MASTER IN ENERGY MANAGEMENT AND SUSTAINABILITY

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Assessment of long term solar PV diffusion in Switzerland

Agent-based diffusion model for single family houses

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Abstract

Shortly after the Fukushima disaster in 2011, the Swiss Government decided to gradually phase out of nuclear energy. This decision was coupled with the adoption of a challenging national energy strategy (Swiss energy strategy 2050), which among others focuses on increasing the non-hydro renewable electricity production. Among the technological options, solar photovoltaics (PV), displays a significant potential and it also enjoys high social acceptance. This study investigates the decision to adopt the PV technology at a residential level according to four major criteria: the economic profitability of the investment, the environmental benefit, the income level of the household and the impact of the social networks; the so-called "neighboring effect". To this extent, an agent-based model is developed, including agents that represent single-family houses located at all cantons of Switzerland and classified into several demographic and socio-economic categories. The decision of each agent is stochastic, it is obtained by suitable fitted probability distributions and it is evaluated upon the above mentioned criteria. The scope of the study is to forecast the future PV residential deployment and provide the drivers which affect the most in the adoption decision. Therefore, several scenarios are examined, representing different regulations and policies that support solar PV penetration, as well as sensitivities on technical and economic prospects of solar panels. In addition, the model quantifies the uncertainty surrounding the decision of an agent to install a solar PV system by running with different synthetic populations. In the present study, we test this concept by creating six different synthetic populations of the agents, based on Monte Carlo simulations with probability distributions fitted from real data. However, we don't provide quantification of the uncertainty in terms of variance and other moments, because of the limited number of synthetic populations.

The results show that the economic and the income criteria have the biggest influence on the decision of installing or not a solar PV system, especially in the near-term period, while the effect of the social network accentuates towards the end of the forecast horizon. The analysis also suggests that the cumulative number of adopters and consequently the total installed solar PV capacity in single family houses do not vary significantly between the best and the worst scenario. However, the underlying policies and technical progress significantly affect the timing of the investment. This means that better scenarios lead to faster diffusion of the technology and are to be preferred for a successful implementation of the challenging Energy Strategy 2050. Expanding this work to all potential adopters (including industrial, commercial and multi-family houses, markets) will give more insights on the diffusion of solar PV and will lead to more accurate predictions and testing of new regulations. It should be noted that in designing and implementing the model we didn't conduct specific surveys among the private investors, but we relied on publicly available studies and data. At the same time, we do not go below the cantonal level in terms of spatial resolution. These two limitations should be taken into account when interpreting the results of this study and they constitute two important extensions for future research work on this topic. Another important extension could be the application of the model to more than six synthetic populations.

Acknowledgments

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1. Introduction

Electricity production in Switzerland is dominated by hydropower and nuclear energy. Hydropower represents 56% whereas nuclear energy 39%. Renewable energy contributes 2% and the rest (e.g. fossil fuel power plants) make up 3%. Solar photovoltaic (PV) energy accounts for less than 1% of the total electricity generation [1].

In 2009, a federal feed-in-tariff scheme was implemented and PV energy diffused significantly**.** Figure 1 illustrates the annual installed and cumulative capacity in the period 2006-2013 [2]. It is noteworthy that in 2012, 226MW were connected to the grid, which is higher than the cumulative capacity at the end of 2011.

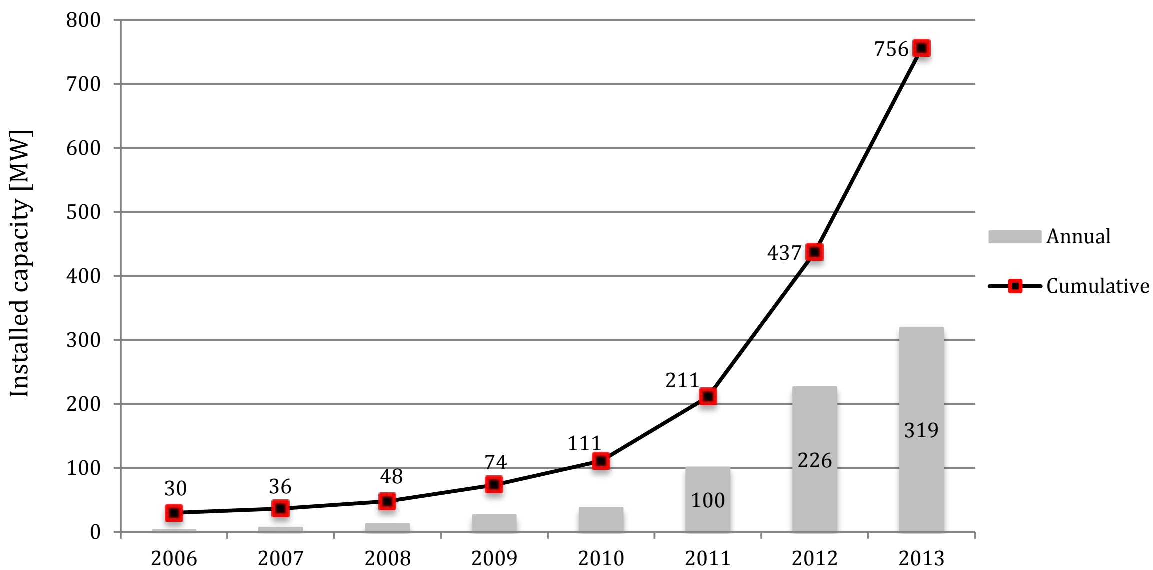

Figure 1: Annual and cumulative installed PV capacity in Switzerland (2006-2013).

Under the new feed-in scheme, the local utilities are obliged to buy electricity from private producers at a fixed price (fixed tariff) that covers the production cost of the specific renewable technology plus a premium (Figure 2). However, the total cost cap is not a fixed sum but instead it is influenced by several factors that change dynamically. The two main factors are: the investment costs and the market price of electricity. The higher the market price of electricity or the lower the investment costs respectively, the less additional cost have to be covered by the feed-in remuneration. The production costs are calculated for predefined reference installations, corresponding to the most efficient technology in the year of construction. The payments occur over a period of 20 (for geothermal, biomass, wind) to 25 years (for PV, hydropower). The payment for each unit of electricity is covered by two different money sources. The power companies pay the current spot market price of electricity and a central fund adds the difference between the spot market price and the fixed tariff. The fund is fed by all end-consumers through a surcharge on the electricity bill.

A foundation ("KEV Stiftung") has been set up to manage the fund. New projects are realized on a first come, first served basis until the fund is exhausted.

In addition, specific caps for each technology have to be respected. Each technology can only receive a fixed share of the total fund. The share of photovoltaic electricity was initially set at 5%. This limit created a long waiting list as more projects than expected applied for the feed-in remuneration. Indeed, six months after the registration date, 5’426 plants had already applied and 3’000 registered photovoltaic plants were on a waiting list. The total cost cap for compensatory feed-in remuneration had been exhausted. As an instant measure, the Parliament approved a stabilization program in 2009, upon which, an exceptional fund of CHF 20M was granted to photovoltaic projects that were on the waiting list. In 2011, the cap increased to 10%, leading to an amount between CHF 25M to 32M per year for photovoltaic projects [3], [4].

In March 2011, following the nuclear disaster in Fukushima, the Federal Council announced that nuclear power will be phased out gradually and will be replaced mainly by renewable power. Consequently, PV was perceived as a potential source of electricity to be developed. The new energy policy implied that PV energy should contribute by 4% in 2030 and by 17% in 2050 with a total installed capacity of 9.5 GW [5].

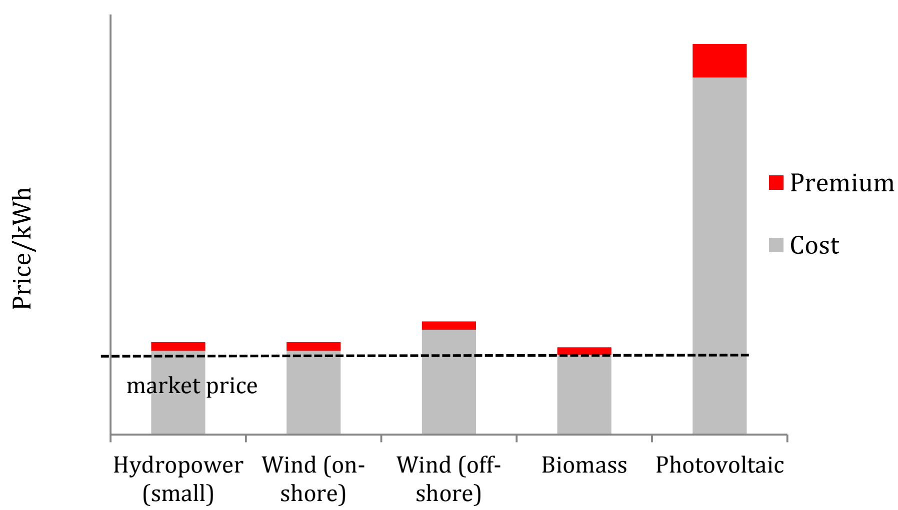

Figure 2: The principle of feed-in tariffs [4].

With respect to small PV installations, Figure 3 and Figure 4 illustrate the share and the cumulative capacity of installations in single-family houses. The capacity share of installations in single-family houses reached its peak in the years 2008-2009, and it is thereafter decreasing. One can conclude that small installations benefited from the exceptional funding, since then, if applying the same year, a priority is given to large plants for the feed-in remuneration [3]. However, owners of small PV installations will wait another six years for a favorable policy to be introduced.

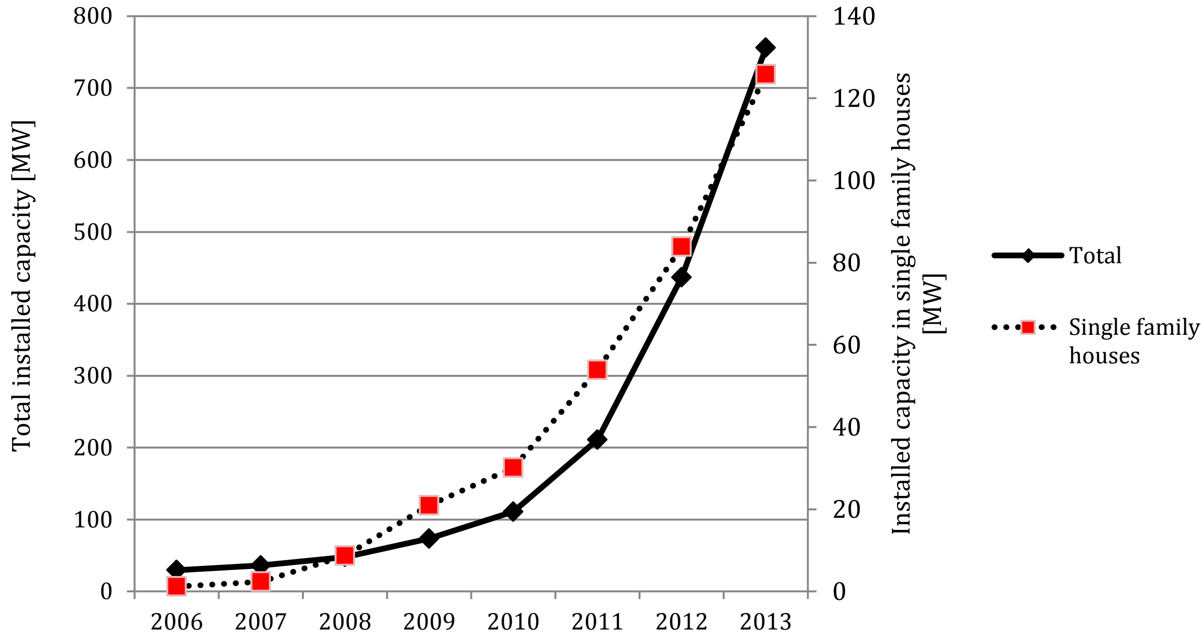

Figure 3: PV installed capacity (in total and in single family houses, 2006-2013).

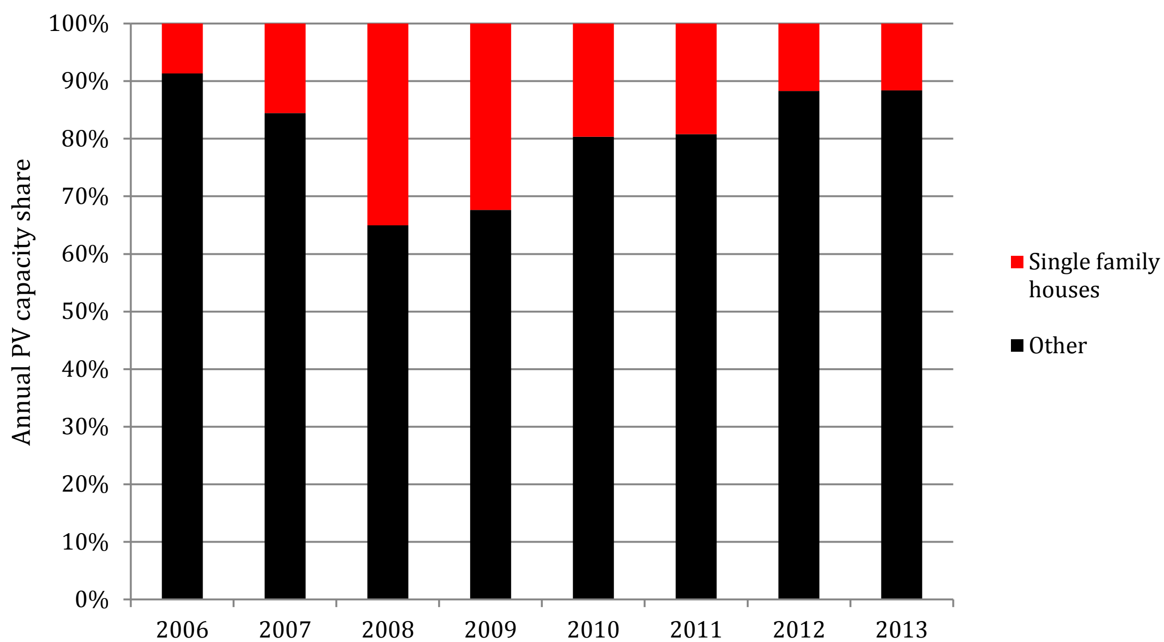

Figure 4: Capacity share of single family houses (2006-2013).

1.1. The new supporting scheme for small PV systems

In 2014, a new policy was launched aiming at reducing the waiting list of PV projects by encouraging small PV applications. This new policy stipulated that small installations do not have to apply for the feed-in remuneration but instead they can benefit from a 'one-off investment grant' (unique payment). This new financial instrument covers a maximum of 30% of the investment costs, according to a reference (cost-optimal) installation each year. Therefore, from the 1st of January, 2014, the energy law has been modified as follows [6]:

- PV installations with a nominal capacity of 2kW-10kW are no longer eligible for the feed-in remuneration but instead they can receive the unique payment.
- PV installations with a nominal capacity of 10kW-30kW can choose between the feed-in remuneration and the unique payment.
- PV installations with a nominal capacity larger than 30kW are obliged to receive the feed-in remuneration.
- PV installations with a nominal capacity less than 2KW are no longer eligible to federal financial incentives.
- The one-off investment grant is not available to applicants registered before 2012.

Under the current system, the candidates must wait years until their application is approved. The date of the commissioning is key to determining the amount of compensation. The installation will remain on a waiting list until it receives a positive decision. Once a positive decision will be issued, the owner will receive the compensation for 25 years. The years on the waiting list are not considered (even retroactively). In addition, if the plant is built in 2015 but receives a positive decision in 2013, the installation will be treated under the law of 2013. It will receive the compensation as in 2013, but with an annual reduction of 8% [7] for 25 years from the commissioning.

On the contrary, with the one-off investment grant, payments take place in a much shorter time. The general rule implies that the length of time between the candidate's application and the date of approval is 3 months. However, due to the numerous cumulated applications waiting for a green light, it is estimated that until 2015 this procedure might take longer. From 2015, the deadline for the commissioning of the plant will now be 15 months from the receipt of the positive decision. The annual reduction rates of compensation are 0% from 2014 and the retribution period is 15 years from commissioning [8].

In addition to the above, producers who receive the one-off investment grant can consume the electricity they generate. If the production exceeds the consumption, the producer can sell his remainder production in the electricity market. Electricity companies have to buy the remainder electricity at a price of 6-10 Rp/KWh, which corresponds to the average production cost of an electricity company. Electric companies are required to buy electricity at the market price (prices may vary depending on the year and currently fluctuates on average between 6 and 10 Rp/ KWh). Furthermore, the ecological added value (the added value of green production compared to current electricity conventional manner) can be sold to respective enterprises [6]].

1.2. Problem statement and research question

The targets to be reached for a sustainable energy system in Switzerland by 2050 seem rather challenging. Energy laws are constantly updated in order to meet new energy requirements. Renewable energy should inevitably play a leading role in the future. Among all renewable technological options, photovoltaics have gained increasing attention the recent years in respect of its future potential growth. The current regulation of federal feed-in remuneration to PV producers has been criticized for its contradictory behavior; it initially triggered the PV deployment and it later caused a moratorium. To this end, a new regulation was launched to encourage mostly the residential PV market.

In light of the new energy perspectives driven by new regulations this study focuses on the future diffusion of PV technology in Switzerland. More specifically, it aims at developing a reliable tool in order to predict the future PV residential deployment until 2050. An agent-based model has been developed to analyze a household's decision to adopt PV technology. An agent-based model can explicitly simulate the adoption process of individual entities that live and interact within a heterogeneous social system. To avoid complex behavior patterns resulting from joint multi-family decisions, this study considers as agents only the single-family houses. The agent's unique characteristics will result from Monte Carlo simulations. Moreover, the agents are distributed geographically and demographically in order to account for the different regional and social differences. It is assumed that the main factors affecting a household to install a PV system are the economic profitability of the investment, the household's income, the environmental benefit of the investment and the impact of social networks.

The current work tries to understand the uncertainty surrounding the penetration rate of solar PV by assessing a number of scenarios. These scenarios have been designed in order to provide insights regarding the following questions:

- What is the role of the current supporting policies in accelerating the difussion of the solar PV systems? Should they phased out or be continued?
- How sensitive is the adoption rate of solar PV systems with respect to electricty price?
- What are the key drivers influencing the timing of the investment in solar PV? Which of them can bring the investments forward and which of them delay the difussion?
- How important is the social component and the neighbouring effect in the adoption of the solar PV system?
- How the attractiveness of the investment in solar PV is affected by its technico-economic characteristics?

- What is the role of the discount rate in evaluating the investment in solar PV?

2. Literature review on agent-based modeling

Agent based modeling (ABM) is a simulation technique, that is widely used in the recent years due to its numerous applications in real-life problems. In agent based modeling (ABM), a system is modeled as a collection of individual entities called agents. The scope of an ABM is to give an insight not only to the individual behavior and decision-making of its entities but also to reflect the interactions between different entities within an environment. An ABM is a synonym to microscopic simulation. At the simplest level, an ABM consists of a system of agents and the relationships between them. An ABM is a powerful tool providing behavior patterns and valuable information about the dynamics of a real-life complex system [9].

