creating_proposed_system through assess_interest is called correctly
Bug 53 : Vendor's ProductSold's PowerProduction was not cleared after the encounter

Test 48 : Decision to making_purchasing_deal or become_rejecter are chosen correctly
Bug 36 : Condition for 'Potential Ad' which have 2 KnownPVType but only 1 Interest was not created

Test 49 : Decision in evaluating_interest_liking action is chosen correctly

Test 51 : Loop to choose AdopterConnection to be asked and

Bug 37 : The pool which can be chosen to be asked for was not determined correctly in every loop

Residents Action (socializing and behavior)

Test 52 : Resident and its Partner change their SocializingState, Partner, and Last3Partners at the end of socializing action

Test 53 : Non Adopter's socialization effect with Early Re and Knowled Re is executed correctly

Test 54 : Adopter's socialization effect influencing others is executed correctly (KnownPVType, knowledges, and AdopterConnection)

Test 55 : Potential Ad's socialization effect being influenced by Adopter is executed correctly
Bug 38 : When Potential Ad's knowledge was higher, it was possible for it to go down instead

Test 56 : SocialPress in behavior updated correctly based on SocializationPressure
Bug 39 : There was no condition for residents without Neighbors
Bug 40 : Value of SocializationPressure went down excessively to negative value

Test 57 : Last3Partners updated with none and to keep it having only 3 members
Bug 41 : Last3Partners will always be 0 because it starts with 0 and not added

Test 58 : Requirements to become Potential Ad from Non Adopter or Early Re is correct
Bug 42 : The code for condition based on Motivation was repeated

Test 59 : Early Re becomes Potential Ad after socializing with an Adopter and having a Motivation

Test 60 : When becoming a Potential Ad, Blacklist is updated correctly based on Last3Partner
Bug 43 : "none" in Last3Partners may also be added to Blacklist

Test 61 : Potential Ad updates its Blacklist based on Last3Partners

Test 62 : Potential Ad becomes Rejecter when it reaches TimeLimit

Test 63 : Potential Ad keeps adding TimeAsPotentialAd when not reaching TimeLimit
Bug 44 : MakeDecisionTimeLimit was not implemented

Test 64 : Knowled Re becomes Potential Ad when its ConnectionRemains is 3

Actions to making_purchasing_deal, creating_proposed_system, and calculate_power_production

Test 65 : Interest is calculated with detail calculation with Vendor's creating_proposed_system action
Bug 45 : Condition to ask Vendor to creating_proposed_system was $>$ instead of $\geq$

Test 66 : ObservedHouse and RooftopFactor determined correctly
Bug 46 : Orientation condition should be 135 instead of 130

Test 67 : Maximum ModuleAmount, TotalArea and TotalCost set correctly under default Scenario

Test 68 : ModuleAmount and TotalArea based on TotalCost set correctly under default Scenario

Test 69 : ObservedHouse and Irradiance data assigned correctly

Test 70 : Irradiance data specific for each Orientation chosen correctly
Bug 47 : Condition for flat houses with 0 RooftopTilt was incorrect

Bug 48 : Matrix index should start at 0
Bug 49 : Condition for flat house was not specific enough

Test 71 : Irradiation and PowerProduction calculated correctly with the matrices
Bug 50 : There was no condition for when having 3 sides of Orientation being used altogether

Test 72 : AnnualSaving calculated correctly for default Scenario
Bug 51 : Power was still in Wh unit
Bug 52 : **Sum function does not work correctly**

Test 73 : PaybackPeriod calculation is correct

Test 74 : WillingToPay calculation is done correctly
Bug 53 : Value taken from Interest for Intention should always be at index 0

Test 75 : The resident's new OwnedPV obtains its attributes correctly from Vendor proposal

Test 76 : Vendor asked to do another creating_proposed_system correctly if necessary

Test 77 : Neighbors' AdopterConnection, NumberOfInstalledPV and PowerOfInstalledPV is updated

Power Demand and Other Different Scenarios

Test 78 : PowerDemand for Net Metering Scenario calculated correctly in creating_proposed_system
Bug 54 : Indexes were not correct

Test 79 : InstantSelfUsed and StoragePower calculated correctly under the other Scenarios when PV produces any power

Test 80 : Power fed back to the grid and power used alone calculated correctly

Test 81 : InstantSelfUsed and StoragePower when PV does not produces power calculated correctly
The problem in sum function in GAMA is a shocker as the function is a fundamental function which often used in various calculation. It forces the author to contemplate for a long time on whether the model was wrongly built or not, and has to spent lots of time wasted on figuring out the problem.

Appendix F

Model to Calculate Power Production for Different Roofs

Irradiance data from weather data in Hoek van Holland for the year of 2017 was used predict the amount of irradiance received on a surface at different angle in a year. The script is built in MATLAB and includes function to determine sun position and irradiance received by the module for the whole year. The model was mainly built from Smets et al. (2016). The first 2 sections describes this script.

After having the appropriate received irradiance value, the amount of PV surface area at each roof orientation and angle is needed to calculate the total power produced by the system. This process to calculate power production is part of the GAMA software implemented in chapter **??**.