One of the strongest advantages of the ABM is that it provides a realistic description of a system by reducing restrictions and assumptions such as homogeneity, stationary, linearity etc., that are imposed by other simulation techniques that mostly rely on statistical modeling [Zhao]. Moreover, by modeling the relationships on the level of individuals in a rule-based way, agent based simulations can capture emergent phenomena without having to make a priori assumptions regarding the aggregate ("macroscopic") system properties [10]. Lastly, an AMB is characterized as flexible, allowing changes in sub-models rather than restructuring the system as a whole [11].

Its four major areas of applications are: flows (e.g. traffic dynamics, evacuation), financial markets (e.g. stock markets), organization and managerial decisions (e.g. operational risk) and diffusion innovations and adoption dynamics [12]. The latter has gained significant scientific attention in recent years due to the forementioned characteristic of an ABM to capture complex emergent phenomena such as the diffusion of an innovation on a socio-economic system and its ability to provide forecasts, decision support and policy analyses for specific applications based on empirical data [13].

The present study focuses in the diffusion of PV innovation technology. In recent literature there are only a few researchers who have applied an ABM to simulate the diffusion of PV systems (e.g. [14],[15],[16]). Zhao et al., studied the effectiveness of various policies and regulations in the adoption growth of PV systems in two regions in US. Palmer et al., modeled the diffusion of residential photovoltaic systems in Italy. The former defined four main factors affecting the adoption process: the payback period, the household income as well as the impact of the neighborhood and advertising whereas the latter united the impact of the neighborhood and advertising in a larger factor that account for the social network influence and added the impact of environmental awareness. These studies highlight the importance of human perception about PV technology in addition to financial incentives and governmental policies. Nevertheless, the factors influencing PV adoption and their modeling have been the subject of several publications who conducted surveys (e.g. [17], [18]) or forecasting models other than ABM (e.g. [19]).

Our model is mostly inspired by the work of Palmer et al. and aims at providing a reliable tool in forecasting the growth of adoption of PV systems in single-family houses in

Switzerland by incorporating four main factors: the impact of financial incentives and purchasing costs of a PV system, the agent's eco-friendliness, the agent's income and the influence of communication between agents.

3. Modeling an agent's adoption decision

An agent represents a single-family house in Switzerland. The level of willingness of an agent (i) to install a PV system is a function of four factors, each one represented by a utility function: the economic utility (the agent's payback period), the environmental utility (the agent's eco-friendliness), the income utility (the agent's income), and the communication utility (the agent's communication links with other adopters). The total utility is expressed as the weighted-sum of the above utilities given by the following formula:

$$U_{total}(i) = u_{ec}(i) \cdot w_{ec}(i) + u_{en}(i) \cdot w_{en}(i) + u_{in}(i) \cdot w_{in}(i) + u_{com}(i) \cdot w_{com}(i) \quad [1]$$

Where:

- $w_n,\ n \in N: \{ec, env, in, com\}$ are the corresponding weights of the partial utilities
- $\sum_n w_n(i) = 1,\ n \in N: \{ec, env, in, com\}$ and $w_n(i), u_n(i) \in [0,1]$.

All utilities are normalized between 0 and 1, with 0 denoting no willingness and 1 strong willingness to install a solar PV system. All utility functions create an S-shape curve. It is assumed that if the agent's total utility is higher or equal to a certain threshold it will become a PV adopter. The threshold and the weights of the partial utilities are defined from the model's calibration; that is the model's comparison to historical data (see Chapter 6).

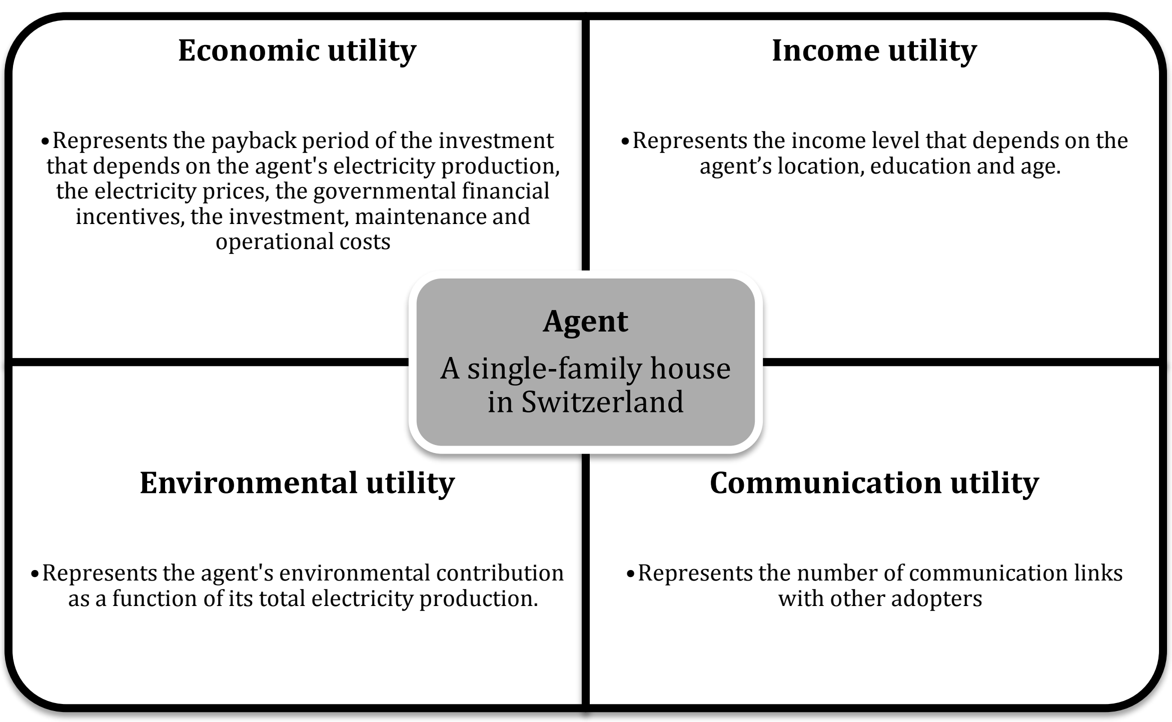

Figure 5: Representation of the agent and the factors affecting its decision to adopt.

3.1. Economic utility

The economic utility represents the expected payback period of an agent's specific investment. The time length of the investment is assumed to be 25 years for all agents; it is the current lifespan guaranteed by the PV solar panel manufacturers. Within this time length, the projects will generate multiple cash flows that are mainly determined by the energy production of the PV system. Since the multiple cash flows occur at different times, it is necessary to express them in present values, to make them comparable. In order to move all future cash flows backward in time we must discount them. The present values obey the principal of value additivity. The net present value (NPV) of an investment is the difference between the present value of its benefits and the present value of its costs:

$$NPV = -I_0 + \sum_{n=0}^{N} PV(CF_n) = -I_0 + \sum_{n=0}^{N} \frac{CF_n}{(1+r)^n} \qquad [2]$$

Where:

- $CF_1, CF_2, \dots CF_N [CHF]$ are the cash flows at dates $1,2, \dots N$, including both negative and positive flows.
- $I_0 [CHF]$ is the initial investment cost that occurs in year 0.
- $r[\%]$ is the discount rate or return on investment, one would anticipate receiving, it is the annual percentage yield on the investment. The expected return on investment is the rate, with which we discount the future cash flows into present values. It does not take into account only the time value of money, but also the risk or uncertainty in future cash flows. In the present study the annual discount rate is assumed constant in all horizons and equal to 5.5%.

The payback period is the length of time required to recover the initial investment. Although the payback period is sometimes used as a financial tool, it has some serious drawbacks as it doesn't take into account the time value of money. To mitigate this limitation of the simple payback period an alternative procedure called discounted payback period is followed, which computes the length of time to recoup the initial investment, based on the investment's discounted cash flows, thus taking into consideration the time value of money. The discounted payback period is therefore the year in which the NPV switches from negative to positive. This is more reliable, but still ignores the cash inflows from the project after the payback period.

The economic utility is represented in Figure 6 and is expressed by the following formula:

$$u_{ec}(i) = \frac{e^{\frac{-(pp(i)+pp_{avg})}{a}}}{1+e^{\frac{-(pp(i)+pp_{avg})}{a}}} \qquad [3]$$

Where:

- $pp(i)[years]$ is the discounted payback period of the agent's investment.

- $pp_{avg}[years]$ is a constant value set to 13 years. In that way, an agent that has a payback period of 13 years will have an economic utility equal to 0.5.
- $a[-]$ is a constant that defines the slope of the curve. It is set to 2.7; a lower (a) will create a steeper curve whereas a higher (a) a more shallow one.

Given that the lifetime of the investment is 25 years, the economic utility is approximate 0 when the payback period is 25 years and 1 when the payback period is 0, as can be seen in Figure 6.

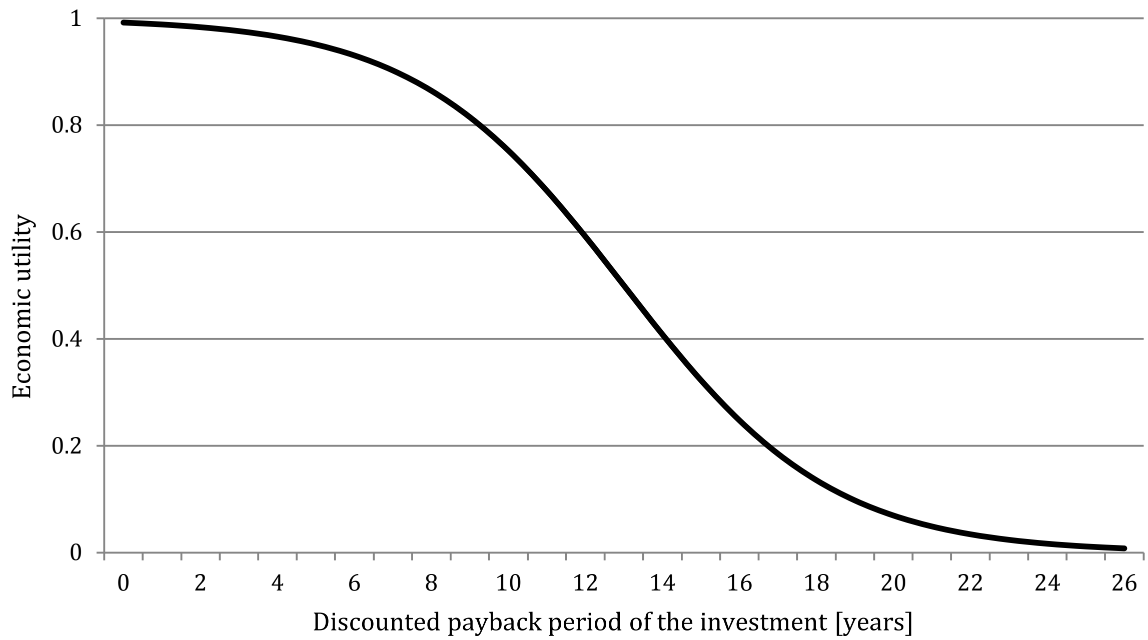

Figure 6: Economic utility function curve.

As described in Chapter 1.1, the governmental policy, starting from 2014 (i.e. the staring year of our simulation) is different for producers of an installed capacity less than 10kW and higher than 10kW. Therefore, the cash flows of each category have to be calculated accordingly. If the agent's installed capacity is less than 10kW the cash flows of year n are calculated as follows:

$$CF_{n_i} = El_{cons_i} \cdot p_{el_{n_i}} - C_{maint_n} \cdot cap_{installed_i} \quad [4]$$

Where:

- $El_{cons_i}[kWh]$ is the annual electricity consumption of agent (i). It is assumed constant each year.
- $p_{el_{n_i}}[\frac{CHF}{kWh}]$ is the electricity price of agent (i) in year n, according to its location.
- $C_{maint_n}[\frac{CHF}{kW}]$ is the annual maintenance and operational cost. It is constant to 5 $\frac{CHF}{kW}$ [20] per annum.
- $cap_{installed_i}[kW]$ is the nominal installed capacity of agent (i).

In the case where the amount of electricity produced exceeds the amount of electricity consumed the agent can sell its energy to the grid at a price that corresponds to the cost of production of electricity companies. Therefore the cash flows in year n become:

$$CF_n = El_{cons_i} \cdot p_{el_{n_i}} - C_{maint_n} \cdot cap_{installed_i} + (El_{prod_{n_i}} - El_{cons_i}) \cdot p_{prod_n} \quad [5]$$

Where:

- $El_{prod_{n_i}}[kWh]$ is the electricity production of agent (i) in year n. The electricity production of year n is equal to the electricity production of the previous year decreased by a degradation rate. (See chapter 0)
  $$El_{prod_{n_i}} = El_{prod_{n-1i}} * (1 - r_{deg}) \quad [6]$$
- $p_{prod_n}\ [\frac{CHF}{kWh}]$ is the production cost of electricity generation companies in year n.

The producers with a nominal capacity of less than 10kW are eligible to a single payment in year 0 that covers approximately 30% of the initial investment cost. Therefore:

$$I_{0_i} = (1 - x_{inv}) * C_{inv_i} + C_{grid} \quad [7]$$

Where:

- $x_{inv}[\%]$ is the share of unique payment.
- $C_{inv_i}[CHF]$ is the investment cost of agent (i)
- $C_{grid}[\frac{CHF}{kW}]$ is a fee for connecting to the grid [21].

On the other hand, if the agent (i) has a nominal installed capacity higher or equal to 10KW, it can choose whether to receive the feed-in-remuneration for a period of 15 years or the unique payment in the starting year of the investment. If it chooses the latter, then the cash flows and initial investment cost are expressed by formulas [4], [5], [7]. If the agent (i) chooses the feed-in remuneration, it can decide whether to sell its entire electricity outcome or a portion of it and self-consume the remainder. The cash flows of year n in the period of 15 years are given by:

$$CF_n = (1 - x_{DC}) \cdot El_{prod_{n_i}} \cdot FiT_i + x_{DC} \cdot El_{cons_i} \cdot p_{el_{n_i}} - C_{maint_n} \cdot cap_{installed_i} \quad [8]$$

Where:

- $x_{DC[\%]}$ is the share of direct electricity consumption (self-consumption).
- $FiT[\frac{CHF}{kWh}]$ is the feed-in tariff received by agent (i), according to its installed capacity.

Since there is no regulation directive defining the share of direct electricity consumption, it can be easily calculated to optimize the cash flows each year by:

$$x_{DC} = \begin{cases} 0, & if\ El_{prod_{n_i}} \cdot FiT_i \geq El_{cons_i} \cdot p_{el_{n_i}} \\ 1, & otherwise \end{cases} \qquad [9]$$

After the period of 15 years where the agent (i) will no longer receive the feed-in-tariff, it can either sell the electricity production to the grid in the price of production cost or directly consume it. For the remainder period of the investment's lifetime the cash flows of year n are calculated as follows:

$$CF_n = (1 - x_{DC}) \cdot El_{prod_n} \cdot p_{prod_n} + x_{DC} \cdot El_{cons_i} \cdot p_{el_{n_i}} - C_{maint_n} \cdot cap_{installed_i} \qquad [10]$$

The share of direct electricity consumption is now calculated as follows:

$$x_{DC} = \begin{cases} 0, & if\ El_{prod_{n_i}} \cdot p_{prod_n} \geq El_{cons_i} \cdot p_{el_{n_i}} \\ 1, & otherwise \end{cases} \qquad [11]$$

If any case the initial cost is expressed as:

$$I_{0_i} = C_{inv_i} + C_{grid} \qquad [12]$$

If agent (i) has a capacity larger or equal to 10kW the model computes the discounted payback period for both options (i.e. feed-in remuneration and unique payment) and selects the one with the smaller payback period.

3.2. Environmental utility

The environmental utility captures the ecological awareness and sensitiveness of an agent toward renewable energy and specifically PV energy. Viewed another way the environmental utility represents the responsibility of the individual agent towards society. To measure the environmental utility, one can calculate the amount of CO_2 emissions saved by producing "green" energy, however, this would require a further study in the energy mix of Switzerland and its dependency on conventional energy in the future. Therefore, for simplicity reasons, the environmental utility is assumed to represent the total amount of electricity produced by a PV system throughout its lifetime. The environmental utility for agent (i) is expressed by the following formula:

$$u_{env}(i) = \frac{e^{\frac{(E_{total}(i) - E_{total_{avg}})}{a*10^4}}}{1 + e^{\frac{(E_{total}(i) - E_{total_{avg}})}{a*10^4}}} \qquad [13]$$

Where:

- $E_{total}(i)[kWh]$ is the total electricity production of agent (i) in a period of 25 years.
- $E_{total_{avg}}[kWh]$ is a constant, equal to the total electricity production of a reference system of 7kW in a period of 25 years. The PV system of 7kW corresponds to the

average installed capacity per agent in the years of calibration (i.e. in the period of 2010 to 2013). Therefore, the constant is equal to 650'000 kWh, assuming an average annual nominal electricity production of 1'000 kWh (see Chapter 4.4) and a degradation rate of 3% for the first year and an annual degradation rate of approximately 0.039% for the following years. (see Chapter 4.5)

- $a[-]$ is a constant that defines the slope of the curve and is equal to 5.

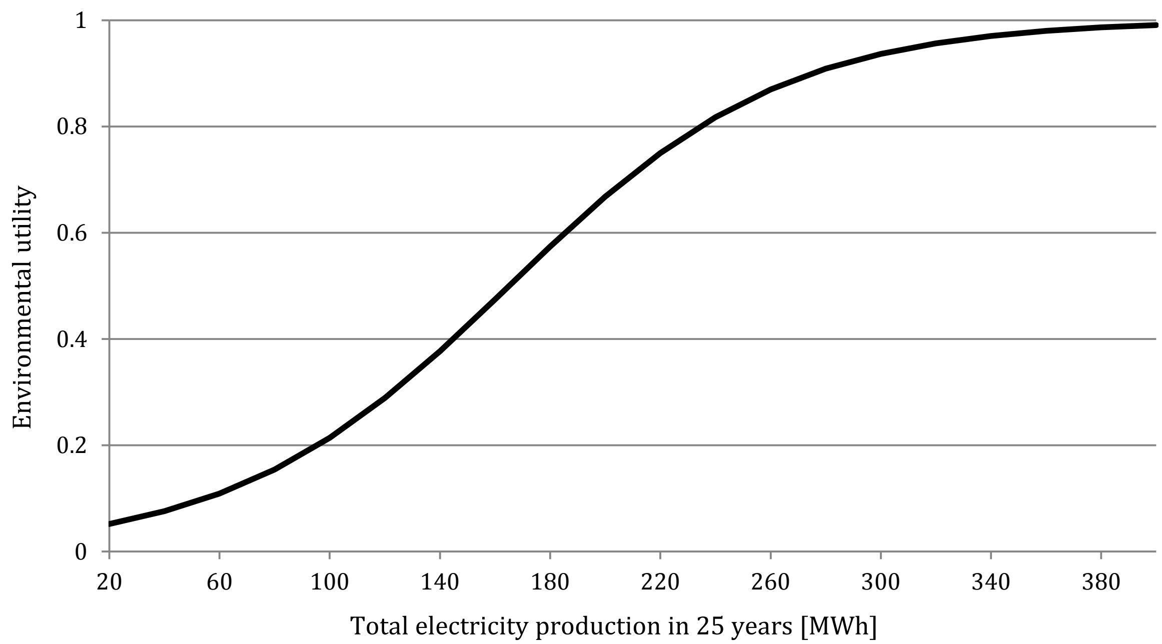

Figure 7: Environmental utility function curve.

3.3. Income utility

The income utility represents the household's income. It is assumed that an agent with an above-average income is more likely to install a PV system. Therefore the income utility of agent i is expressed as follows:

$$u_{in}(i) = \frac{e^{\frac{(Income(i) - Income_{avg})}{10^4}}}{1 + e^{\frac{(Income(i) - Income_{avg})}{10^4}}} \quad [14]$$

Where:

- $Income(i)[CHF]$ is the income of agent (i)
- $Income_{avg}[CHF]$ is the average income of all agents

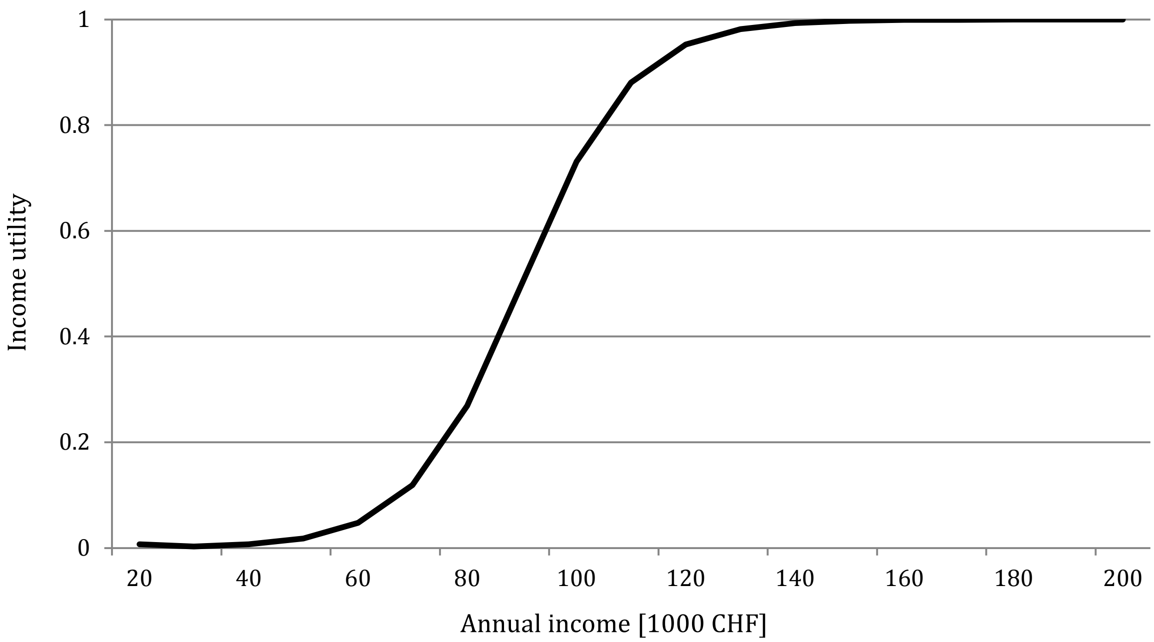

Figure 8: The income utility function curve.

3.4. Communication utility

Innovation adoption and diffusion is significantly affected by the social system in which they are introduced. The nature of people as well as their inter-personal relations will affect an innovation's acceptance. The communication utility is developed to represent the influence of the social communication network in the adoption decision of an agent. In other words, it is developed to quantify the impact of "word of mouth" and the "neighboring effect" among agents.

To this scope, we model the social network of each agent by creating its interpersonal links (i.e. its friends) and we consider the number of friends that are actual adopters. The likelihood of an agent adopting the PV technology increases as the number of friends who are actual adopters increases. The communication utility is therefore expressed as a function of the agent's communication links with actual adopters in relation to a constant average of 5 links:

$$u_{com}(i) = \frac{e^{\frac{(links_{adopters} - links_{avg})}{a}}}{1 + e^{\frac{(links_{adopters} - links_{avg})}{a}}}$$

[15]

Where:

- $a[-]$ is a constant value that defines the slope of the curve and it is equal to 2*.8.*

As can be seen in Figure 9 an agent who has 5 or 10 connections to actual adopters has a communication utility 0.5 and 1, respectively. Since there are only few agents that are actual adopters in the starting year of simulation the communication is very weak. This is the reason why it not exactly zero when the number of links to adopters is zero but slightly larger.

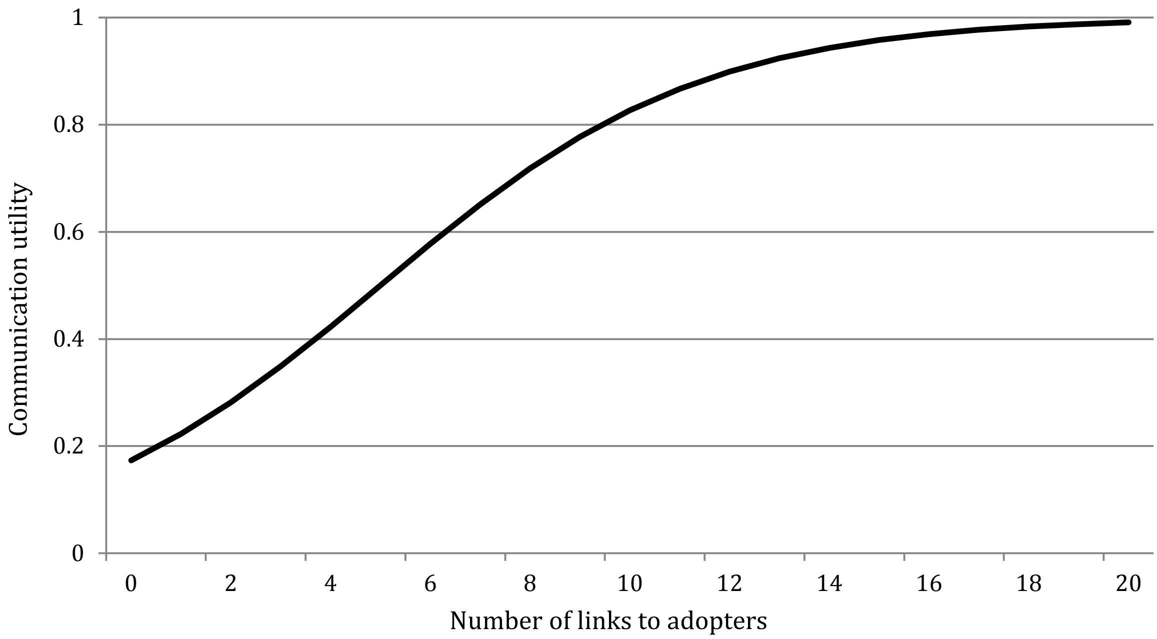

Figure 9: The communication utility function curve.

To create the social network of an agent requires an in-depth analysis of the agent's socio-economic and demographic attributes. In the model, the social system is consisted of different socio-economic categories that host agents which show similarities in their fundamental values, social status, consumption patterns etc. To do so, we follow the Sinus-Milieus model, which classifies people according to demographic criteria and ethics. The resulting sub-groups of people share common values and attitudes towards work, leisure, family, money, technology etc. It has been established as a reliable scientific tool that is constantly updating in order to meet new socio-cultural trends. This social tool is developed and validated for each individual country. The Sinus-Milieus categorization in Switzerland (updated in 2013) [22] can be seen in Figure 10 accompanied by an approximate share and absolute number of the population belonging to each category. People are grouped into 10 categories according to their fundamental values (X-axis) and social status (Y-axis).

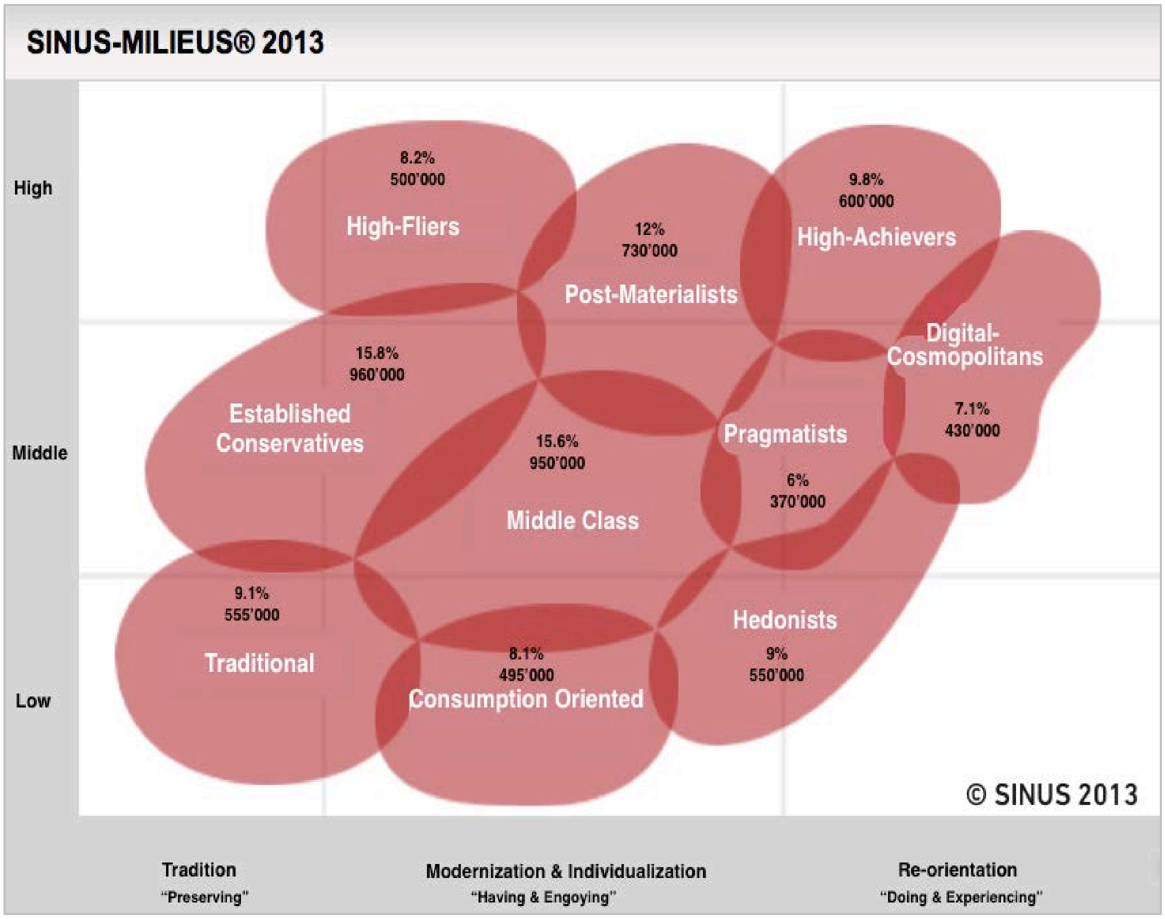

Figure 10: Sinus-Milieus categories in Switzerland, 2013.

General characteristics of Sinus-Milieus categories, such as the age, level of education and income are presented in Table 1. The fundamental values that describe each category are displayed separately in Figure 11. For simplicity, each category each assigned with a number from 1 to 10 and hereafter we will be referring to these categories according to their number. Starting from category 1 down to category 10, it can be observed the incremental trend in income as a result of higher level of education and in turn higher qualification employment. Nevertheless, these categories are also characterized by open-mindedness and technological acceptance. Therefore, we can conclude that those categories that are closer to category 10 are more likely to adopt PV innovation technology as a result of their highest income, environmental awareness, sociability and risk acceptance.

Table 1: General characteristics of Sinus-Milieus categories.

Category	Number of category	Average age	Education	Profession	Monthly income per household [CHF]
Traditionnalistes Populaires: Traditional	1	64	Secondary Vocational	Retirees Workers Freelancers	4’500-6’000
Consommateurs Modestes: Consumption oriented	2	55	Secondary Vocational	Retirees Workers Freelancers	<4’500
Hédonistes: Hedonists	3	35	Secondary Vocational	Employees Workers	4’000-6’000
Moyenne Bourgeoisie: Established conservatives	4	48	Secondary Vocational University	Employees	4’500-9’000
Bourgeois Modernes: Middle class	5	50	Secondary Vocational University	Employees	4’500-6’000
Pragmatique: Pragmatists	6	35	Secondary Vocational University	Employees Workers	6’000-9’000
Cosmopolites Digitaux: Digital cosmopolitans	7	32	University	Qualified employees	6’000-9’000
Bourgeois Superieurs: High-fliers	8	47	University	Superior professionals Employees	9’000
Post-Matérialistes: Post-materialists	9	45	University	Qualified employees	6’000-9’000
Battans: High-achievers	10	39	University	Staff officers Directors Proffesionals	9’000

Traditional	• Strong regional roots, commited to tradition, family-oriented, peaceful, overwhelmed by modern society, pessimistic about the future.
Consumption oriented	• Social and financial insecurity, perpetual struggle against social decline and marginalization, lack of confidence, desire for belonging, consumer desires.
Hedonists	• In search of excitement/entertainment, "peer group", tendency to feel uncontrolled/independent, rejection of performance requirements, aggressive with higher status groups.
Established conservatives	• Aspiration for material comfort, personal responsibility, in compliance with rules and requirements, protection and harmony within the family, realistic, need for security.
Middle class	• Desire of harmonious family life with a guaranteed material comfort, desire for social recognition and integration, seeking security rather than performance, conventional modern lifestyle, austerity and pragmatism.
Pragmatists	• Tendency for belonging, physical and emotional safety, close family ties, clear separation between work and leisure, motivated to make money, want to entertain/controllably consume, willing to adapt.
Digital cosmopolitans	• Eager for new experiences, fulfillment and personal development, spontaneity, flexible principle, individualists, in need of freedom, against fundamentalism, openess to other lifestyles and culture, digital connection.
High-fliers	• Achievement and success, performance and accountability, environmental awareness, tolerance and liberality, education, culture, intensive participation in social life, challenged by globalization and digitization.
Post-materialists	• High ecological and social awareness, cosmopolitan orientation, "citizens of the world", openness, tolerance, multiculturalism, individualism, personal development.
High-achievers	• Driven by performance, ambitious, self-confident, globalization is seen as opportunity, striving for success and recognition, autonomy and personal initiative ,seek experiences, addicted to new technologies.

Figure 11: Fundamental values of Sinus-Milieus categories.

As mentioned before, the model creates the social network of each agent by creating its friends. However, not all categories are likely to link with each other. The probabilities of an agent having a friend who belongs to the same or a different category is given in Table 2 [15]. As expected an agent is most probable to have a friend from the same category. In addition, according to literature [16] the links between people are composed primarily of local connections and less of non-local connections. Therefore, the model considers a higher probability of having a friend from the same location. However, in both cases (e.g. having a friend from the same or different location) the linking probabilities according to Sinus-Milieus are respected. Moreover the number of friends varies among the different categories [Table 3]. Since creating friends implies creating bilateral connections (agent (i) is a friend of agent (j), thus agent (j) is a friend of agent (i)), the model uses the number of links per category according to Table 3 as the minimum number of potential links for each agent and therefore considers it the possibility of an agent having more links than the predefined ones in Table 3. Lastly, the model also considers a small probability of an agent losing a friend (e.g. breaking a link) and reconnect to another agent [Table 3].

Table 2: Probability of an agent connecting to different Sinus-Milieus categories.

	Traditional	Consumption oriented	Hedonists	Established Conservatives	Middle Class	Pragmatists	Digital Cosmopolitans	High-fliers	Post-Materialists	High-Achievers
Traditional	70	0	5	10	10	2.5	2.5	0	0	0
Consumption oriented	0	85	10	0	5	0	0	0	0	0
Hedonists	5	10	75	0	10	0	0	0	0	0
Established Conservatives	10	0	0	70	5	5	5	0	0	5
Middle Class	10	5	10	5	70	0	0	0	0	0
Pragmatists	5	0	0	10	0	35	35	2.5	2.5	10
Digital Cosmopolitans	5	0	0	10	0	35	35	2.5	2.5	10
High-fliers	0	0	0	0	0	2.5	2.5	42.5	42.5	10
Post-Materialists	0	0	0	0	0	2.5	2.5	42.5	42.5	10
High-Achievers	0	0	0	5	0	5	5	5	5	75

Table 3: Probability of an agent connecting to different Sinus-Milieus categories.

	Traditional	Consumption oriented	Hedonists	Established Conservatives	Middle Class	Pragmatists	Digital Cosmopolitans	High-fliers	Post-Materialists	High-Achievers
Number of links	6	10	9	8	8	7	7	7	7	6
Probability to reconnect [%]	0.25	0.25	1	0.75	0.5	1	1	0.5	0.5	1

4. Creating the agents

The development of an agent-based model requires a microscopic analysis on its individually interacting agents. It is important that each agent has a unique identification; although different agents do not necessarily have to have different properties, they have to remain distinguishable. In our case, examples of the agent's unique properties/characteristics are the agent's income, age or the category of Sinus-Milieus in which it belongs. In order to generate the individual characteristics for each agent, we apply a Monte Carlo simulation based on historical data, when available, to generate the population of the agents used in the model.

4.1. Monte Carlo simulations to create the population

A Monte Carlo simulation is a modeling technique, commonly used among risk analysts who aim at minimizing the risk of an investment by predicting all its potential outcomes. In a Monte Carlo simulation an analyst inputs a range of values -a probability distribution- and the program simulates all possible outcomes by running multiple trials, each time selecting a different set of random values from the input probability distributions. The results, therefore, provide the range of possible outcomes and the likelihood of any of the possible outcomes to occur. In a more simplistic interpretation, a Monte Carlo simulation generates a probability distribution of outcomes from a probability distribution of incomes.

Once designed, executing a Monte Carlo simulation requires a tool that generates random numbers. The two most common tools are @Risk and Crystal Ball, both allowing random sampling to be incorporated into spreadsheet models. In the present study, for the purpose of performing Monte Carlo simulations, Crystal Ball was used as an add-in for Excel.

The most challenging part in creating a Monte Carlo model is to define the most suitable distribution to represent the input variables. The most common probability distribution is the normal distribution (bell curve), where all occurrences are equally (symmetrically) distributed around the mean value, which represents the most probable outcome. About 68% of the values fall within one standard deviation of the mean, 95% within two standard deviations, and 99.7% within three standard deviations (''68-95-99.7 rule or "empirical rule"). In a normal distribution the mean value (arithmetic average), the median value (middle value) and the mode (the most frequent value) coincide. Another common probability distribution is the lognormal distribution that represents the logarithm of a normally distributed variable. In a lognormal distribution all values are positive and create a right skewed curve shape. In comparison to the normal distribution, the mode is lower than the mean value as shown in Figure 12.