F.1 Sun position

The sun position can be evaluated with D, that is the number of days passed since Greenwich noon, 1 January 2000, in days. With D, the *mean longitude* of the sun corrected to the aberration of the light can be evaluated by

$$q = 280.459^o + 0.98565^o D. \tag{F.1}$$

Mean anomaly of the sun will be necessary to correct q because of the elliptic orbit of the Earth. It is formulated as

$$g = 357.529^o + 0.98560^o D. \tag{F.2}$$

Both q and g was normalized to the value of between 0^o and 360^o. Then, the *ecliptip longitude* of the sun is

$$\lambda_S = q + 1.915^o \ sing + 0.020^o \ sin2g. \tag{F.3}$$

The number of centuries passed after the date and time as mentioned above is given by

$$T = \frac{D}{36525} \tag{F.4}$$

and the *Greenwich mean sidereal time (GMST)* is given by

$$GMST = 18.697374558h + 24.06570982441908h \ D + 0.000026h \ T^2. \tag{F.5}$$

GMST is also normalized to the value between 0^o and 360^o. Then the *local mean sidereal time*, θ_L, can be calculated with

$$\theta_L = GMST\frac{15^o}{hour} + \lambda_0 \tag{F.6}$$

where λ_0 is the longitude of the location. The *axial tilt* of the Earth is also put as a function of time

$$\epsilon = 23.429^o - 0.00000036^o D. \tag{F.7}$$

Knowing the longitude and latitude of the location (Φ_0), Earth axial tilt, and ecliptic longitude of the sun, both azimuth (A_S) and altitude (a_S)of the sun can be evaluated with

$$sin a_S = cos\phi_0 \; cos\theta_L \; cos\lambda_S \; + \; sin\lambda_S \; (cos\phi_0 \; sin\theta_L \; cos\epsilon + sin\phi_0 \; sin\epsilon) \tag{F.8}$$

$$tan A_S = \frac{-sin\theta_L \; cos\lambda_S \; + \; cos\theta_L \; cos\epsilon \; sin\lambda_S}{-sin\phi_0 \; cos\theta_L \; cos\lambda_S \; - \; sin\lambda_S \; (sin\phi_0 \; sin\theta_L \; cos\epsilon - cos\phi_0 \; sin\epsilon)}. \tag{F.9}$$

Attention must be given when applying arctan function as it may be ambiguous as each quadrant corresponds to the same tangent value. Therefore, the relation can be further separated depending on the numerator and denominator:

$$denominator > 0 \; \wedge \; numerator > 0 \; \Rightarrow \; A_S = arctanf(...), \tag{F.10}$$

$$denominator < 0 \; \Rightarrow \; A_S = arctanf(...) \; + \; 180^o, \tag{F.11}$$

$$denominator > 0 \; \wedge \; numerator < 0 \; \Rightarrow \; A_S = arctanf(...) \; + \; 360^o. \tag{F.12}$$

F.2 Received irradiance

There are three types of irradiance that may be received by the module, direct irradiance, diffusive irradiance and reflective irradiance. Only direct irradiance is modeled as it is the most dominant one out of the three.

An important parameter which determines the received irradiance by the module is the *angle of incidence* (AOI). AOI can be obtained from 4 variables, sun azimuth (A_S), sun altitude (a_S), module azimuth (A_M) and module altitude (a_M), with the following relation

$$cosAOI = cos \; a_M \; cos \; a_S \; cos(A_M \; - \; A_S) \; + \; sin \; a_M \; sin \; a_S \tag{F.13}$$

with module altitude is given by a_M = 90^o - θ_M, where θ_M is the *tilt angle* of the module. There are also 3 other variables that essentially affect the amount of received irradiance: *direct normal irradiance* (DNI), *global horizontal irradiance* (GHI), and *direct horizontal irradiance* (DHI). All of these sun-related variables are usually available in weather condition database.

Direct irradiance can then be obtained with the following relation

$$G_{DIR} = DNI \; cosAOI. \tag{F.14}$$

This relation is only valid when A_S is within $\pm 90^o$ of A_M, implying the sun is in front of the module. Beyond this value, $G_{DIR} = 0$.

It is important to be noted that G_{DIR} automatically becomes equal to 0 W/m^2 when the altitude of the sun is smaller than 0, implying that the sun is below the horizon.

F.3 System Design and Power Produced

Depending on the rooftop type, installer assign the amount of PV module differently. For a house with flat roof, this is rather straight forward. For a gable roof, the orientation also determine the selection design process. If the roof is facing east and west, both roof slopes are filled with PV with the same amount. If not, the only roof slope that is used is the slope that faces to the south, or southwest or southeast.

For a hip-pyramid roof, once again, the orientation matters. For roof which faces north-south-east-west, it is either 1 slop or 3 slopes are used, depending on the amount of PV module. Roof that faces south is filled first. If the module has not covered all area on the roof slope that faces south, the remaining modules are distributed between the east and west slope evenly. If the roof is facing the southwest-southeast etc., only 2 roof slopes are filled, the two that faces to the south.

Again, both slopes are filled with the same amount of PV.

After having the orientation and PV size of each roof slope, the irradiation for that orientation (and roof angle) is selected. This irradiation is then multiplied by total PV area, PV efficiency, and BOS efficiency to determine the hourly power production (equation F.15).

$$\mathit{PowerProduction} = \mathit{Irradiation} \times \mathit{ProposedTotalArea} \times \mathit{PVEfficiency} \times \mathit{BOSEfficiency} \tag{F.15}$$