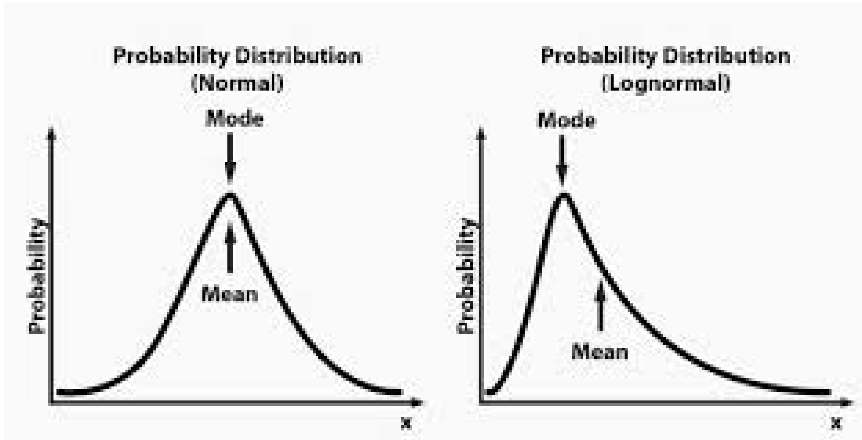

Figure 12: Location of the mode and the mean value in a normal and a lognormal probability distribution.

Moreover, when designing a Monte Carlo simulation, it is important to define the constraints that accompany each input variable as well as the relationship between the variables. In the case where the variable is correlated to another variable a Monte Carlo simulation provides the joint probability distribution outcome. This is the case with our study; the variables of income, age or Sinus-Milieus category have been proven from empirical analysis to be correlated, thus we generate joint probability distributions.

4.1.1. Input variables

Before creating joint probability distributions, we should define a suitable probability distribution to represent each of the input variables. This is achieved by applying distribution fitting, the process of which is described below. First, we introduce the input variables of our agents.

4.1.1.1. Income

As mentioned, this study aims at forecasting not only the adopting rate of PV in residential houses at a national level but also at a cantonal level. This implies a differentiation in agents' characteristics, such as their income, according to their region; an agent located in the canton of Zurich may have a different salary from an agent located in the canton of Vaud. Therefore, we use 26 different income distributions, one for each canton, as input parameters in our Monte Carlo simulations. Data on income per canton, can be found in [23], and provide the number of natural persons that belong in a specific range of net revenue, in Swiss Francs of 2011. Unfortunately, there was no such data as the income of specifically single-family houses classified by canton, thus, we applied data accounting for all physical persons. One can expect that the lower limit of income according to [23] is too low for owners of single-family houses; however, assumptions that our agents always belong in the higher revenue classes cannot be made either. To represent our data, the gamma probability distribution was selected as the most suitable one (see Chapter

4.1.3). Examples of our income distributions in 2014 can be seen in Figure 13 for the cantons of Zurich, Bern, Vaud and Ticino respectively. As illustrated, there are slight differences in the income distributions with some cantons creating a sharper right skewer shape, some having a higher upper limit or higher lower limit etc. For example, a comparison of the canton of Zurich (top left) with the canton of Ticino (bottom right), shows that the latter has a lower mode (lower frequent value) due to the fact that in Ticino 50% of people have an annual salary in the range of approximately 50’000 to 54’900, whereas in Zurich this range is between 60’000 to 62’500. Additionally, there are higher probabilities for higher incomes in Zurich than in Ticino since in Zurich 5% of people have an annual salary above 200’000 CHF versus 3% in Ticino.

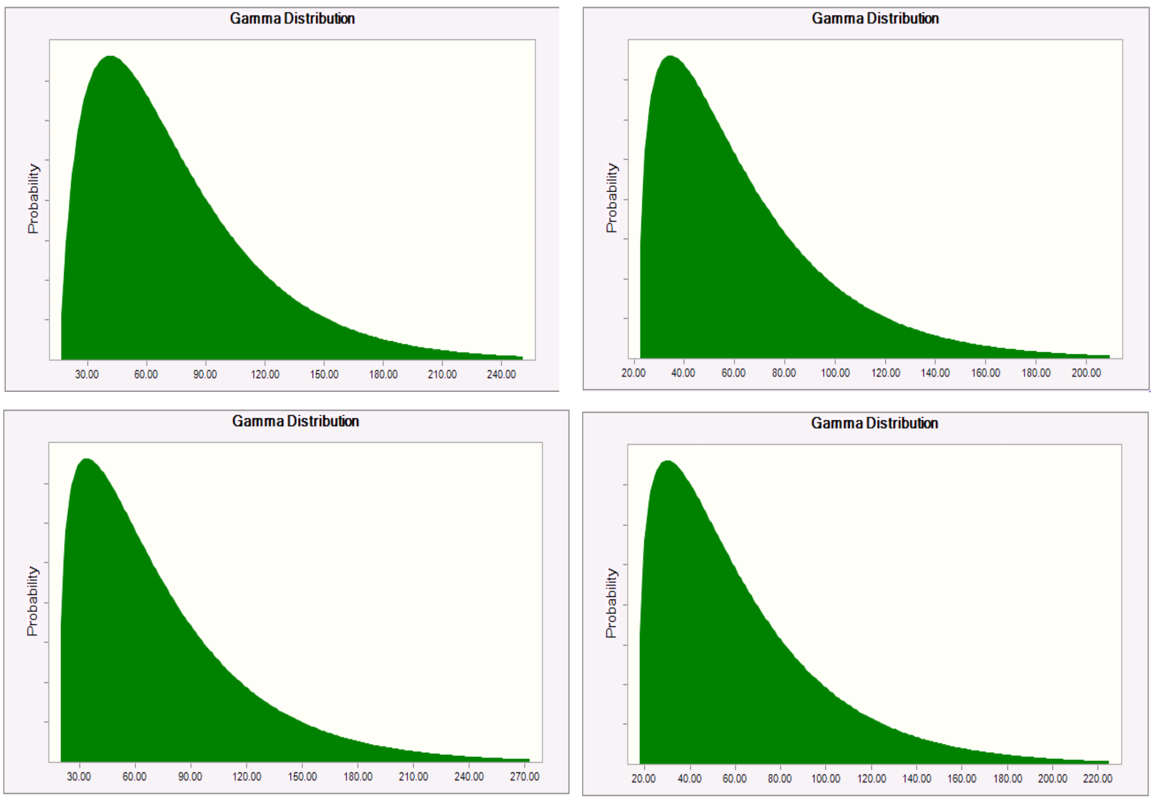

Figure 13: Income [CHF] probability distribution in the canton of Zurich (top left), Bern (top right), Vaud (bottom left) and Ticino (bottom right).

4.1.1.2. Age

Similarly, age distribution differs from canton to canton. This results in having, as previously, 26 different age distributions [24]. Distributions of income data, of people, in relation to their ages is only publicly available in ranges of 20-29, 30-39, 40-49 and 50-65 [25]. Therefore, we grouped the agents’ age into four categories (Table 4) according to the age ranges and we thus obtained explicit discrete values (1,2,3,4) with an assigned probability weight. Examples of our age distributions in 2014 in the cantons of Zurich, Bern, Vaud and Ticino can be seen in Figure 14. As illustrated, in Zurich (top left), 25% of people have an age of 30-39 and 30% of 50-65, whilst in Ticino (bottom right) the figure is different with 21% and 34% belonging to the respective ranges.

Table 4: Age ranges and categories of our agents.

Age range	Age category
20-29	1
30-39	2
40-49	3
50-65	4

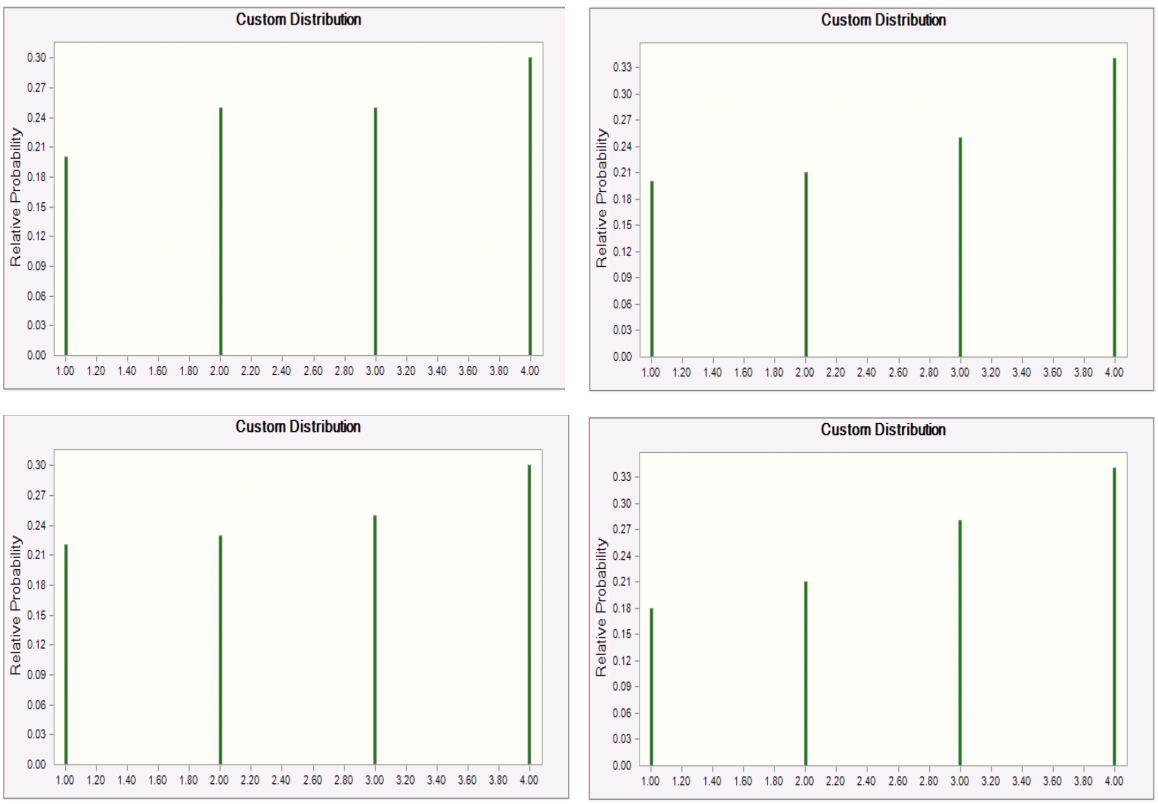

Figure 14: Age probability distribution in the canton of Zurich (top left), Bern (top right), Vaud (bottom left) and Ticino (bottom right).

4.1.1.3. Sinus-Milieus

Regarding the agent's socio-demographic characteristics, data on the share of population belonging to a specific Sinus-Milieus category in each canton could not be publicly found. Therefore we assumed that the federal Sinus-Milieus distribution (see Chapter 3.4) is respected also at a cantonal level, slightly adjusted to give a sum of 100%. The Table 5 summarizes the Sinus-Milieus categories and the people's allocation in the respective categories. The Sinus-Milieus probability distribution is illustrated in Figure 15 and is common in all cantons.

Table 5: Sinus-Milieus categorization in Switzerland and its share of population.

Sinus-Milieus categories		Share of Swiss population
Traditional	1	8%
Consumption oriented	2	14%
Hedonists	3	8%
Established Conservatives	4	15%
Middle Class	5	14%
Pragmatists	6	6%
Digital Cosmopolitans	7	7%
High-fliers	8	8%
Post-Materialists	9	11%
High-Achievers	10	9%

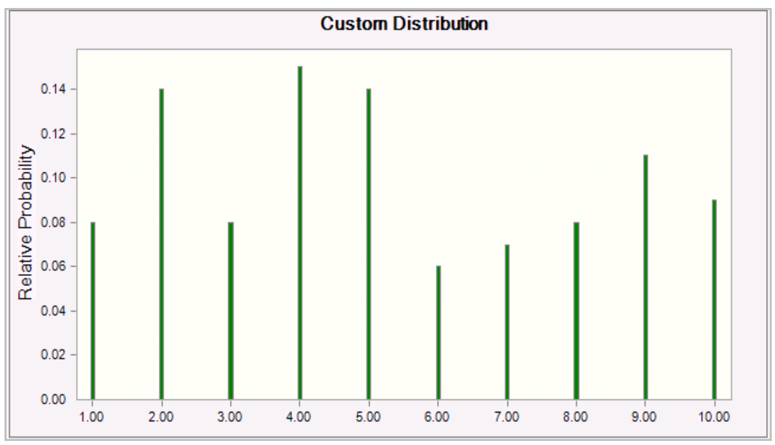

Figure 15: Sinus-Milieus probability distribution in all cantons .

4.1.1.4. Electricity consumption

In Switzerland, electricity consumption in residential houses is categorized into 8 groups [26], mostly according to the size of the house and the presence or not of electrical heating. Therefore, a small apartment with two rooms and an electric kitchen has an average annual electricity consumption of 1600kWh whereas an individual house with 5 rooms, an electric kitchen, electric water heating, a tumble dryer and electrical resistance heating has an average annual electricity consumption of 25000kWh (Table 6).

Table 6: Categories of electricity consumption in residential houses in Switzerland [26].

Category	Electricity consumption (kWh/year)	Description
H1	1600	2-room accommodation with electric stove
H2	2500	4-room accommodation with electric stove
H3	4500	4-room accommodation with electric stove and electric water heater
H4	4500	5-room accommodation with electric stove and dryer (without electric water heater)
H5	7500	Detached house with 5 rooms with electric stove, electric water heater and dryer
H6	25000	Detached house with 5 rooms with electric stove, electric water heater, dryer and electric heating resistance
H7	13000	Detached house with 5 rooms with electric stove, electric water heater, dryer and 5 kw heat pump for heating
H8	7500	Large residential property, with wide use of electricity

According to Table 6, single-family houses are found in categories H4-H8, thus having annual electricity consumption in the range of 4’500kWh-25’000kWh. Moreover, from statistical data regarding the end-use of energy in single-family houses [27], one can fir a distribution given the number of single-family houses according to the use of energy and therefore the level of electricity consumption. As an example, houses that have electricity heating for both space and water have the largest electricity consumption. This results in having an electricity consumption distribution with a lower limit of 4’500 and an upper limit 25’000. The fitted gamma probability distribution of electricity consumption can be seen in Figure 16 and is common in all cantons.

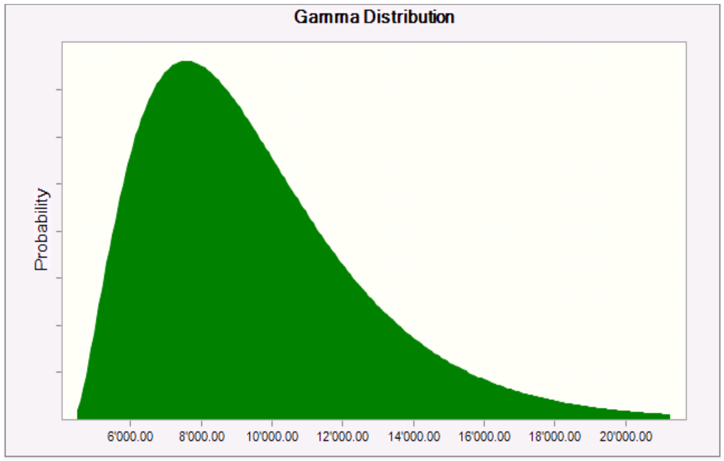

Figure 16: Electricity consumption [kWh/year] probability distribution in all cantons.

4.1.1.5. Usable rooftop area

A crucial variable in modeling an agent' s decision to adopt the PV technology is, the available rooftop area of the house. This will define the maximum size of the PV panels to be placed on the rooftop, and hence the installed PV capacity. No data was found on the available rooftop area in single-family houses in Switzerland. However, we fitted a rooftop area lognormal distribution (Figure 17) by collecting a large number of projects by Solstis Company which show the usable rooftop area and installed capacity of all its projects on single-family houses since 2010 [28]. Given that the installed capacity is related to the available rooftop area we can create an installed capacity distribution for our agents in all cantons. The average ratio between the installed capacity and the rooftop area was calculated approximately 7.15 kW/m^2. This is almost consistent to Viessmann's estimated value of 9-12 kW/m^2 [29] .

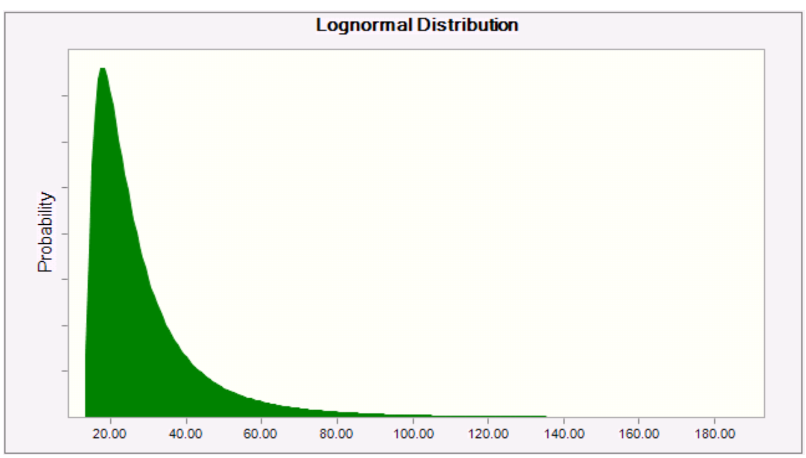

Figure 17: Usable rooftop area [m^2] in all cantons.

4.1.2. Correlation between input variables

The purpose of performing Monte Carlo simulations is to create agents with certain characteristics (input variables) that correlate with each other. In this way, an agent will have an income that is related to its age, its location, and its socio-demographical attributes. The more correlations are between an agent's characteristics the more realistic is the agent. As previously mentioned, there is available data on the income (median and quartile range) by age, including both private and public sector [25], hence a correlation of income and age can be calculated. Moreover, we can calculate the correlation between income and Sinus-Milieus category according to Table 1. All correlations used in the Monte Carlo simulations are summarized in Table 7. Regarding the income and usable rooftop area, it is assumed that a correlation of 85% exists, assuming that, if an agent has a high income, it is more likely to have a bigger house or can afford to use a larger rooftop area. However, no correlation of electricity consumption with the income, age or Sinus-Milieus category was found, therefore each agent gets a random electricity consumption value resulting from the electricity consumption probability distribution.

Table 7: Correlations between input variables.

Correlations between input variables [%]	
	Income
Age	89.42(calculated)
Sinus	88.00 (calculated)
Usable rooftop area	85.00 (assumption)

Figure 18 and Figure 19 illustrate the joint probability distributions of income-age, income-Sinus-Milieus, and income-usable rooftop area for the cantons of Zurich, Bern, Vaud and Ticino.

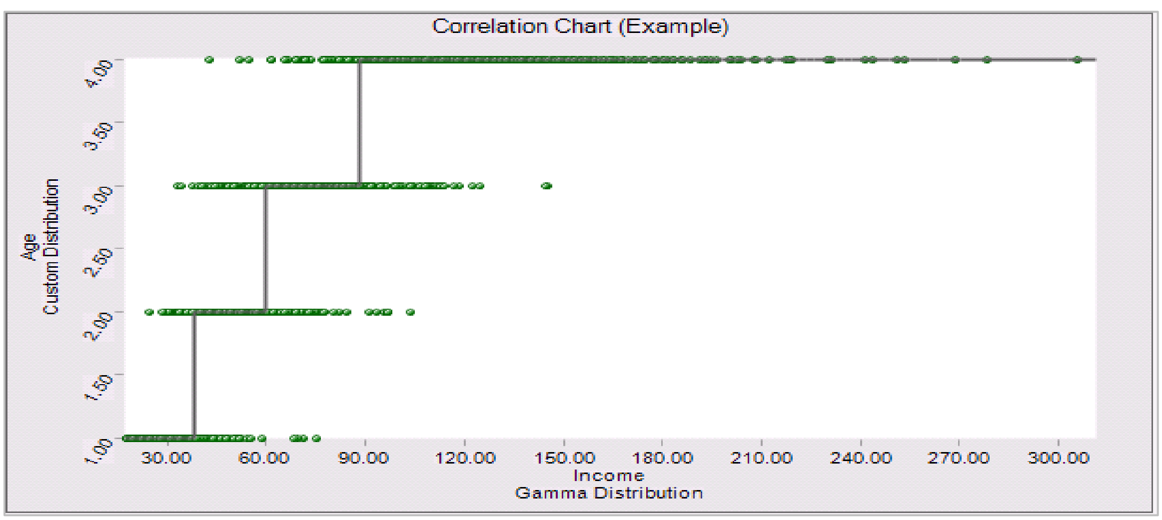

Figure 18: Income [CHF] – age joint probability distribution in the canton of Zurich.

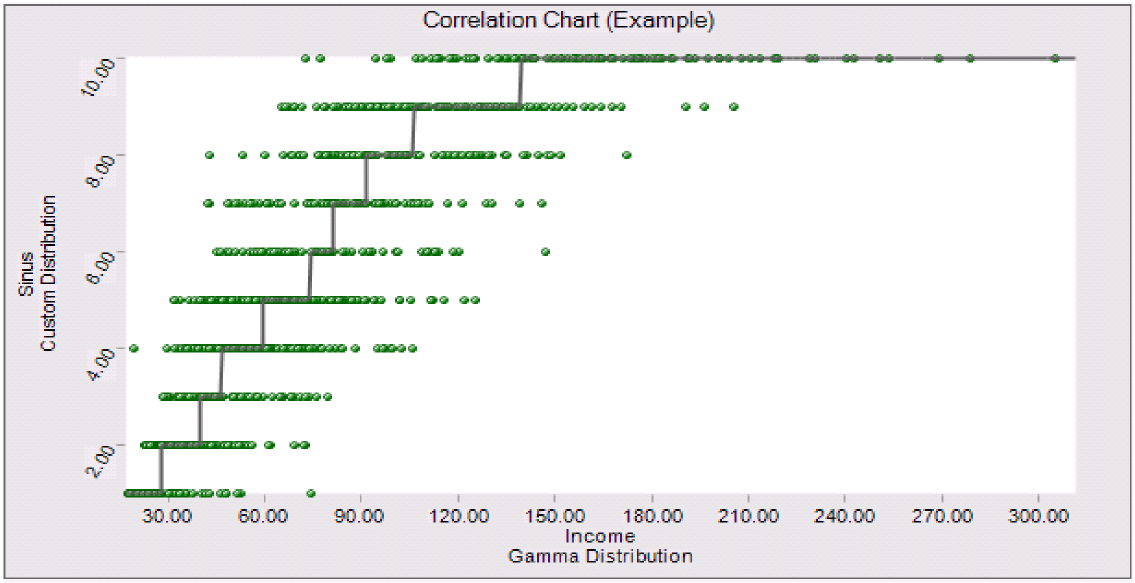

Figure 19: Income [CHF] – Sinus-Milieus joint probability distribution in the canton of Zurich.

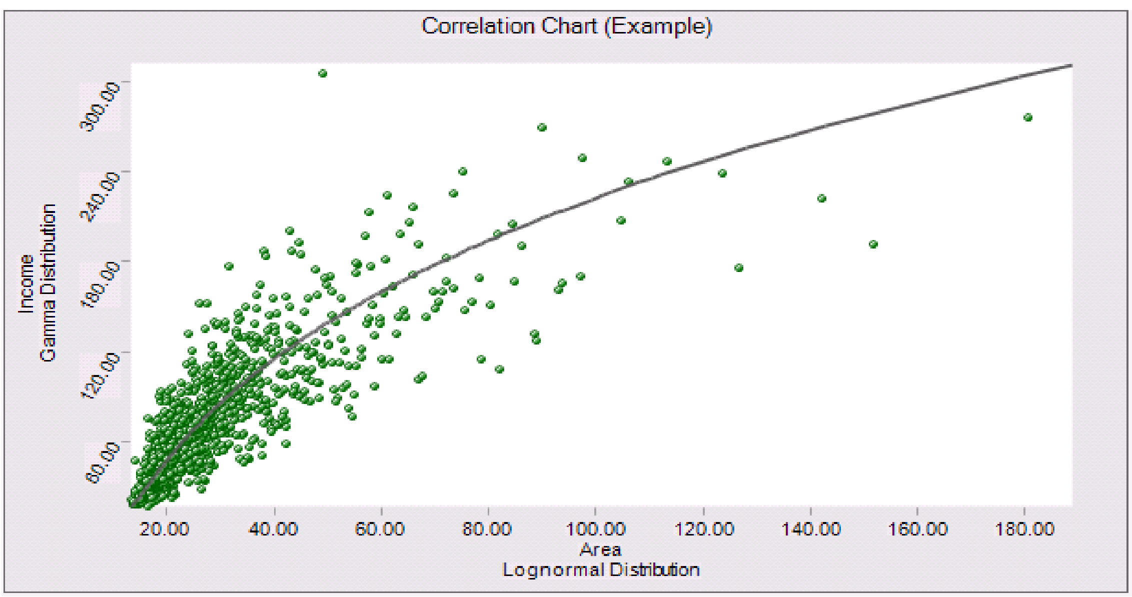

Figure 20: Income [CHF] – usable rooftop area [m²] joint probability distribution in the canton of Zurich.

4.1.3. Defining the suitable distribution-Distribution fitting

As previously mentioned, the most challenging part when performing Monte Carlo simulations is to define the probability distribution that best represents the input variables. Crystal Ball incorporates a distribution-fitting feature in order to simplify the process of selecting a suitable probability distribution. The distribution fitting automatically matches historical data and determines the set of parameters that best describe the characteristics of the data. The closeness of the fit is evaluated by one of several standard goodness-of-fit tests. In the present study, the Kolmogorov-Smirnov test was performed for the selection of the suitable probability distribution. The Kolmogorov-Smirnov test quantifies the vertical distance between two cumulative distributions; when the vertical distance is long the distribution is not a good fit [30]. When performing distribution fitting, the results, starting from the highest-rank distribution (best fit) down to the lowest-ranked distribution are displayed in the Comparison Chart dialog. Figure 21 and Figure 22 illustrate the distribution fitting in the case of income and usable rooftop area where according to the Kolmogorov-Smirnov test, the gamma distribution and lognormal distribution respectively are ranked first.

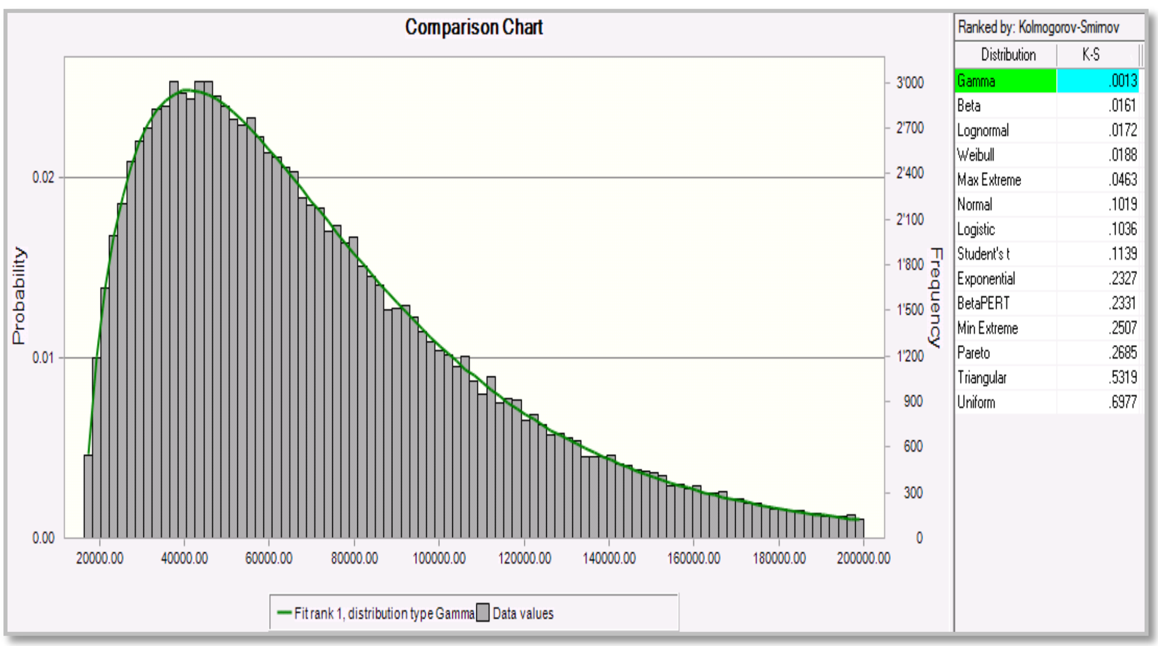

Figure 21: Distribution fitting test ranked by Kolmogorov-Smirnov for the case of income [CHF].

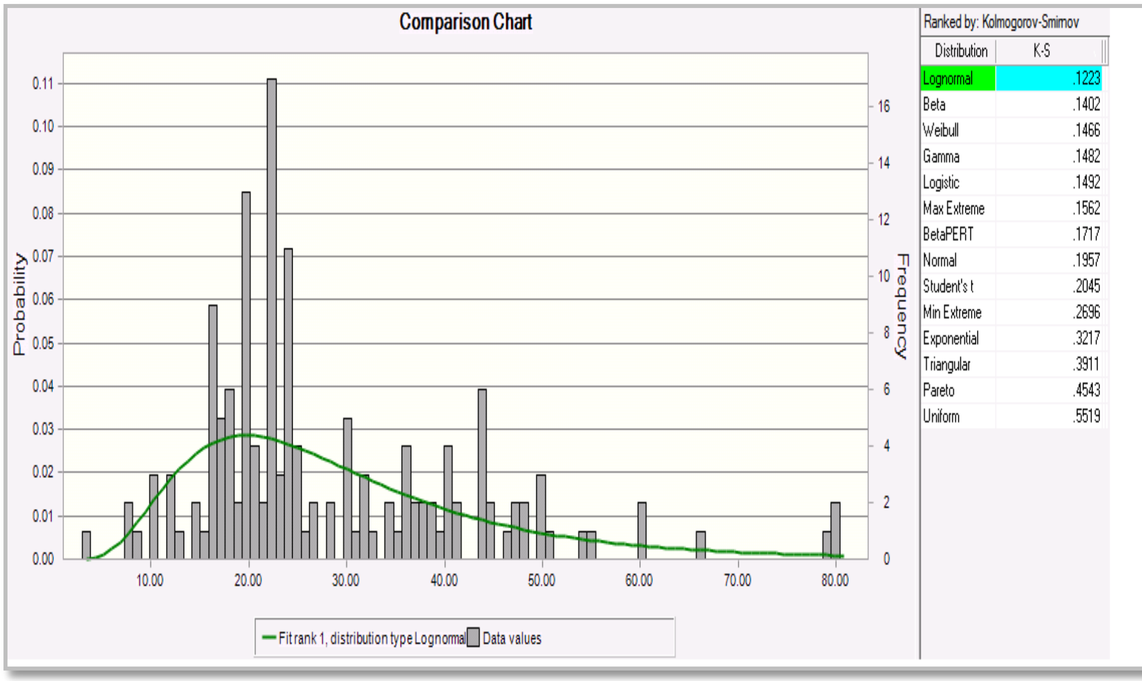

Figure 22: Distribution fitting test ranked by Kolmogorov-Smirnov for the case of usable rooftop area [m^2].

4.1.4. Changing the parameters of input variables

The Monte Carlo simulation will generate agents with their accompanied characteristics each year from 2014 to 2050. Given that some characteristics change dynamically with time, their probability distributions must be adjusted accordingly. Among the agent' s characteristics, age is the one changing with the highest pace, therefore, age distribution must be recalculated each year. To define the annual rate of change from 2014 to 2050 (36 years after), we should study the annual rate of change from 1978 to 2014 (36 years back). Figure 23 illustrates the age distribution in Switzerland from 1978 to 2013 [24], where one can observe the significant change in the distribution of the corresponding age ranges as shares of the current population. As an example, in 1978, 30% of people were aged between 20-39, 28% between 40-64, and the average age was 44 years old whereas in 2050 these shares are 27% and 35% respectively and the average age is 50 years old. We can therefore calculate the average rate of change for each age range and adjust each time the parameters in Crystal Ball. This is really important, as some variables are correlated with each other, such as the income and age. Older agents are more likely to have a higher income, therefore, having proved that people "get older" implies than in 2050 more agents will be older, thus the share of higher incomes will have increased. Figure 24 illustrates the difference in the age probability distributions in the canton of Zurich in 2014 and in 2050.

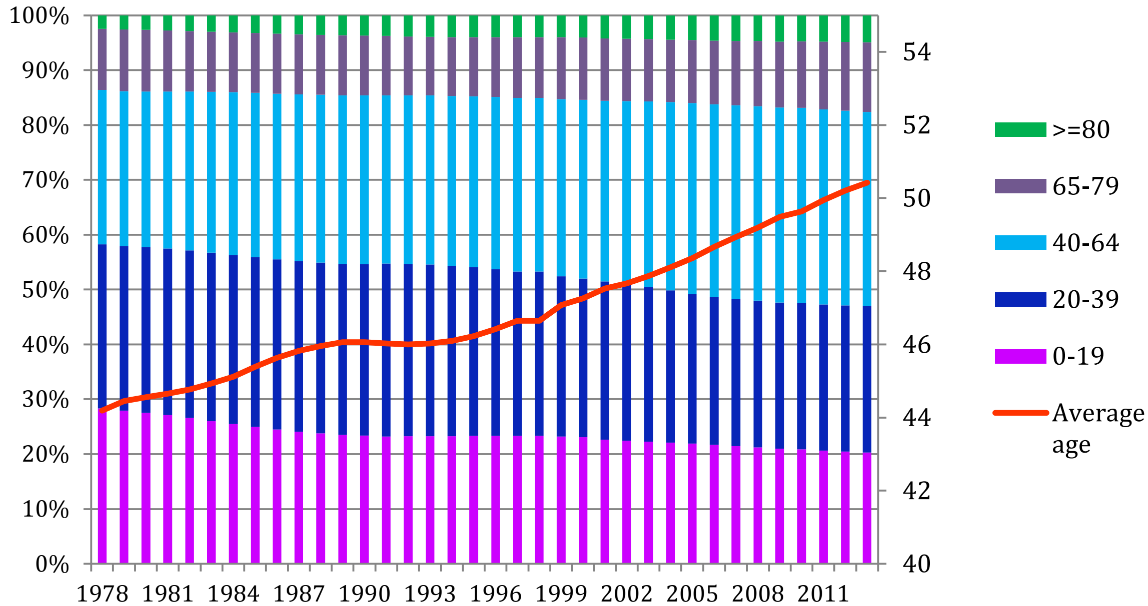

Figure 23: Age distribution and average age in Switzerland from 1978-2013.

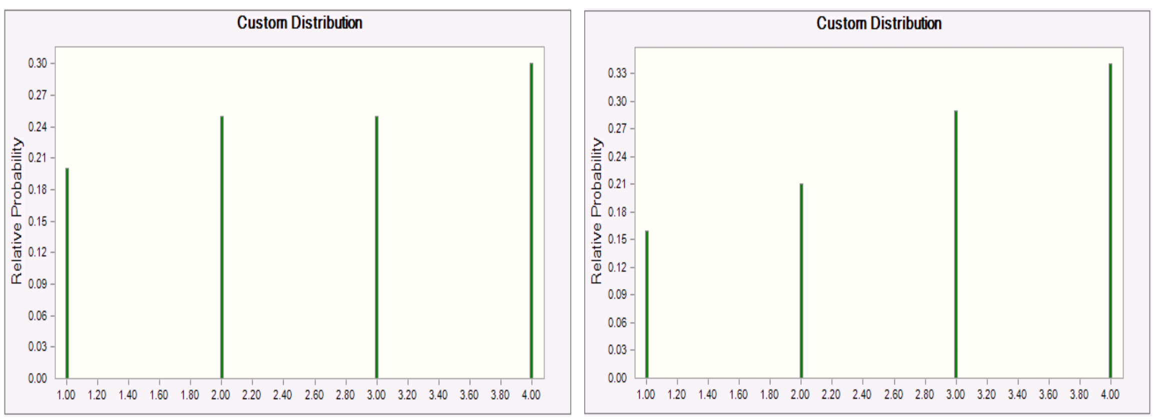

Figure 24: Age distribution in the canton of Zurich in 2014 and 2050.

4.2. Number of simulations

The number of Monte Carlo simulations performed equals to the number of agents (i.e. the number of single-family houses). Nevertheless, the number of agents is not constant but instead increases annually. Therefore, in our model, the number of agents is increased each year in order to follow the annual growth of the single-family houses. To forecast the rate of change in single-family houses for a projection of 36 years we have to study the respective trend in the past. Regarding the single-family houses located in each canton, the available data is only since 2009 [31]. However, Prognos AG, in a study on the energy strategy of Switzerland until 2050, has forecasted the growth of the total households for the next decades until 2050 [32]. Therefore, for the years 2014-2020 we use the annual average growth in single family houses calculated from the data available since 2009, and thereafter we adjust it to the average annual growth in total households in order to ensure that the number of single family households will not exceed the number of total households.

4.3. PV installations in single-family houses

The number of single-family houses that have already adopted PV technology is a crucial input for our model. This will define which of the agents are linked with agents-adopters and will initialize the communication utility. To define which of the agents that enter the model in the first year of simulation are already adopters we studied the cantonal distribution of installed PV systems. Figure 25 illustrates the average allocation of PV systems in single-family houses for the years 2010-2013 [33]. This corresponds to the probability of an agent-adopter belonging to a specific location and is therefore the only criterion assumed to define the agents-adopters of the past years.

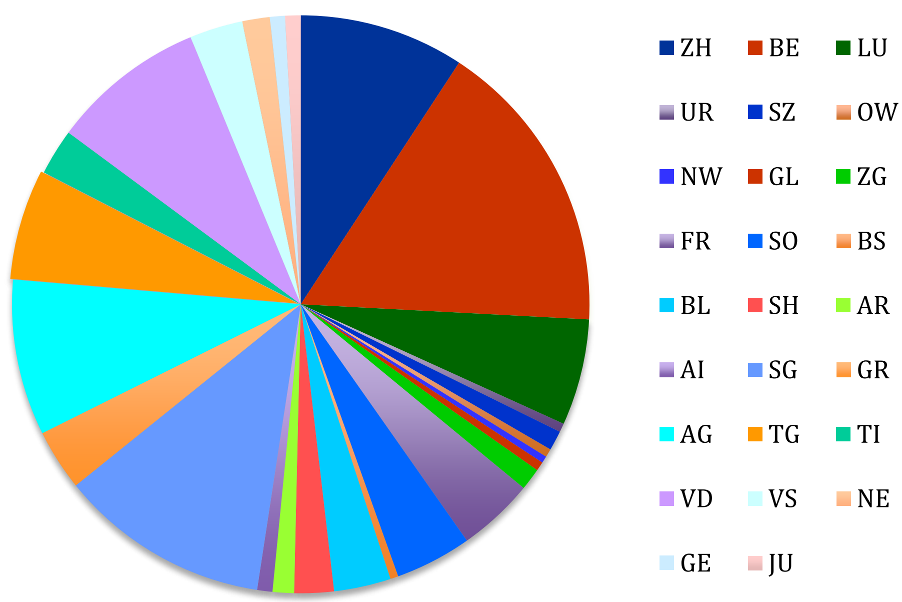

Figure 25: Cantonal distribution of installed PV systems in single-family houses (2010-2013).

4.4. Nominal electricity production

The average annual electricity production of the PV system is calculated with the interactive on-line Photovoltaic Geographical Information System (PVGIS) developed by the European' s Commission scientific service, Joint Research Center (JRC) [34]. This powerful tool allows users to estimate the performance of a grid-connected PV at any given location in Europe based on the geographical coordinates of the location (latitude, longitude, elevation from the sea) and the system' s characteristics: the technology (i.e. crystalline silicon, CIS, CdTe), the estimated system losses, the mounting position (i.e. free-standing, building integrated), the slope angle[1], the azimuth angle[2] and the solar tracking mode (i.e. fixed, one-axis or two-axis tracker). For simplicity reasons, all agents located in the same canton share the same annual average electricity production, which is the one calculated for a PV system located in the most populated city of the canton.For the majority of cantons, the most populated city is also the capital of the canton. Moreover, it is assumed that the PV technology is crystalline silicon and the system is placed on an optimal slope (approximately 35^{o} for every canton) and optimal azimuth (0^{o}), is building integrated and has a fixed mounting structure. The system losses due to cables, inverter etc. are set to default and equal to 14%. Table 8 summarizes the annual average electricity production of a PV system with a nominal capacity of 1KW located in the selected reference cities of each canton.

1: the angle between the surface array and the horizontal (ground) [34]
2: The azimuth angle is the compass direction from which the sunlight is coming At solar noon the azimuth angle is 0^{o}; the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere [34].

Table 8: Average annual nominal electricity consumption of a 1KW PV system located in reference cities.

Canton	Reference city	Average electricity production [kWh/year]
ZH	Zurich	1030
BE	Bern	1040
LU	Lucerne	983
UR	Altdorf	947
SZ	Schwyz	1010
OW	Sarnen	974
NW	Stans	988
GL	Glarus	876
ZG	Zug	977
FR	Fribourg	1070
SO	Olten	1030
BS	Basel	1030
BL	Liestal	986
SH	Schaffhausen	1010
AR	Herisau	928
AI	Appenzell	825
SG	St.Gallen	951
GR	Chur	983
AG	Wettingen	986
TG	Frauenfeld	987
TI	Lugano	1160
VD	Lausanne	1120
VS	Sion	1080

NE	La Chaux-de-Fonds	1020
GE	Geneva	1120
JU	Delemont	946

4.5. Degradation rate

The operating life of a PV module is highly determined by the amount it degrades over time. The degradation rate varies among different technologies and different climates; in the present study we consider only the mono-crystalline silicon technology for the solar PV panel cells.

In general, the degree of degradation is affected by the quality of the materials and more specifically by their resistance to corrosion, the level of water ingress, the temperature stress, the quality of assembling and inserting the cells into the module, the maintenance employed at the site, as well as the manufacturing process. The latter is strongly affecting crystalline technologies, where cells suffer from light-induced degradation. This can be caused by the presence of boron, oxygen or other chemicals left behind by the process of cell production [35]. The initial degradation occurs due to defects that are activated upon initial exposure to light. Therefore, the first year degradation rate is higher upon initial exposure to light and then tends to be stabilized [35], [36]. We must therefore consider a different degradation rate for the first year and a different long-term degradation rate.

4.5.1. First year degradation rate

Makrides et.al, studied and presented the initial first year degradation rate of different PV technologies installed at the University of Cyprus, based on outdoor field measurements. Over the first year, mono-crystalline silicon technologies showed degradations in the range of 2.12 % - 4.73 % [37]. Therefore, we can consider a 3% first year degradation rate (based on Makrides' s mean estimation).

4.5.2. Long-term degradation rate

The National Renewable Energy Laboratory, based in USA, has made an analytical review [38], which summarizes nearly 2000 degradation rates reported globally from field-testing during the last 40 years. The average annual degradation rate is less than 1% for most products manufactured after the year 2000. Crystalline Si technologies appear to have remained steady at rates of approximately 0.5%/year for installation before and after the year 2000 (Figure 26).

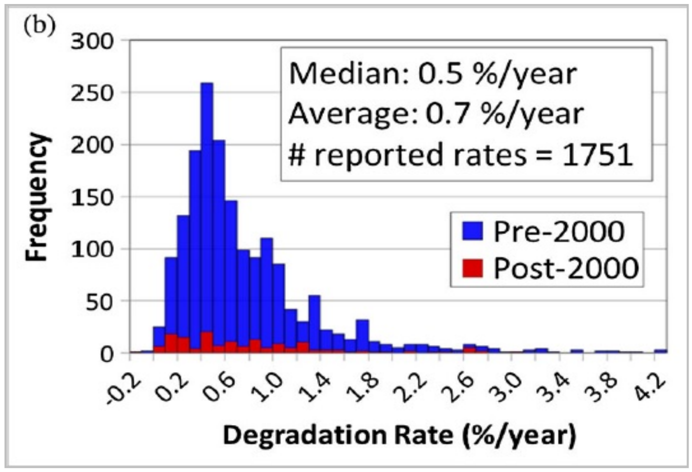

Figure 26: Histogram of reported degradation rates of Si technology for installations pre-2000 and post-2000 [39]

Furthermore, in their most recent study, they have analyzed how degradation rates vary with climate zone. According to the Köppen-Geiger climate map, they distributed geographically the reported degradation rates (Figure 27).

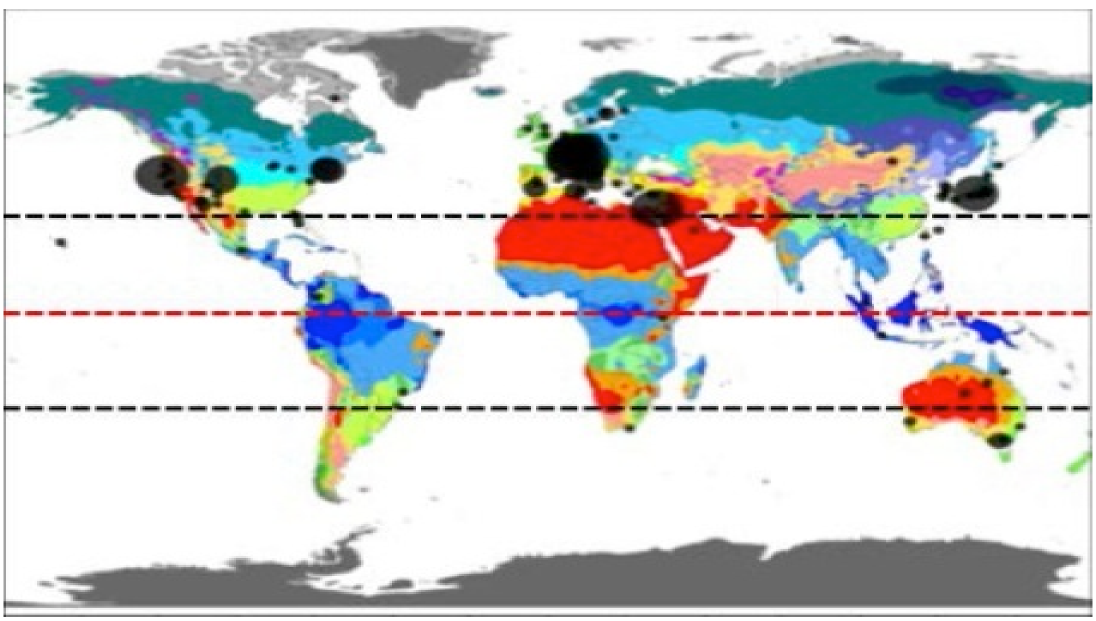

Figure 27: Geographic distribution of reported degradation rates on a Köppen-Geiger climate map. The size of the circles indicates the number of degradation rates at a given location [39].

Due to the lack of information in some climate zones some sensible consolidation such as combining tropical climates (Af & Aw) with the continental hot and humid climate (Cfa) had to be made.

Figure 28 shows the power degradation distribution (pmax) by climate zone for mono-Si and multi-Si technologies. Based on this figure we record the annual degradation rates for mono- Si technology for all climate zones (Table 9). To be precise, since we have assumed a different first year degradation rate of 3%, we must adjust this long-term annual degradation rate to the remaining 24 years. The annual degradation rate for years 2 to 25 is given by the following formula:

$$d^* = 1 - \left[\frac{1-D_{1-25}}{1-0.03}\right]^{\frac{1}{24}} \quad [16]$$

Where:

$$D_{1-25} = (1-d)^{25} \quad [17]$$

- D_{1-25} is the total degradation rate from the 1st to the 25th year
- d is the annual degradation rate of Table 9

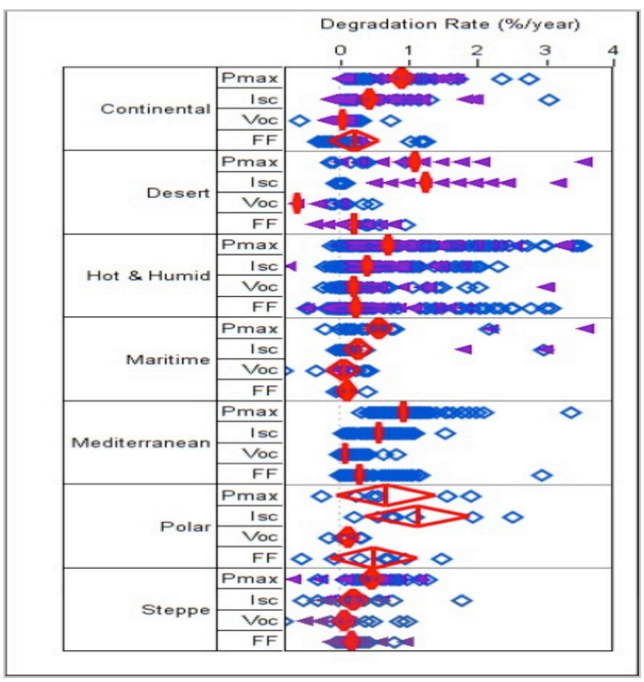

Figure 28: Degradation rates for mono-Si (open diamonds) and multi-Si (filled triangles) by climate zones based on Köppen-Geiger classification. The 95% confidence interval is denoted by the diamonds with the mean as the crossbar [39].

Table 9: Long-term degradation rate based on the climate zones.

Long-term degradation rate [%]				
Continental	Desert	Hot&Humid	Maritime	Mediterranean
0.9	1.1	0.6	0.5	1

The adjusted long-term degradation rate for all climates can be seen in Table 10. According to the Köppen-Geiger climate classification, the Swiss Plateu has a maritime Temperate or Oceanic climate (Cfb) and the Alps are considered Tundra climates or polar climates (ET). For simplicity reasons, all locations studied are classed as Maritime Temperature and therefore have a long-term degradation rate of 0.39%.

Table 10: Fixed Long-term degradation rate based on the climate zones

Long-term degradation rate [%]				
Continental	Desert	Hot&Humid	Maritime	Mediterranean
0.81	1.02	0.50	0.39	0.92

Lastly, it should be noted that questions regarding the linearity of the degradation rate have not been yet satisfactorily proved.

5. Model description

The agent-based model has been programmed in Java and simulates the PV diffusion process on a step-wise yearly basis from 2014 to 2050. Figure 29 illustrates the yearly simulation process focusing on the core steps that occur within year N. The tool's objective is to define the rate of adoption each year. Therefore, in year N it calculates the partial utilities of all agents as described in Chapter 3. It then multiplies the utilities with their respective weights. This calculation defines the agent's total utility in the current year. If the total utility surpasses a certain threshold the agent will become an adopter. If not, the agent remains in the system as potential adopter together with the new agents that enter the system in year N+1. The agents which become adopters in year N are excluded from future calculations however its communication links to other agents remain active.

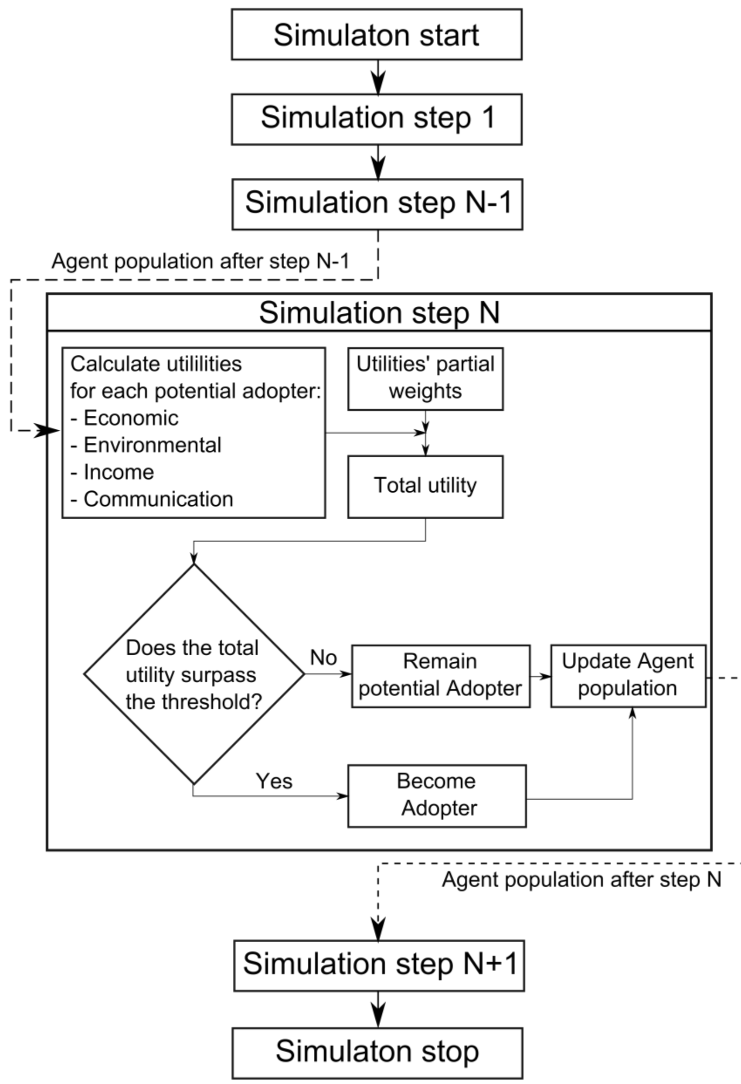

Figure 29: Representation of the step-wise simulation process.

6. Calibration

The model was calibrated in respect to historical data on the annual rate of adoption, the cumulative adopters and the cumulative installed capacity over the period of 2010-2013. The calibration process is crucial for the determination of the weights assigned to the partial utilities as well as the threshold above which an agent is assumed to adopt the PV technology. The threshold and weights that best represent the recorded data were defined by applying multiple trial and error simulations. The annual rate of adoption resulting from different thresholds is illustrated in Figure 30. A small increase in the threshold by approximately 0.05% results in a decrease in the number of adopters mostly in the year 2010 and 2013 by 8% and 3% respectively. Although the differences are not significant, the threshold that gives the best fit is 0.532.

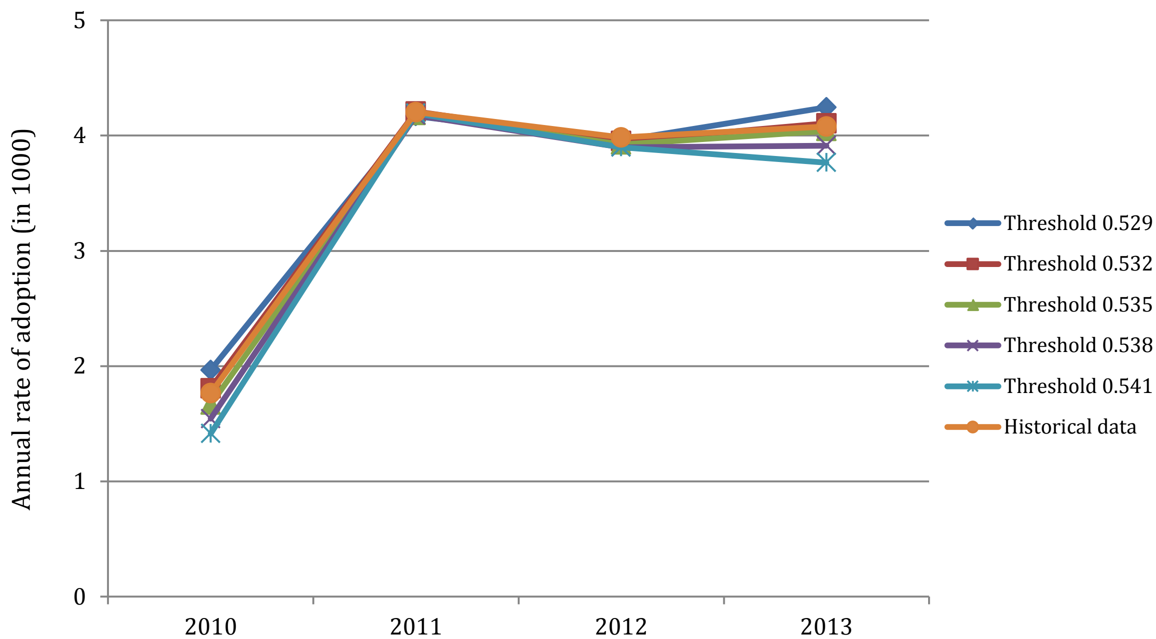

Figure 30: The rate of adoption in the period 2010-2013 for different thresholds.

The calibrated weights are listed in Table 11. We assumed that the weights of the partial utilities vary among the different socio-economic categories identified by Sinus-Milieus according to their characteristics described in Chapter 3.4. The level of differentiation was taken by Palmer et al., adjusted accordingly to our Sinus-Milieus categories and recorded data. The partial weight of the communication utility was calibrated separately in order to comply with studies on the social effect in the diffusion of solar PV technology. According to literature ([40], [41]) the social effect cause an annual increase of the installation rate within one neighborhood by approximately 4%.

Table 11: Calibrated weights by Sinus-Milieus.

Sinus-Milieus	W_{ec}	W_{env}	W_{in}	W_{com}
1	0.256826	0.262055	0.1914	0.289719
2	0.229611	0.266256	0.21692	0.287213
3	0.240298	0.263664	0.21692	0.279119
4	0.262884	0.273343	0.1914	0.272373
5	0.249498	0.267417	0.20416	0.278926
6	0.249498	0.267417	0.20416	0.278926
7	0.249498	0.267417	0.20416	0.278926
8	0.172049	0.245528	0.22968	0.352744
9	0.172049	0.245528	0.22968	0.352744
10	0.172049	0.245528	0.22968	0.352744

The annual rate of adoption, the cumulative number of adopters and the cumulative installed capacity resulting from the calibration are illustrated in Figure 31 and Figure 32 respectively. Although the results give an excellent fit in respect to the number of adopters it seems that they are less accurate in respect to the installed capacity. In fact the model does not seem to follow the increasing trend in the installed capacity per adopter. Although the average installed capacity per adopter in 2010 was 5.2 kW and in 2013 10.2 kW the model shows a constant capacity of approximately 7kW for all the years of calibration. This is probably due to the fact that the distribution of the installed capacity resulted from a relatively small sample of actual projects that took place in specific areas of Switzerland during the period of 2010-2012. A larger sample of usable rooftop areas in all locations studied and for a longer period of time would have given results of higher accuracy. The year 2009 was the first year that a federal feed-in remuneration was applied to encourage the PV technology and therefore it marks the starting point of its significant growth. By the end of 2009, not only the adopters were increased (the cumulative PV systems in single family houses were 3091, in the years 2010 and 2011, 1765 and 4203 new systems were added respectively) but also the installed capacity per adopter was increased. This phenomenon can be explained by three factors: the ongoing fall in the investment costs and in turn the cost advantages of economies of scale, the existence of financial incentives for injecting the electricity production in the grid regardless of the level of self-consumption and the improvement of the technology itself that allows the same nominal power to be installed in a much smaller area. However, although the results may not represent perfectly the current situation, we estimate that in absence of financial support in the future and the compulsory directive for small installations (below 10kW) to produce electricity only for direct consumption residential houses will install smaller systems to cover sufficiently their electricity consumption.

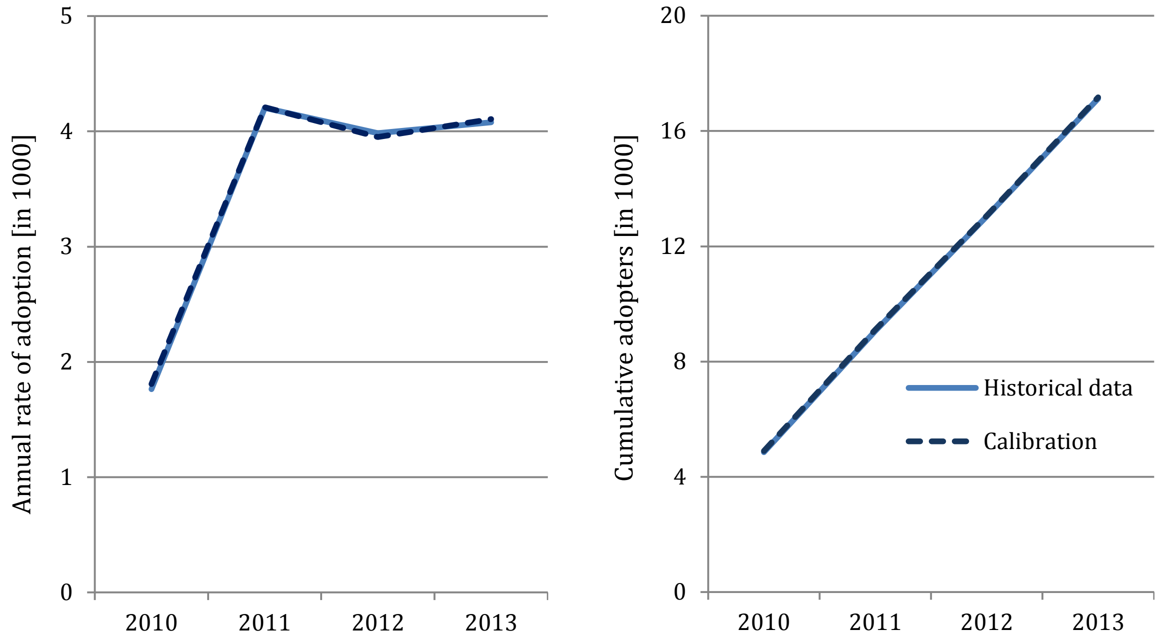

Figure 31: Annual rate of adoption and cumulative adopters (2010-2013).

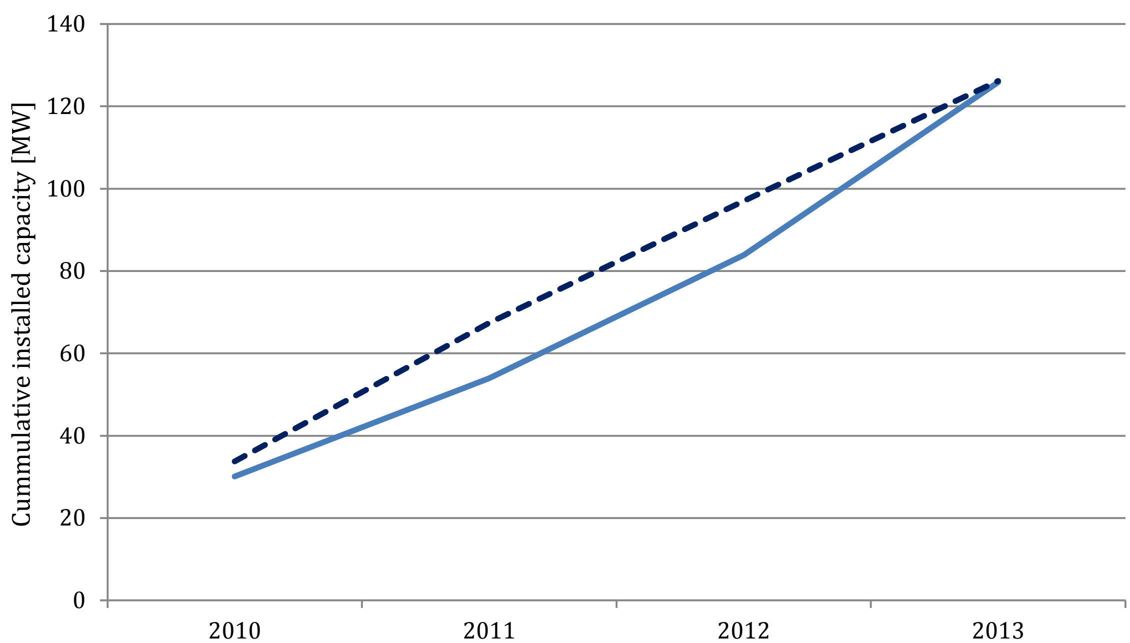

Figure 32: cumulative installed capacity (2010-2013)

In order to consider every possible outcome and further limit the randomness upon which agents and their characteristics are defined (assigned) we created 6 different worlds of agents. (Each world corresponds to the total number of agents in the years 2014-2050).

Table 12 lists the example of agent 1 and its assigned characteristics in different agent worlds. Moreover Figure 33 shows the difference in rate of adoption for the different agent worlds. The results displayed above are simply the average outcome of all worlds. Ideally, the creation of hundreds of worlds would help in quantifying the uncertainty surrounding the penetration of solar PV systems in single family houses, however, time restrictions did not allow us to do it at a full scale though the framework has been designed to support this.

Table 12: Characteristics of agent 1 in different agent worlds

Agent world	Installed capacity [kW]	Annual income [CHF]	Age class	Sinus-Milieus	Annual Electricity consumption [kWh]
1	3.02	88'480	3	6	6'056
2	11.03	136'880	4	8	7'528
3	6.90	233'210	4	10	8'567
4	2.13	33'400	1	1	6'419
5	3.97	110'980	4	8	11'637
6	4.10	78'510	3	8	11'548

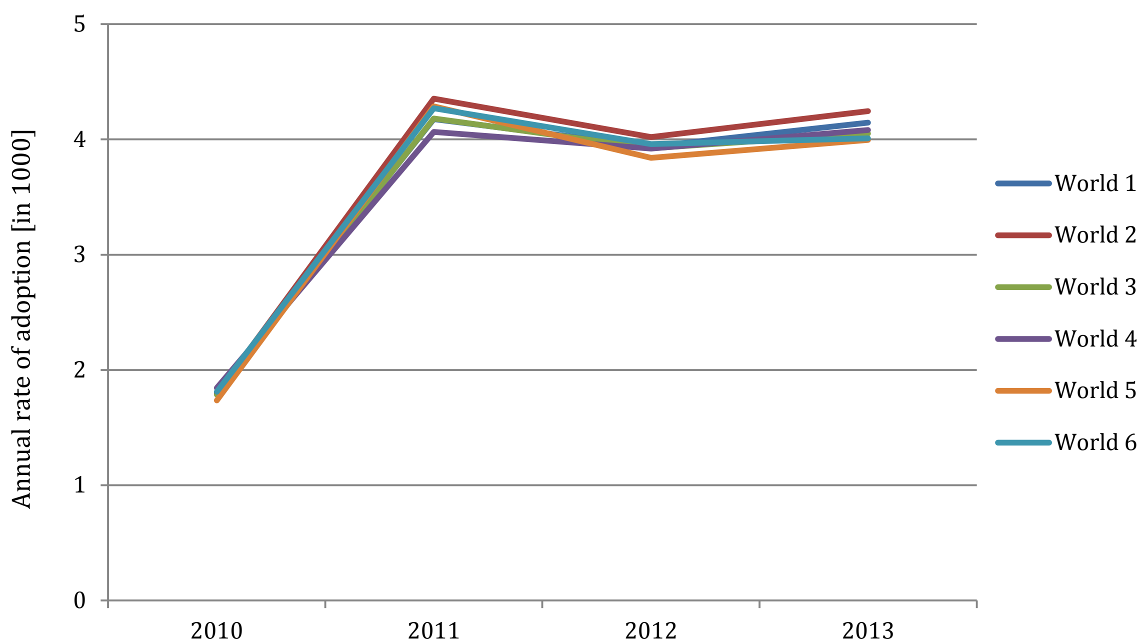

Figure 33: Rate of adoption (2010-2013) for different agent worlds.

Probably the most interesting outcome of the calibration is the allocation of adopters with respect to the Sinus-Milieus categories (Figure 34). Although it was expected**,** the share of agents belonging to Sinus-Milieus 10 (the High-achievers) is impressively large, followed by a modest share of agents of category 9 (Figure 35). This is a very positive feedback from the model and it is consistent to observed trends where the most innovating people trigger the diffusion of a technology, which is much later, followed by technologically immature people such as the Traditional (Sinus-Milieus 1). Figure 35 (right) isolates categories 1-8 for a better observation in the allocation of adopters in the remainder categories.

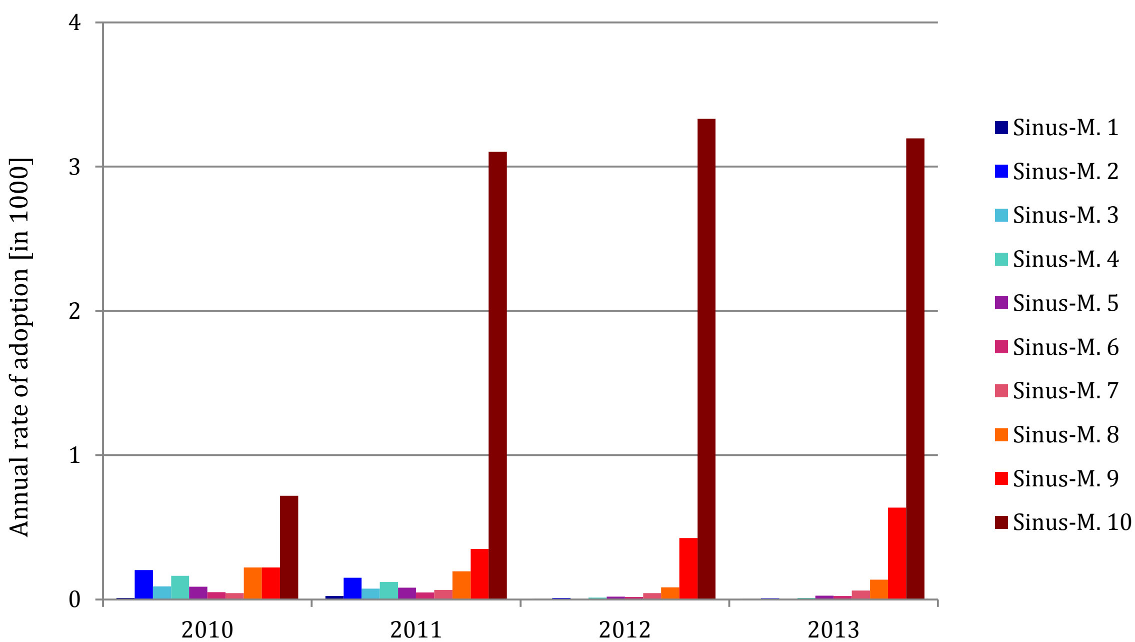

Figure 34: Annual rate of adoption by Sinus-Milieus (2010-2013).

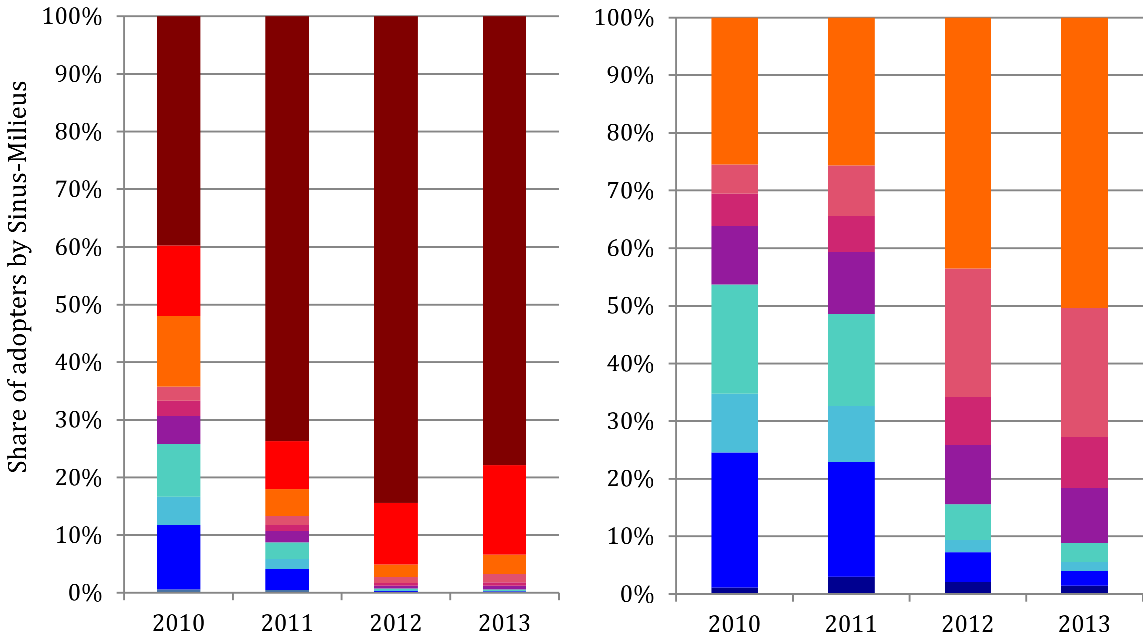

Figure 35: Share of adopters by Sinus-Milieus (2010-2013).

7. Results

The model is developed to forecast the future rate of adoption in Switzerland, starting from 2014 until 2050. The annual agent population is illustrated in Figure 36. Each year the model updates the agent's characteristics that change dynamically in time. Such an example is the agent's income that increases with respect to the average GDP per capita annual growth taken from [32]. Several scenarios are implemented in order to consider the sensitivity and validation of the model with respect to the investment cost, the electricity price, the governmental financial support and the discount rate. One simulation run (i.e. implementing one scenario in the period 2014-2050) lasts approximately 15 minutes in a typical PC with 4 GB RAM and Intel® Core™ i5 CPU processor.

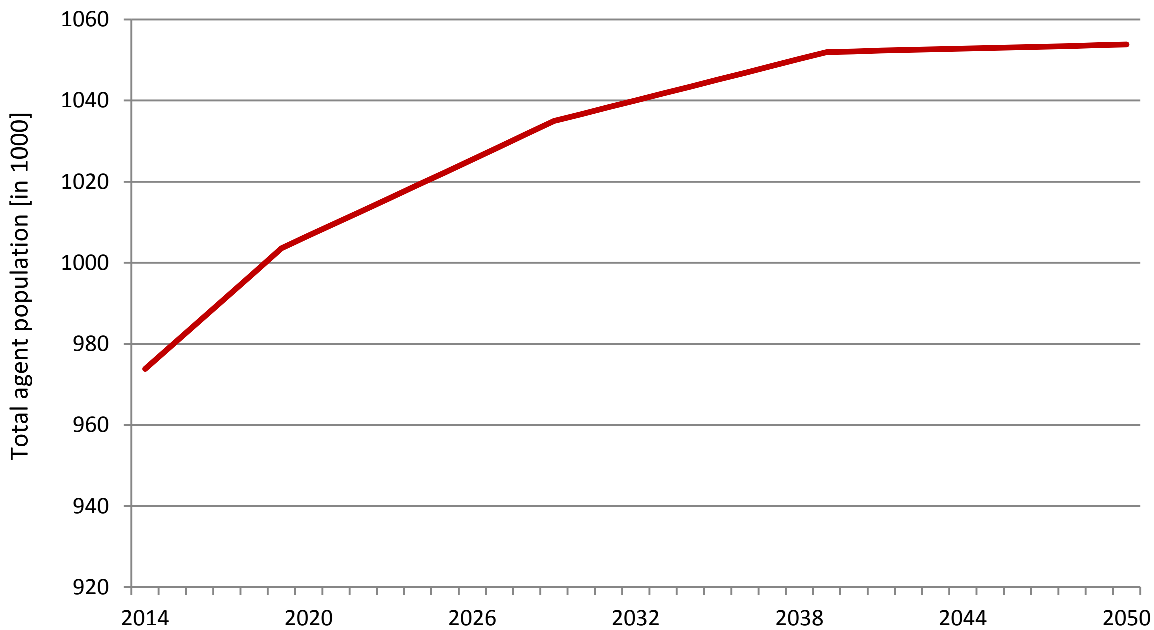

Figure 36: Cumulative number of single family houses in Switzerland (2014-2050).

7.1. Description of the baseline scenario

A baseline scenario is developed in order to represent the most likely future trend of PV deployment in single-family houses in Switzerland. It represents the continuation of the current trends of investment costs, electricity prices and governmental policies and serves as a benchmark upon which alternative scenarios will be evaluated.

The investment costs of PV installations for 2014 are taken from Viessmann [29] and the future investment costs are calculated by applying the learning rates of PV taken from the International Energy Agency (IEA) [42]. The investment costs for various systems in certain years are listed in Table 13. As an example, Figure 37 presents the future trend curve for a 2kW system.

Table 13: Future investment costs [CHF/kW] for various systems in the “Baseline” scenario.

Investment costs [CHF/kW]	**2015**	**2020**	**2030**	**2040**	**2050**
2 kW	2’425	2’128	1’750	1’449	1’200
3kW	2’263	1’986	1’633	1’352	1’120
5 kW	2’231	1’958	1’610	1’333	1’104
7 kW	2’078	1’824	1’500	1’242	1’028
10 kW	1’940	1’702	1’400	1’159	960
20 kW	1’852	1’626	1’337	1’107	916

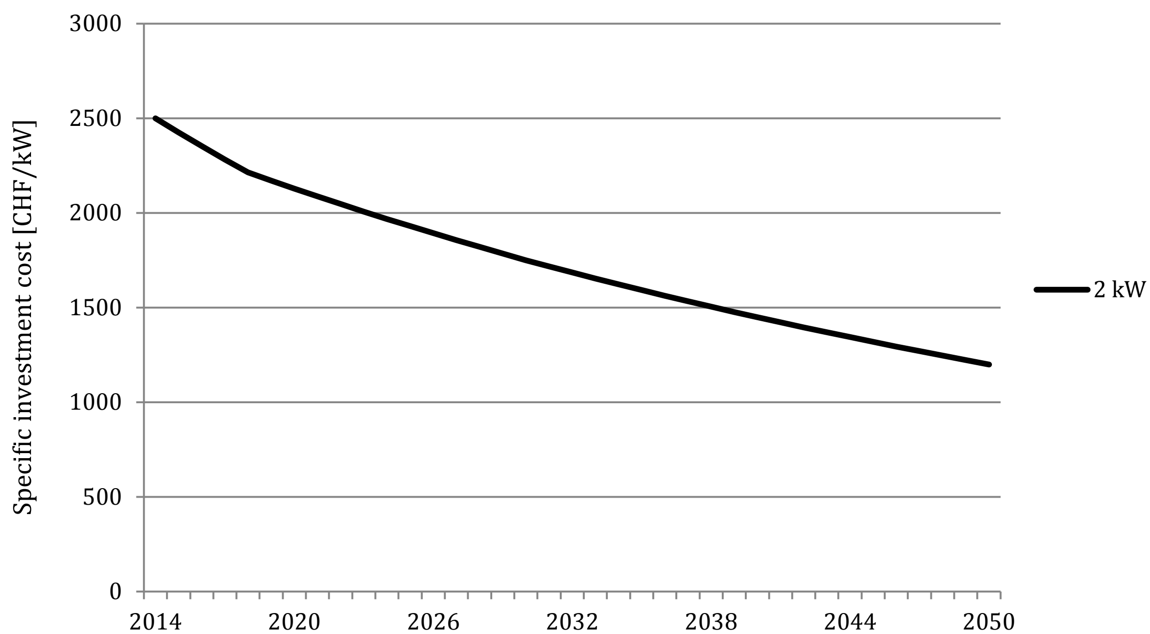

Figure 37: Future investemt cost trend for a 2kW system.

The retail electricity price for all cantons is available by the Federal Electricity Commission [43] according to the consumption categories analyzed in Chapter 4.1.1.4. Due to the insignificant difference in electricity prices that correspond to the consumption categories H4-H8 in which single-family houses fall, we consider only one electricity price per canton and household, which is the average electricity price of all five categories. The rate of change until 2050 is taken by [44], in respect of an average scenario on the Swiss energy mix in 2050 developed by PSI. The estimated retail electricity price for the canton of Zurich in certain years can be seen in Table 14.

Table 14: Future retail electricity price [CHF/kWh] for the canton of Zurich in the "Baseline" scenario.

Electricity price [CHF/kWh]	**2015**	**2020**	**2030**	**2040**	**2050**
	0.145	0.164	0.214	0.242	0.246

The future financial incentives for installations above 10kW and below 10kW are calculated by extrapolating the past trends [45] and listed in Table 15.

Table 15 : Future financial incentives by installed capacity in the "Baseline" scenario.

Installed capacity	**Incentives**	**2015**	**2020**	**2030**	**2040**	**2050**
≥10kW	Feed-in tariff [CHF/kWh]	0.212	0.083	0	0	0
<10kW	One-off payment as share of the investment cost [%]	24.1	9.5	0	0	0

The annual rate of adoption, the cumulative number of adopters and the cumulative capacity resulting from the "Baseline" scenario is presented in Figure 38. It should be noticed that the capacity of installations that have exceeded the lifetime of 25 years is included in the cumulative capacity of 2050. It is thus assumed than an agent which adopts PV technology, will renew the investment after the end of its lifetime.

In order to verify the validity of the model, we consider two studies on the future development of the Swiss energy system in years 2018 and 2050 respectively. According to the European Photovoltaic Industry Association (EPIA) the cumulative installed capacity in Europe could reach between 119 GW to 156 GW in 2018 [46]. If we extrapolate the 2013 share of the Swiss market in the European PV market, then the total cumulative installed capacity, could be according to EPIA between 3.57 to 4.68 GW in 2018. Moreover, if we extrapolated the PV market share of single-family houses in Switzerland in 2013, which is approximately 12% of the total, then the installed capacity in single-family houses could reach between 428MW to 561MW in 2018. The model shows an acceptable consistency to the above estimated capacity range, giving a total installed capacity of 340 MW in 2018 (Figure 38 (bottom left)). In addition, studies on the energy strategy of Switzerland in 2050 [44] forecast that the total PV installed capacity in 2050 will be approximately between 7GW to 15 GW, according to various scenarios. According to the model, 320'502 agents will have installed 1.593 GW in total by the end of 2050. As a result, it is shown that the outcome of the simulations agrees relative well with the studies described above and we can therefore verify the validity of the model.

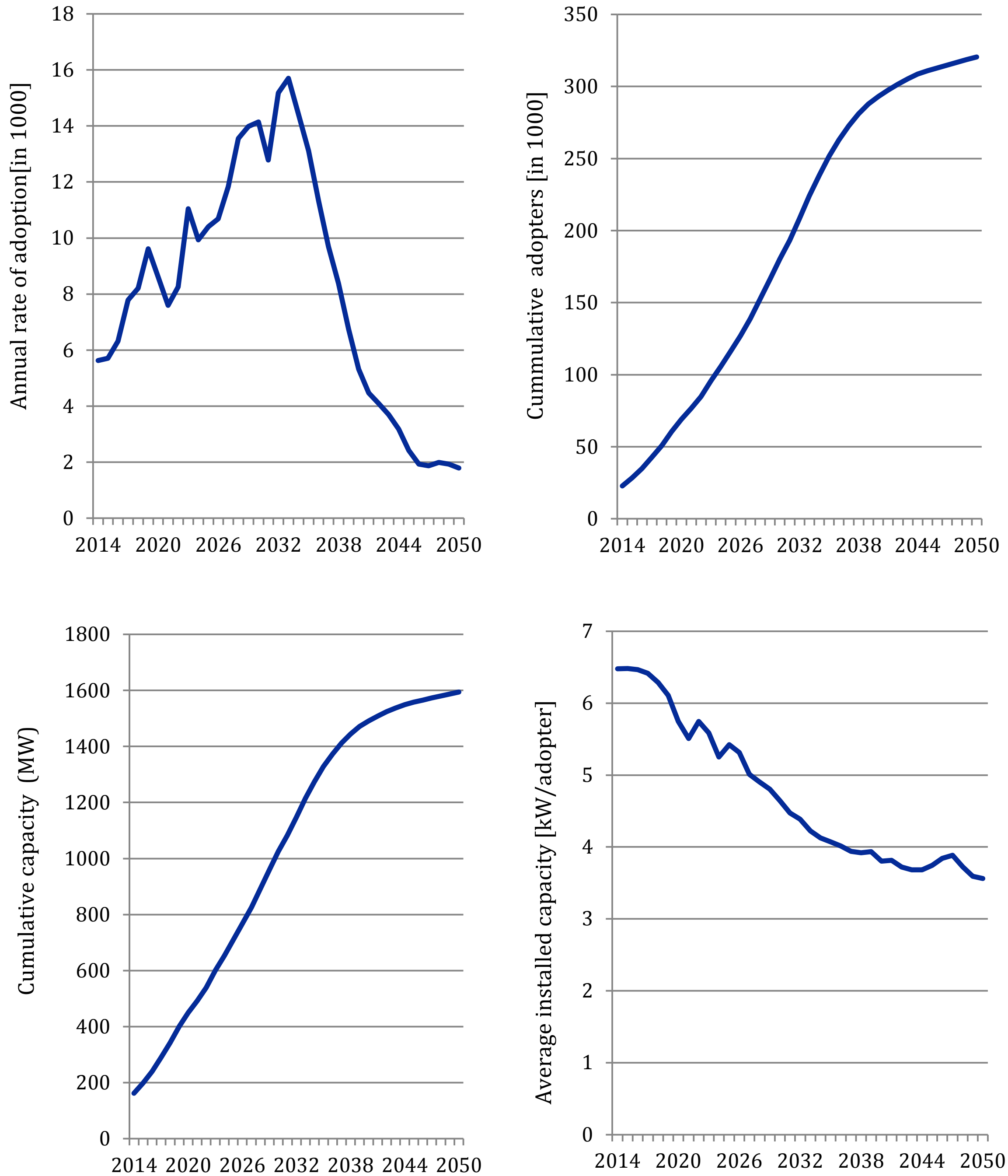

Figure 38: Annual rate of adoption (top left), cumulative adopters (top right), cumulative capacity (bottom left) and average installed capacity per adopter (bottom right) in the "Baseline" scenario (2014-2050).

The annual rate of adoption shows an increasing trend until 2033, where it reaches a maximum of 15'702 new adopters. During this period, an agent's decision to adopt PV technology is mostly affected by the agent's income level and the economic profitability of the investment according to Figure 39. After 2033 the rate of adoption is gradually decreasing. A further investigation on the factors that cause this gradual fall reveals some important insights.

At first, the agents which are the most potential candidates diminish dramatically. Figure 40 illustrates the cumulative adopters classified by the Sinus-Milieus categories in years 2030 and 2050, where one can observe the remarkable share in adopters of categories 9 and 10. In 2030, 76'207 agents belonging in category 10 and 47'000 agents belonging in category 9 have already become adopters. This corresponds to 81% and 41% respectively of the total agents falling in categories 9 and 10 during this year. Consequently, as only 20% of potential agents having the highest income and the most powerful social network remain, the annual rate of adoption declines. After 2033, agents from more conservative categories start adopting the technology; however their rates of adoption are not high enough in order to sustain the general increasing trend up to 2033.

Moreover, the environmental utility has a significant weight in the adoption decision in the early years; however, its contribution decreases with time as a consequence of the ongoing decline of the installed capacity per adopter (Figure 38 (bottom right)). This decline can be explained by the fact that agents of higher Sinus-Milieus categories have become adopters before 2033. These agents have the highest income and therefore the highest installed capacities. In addition, the absence of financial incentives after 2035 does not allow investing in large PV installations.

Furthermore, the economic and communication utility act like the driving forces of the diffusion process, presenting a remarkable increase, mostly until 2033. The existence of financial incentives improves the payback period of the investment that turns from 14 years in 2014 to 7.5 years in 2033. The following years, the economic utility increases much slower (from 7.5 years in 2033 to 5 years in 2050) (Figure 41). The communication utility reaches a saturation point and although it highly weights in the adoption's decision, its impact remains stable and therefore cannot create a further increase in the number of adopters. However, by the end of the period studied the agent seems to be most likely attracted by the economic benefits of the investment rather than by any other factor (Figure 39).

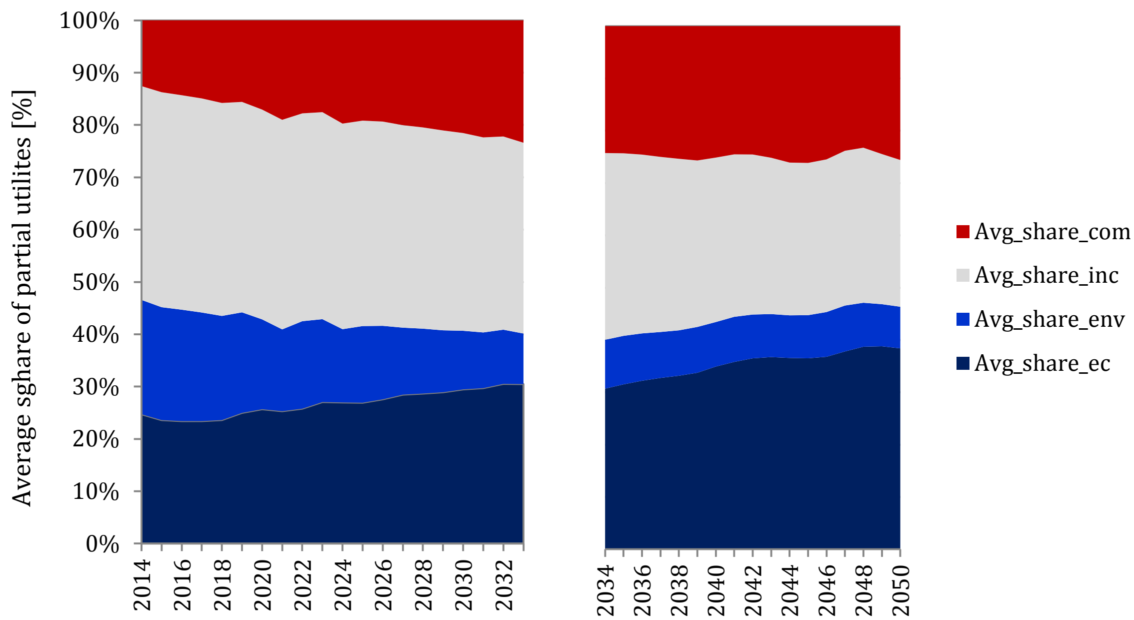

Figure 39: Average share of the weighted partial utilities on the adoption decision.

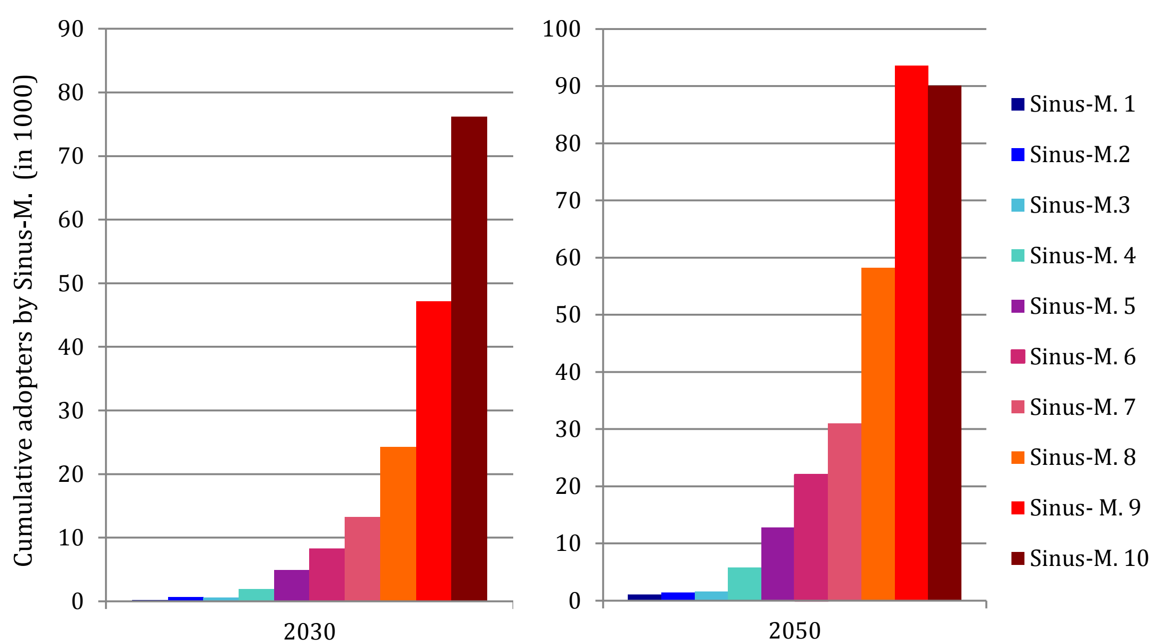

Figure 40: Cumulative adopters by Sinus-Milieus categories in 2030 and 2050.

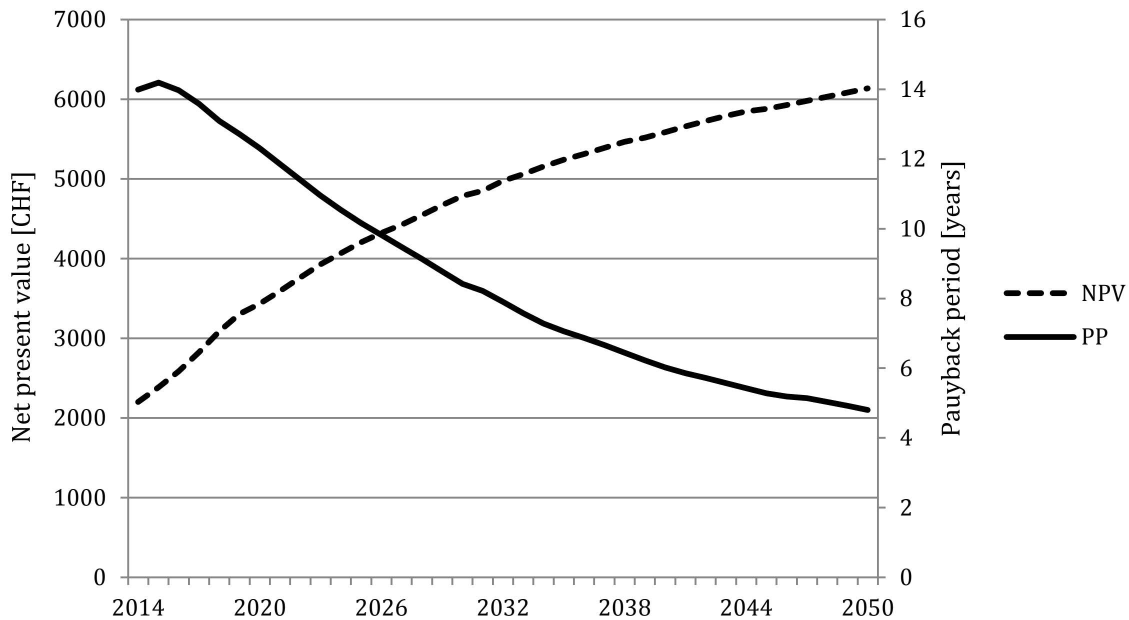

Figure 41: Evolution of the NPV and the payback period in the "Baseline" scenario (2014-2050).

7.2. Scenarios of different investment costs

Two scenarios are developed in order to examine the sensitivity of the model to alternative future investment costs. More specifically, the "High investment cost" scenario assumes that investment costs will be 20% higher in 2030 in comparison to the "Baseline" scenario whereas the "Low investment cost" 20% lower. The future investment costs for various systems in certain years in the two alternative scenarios are listed in Table 16 Table 16 and Table 17 respectively.

Table 16: Future investment costs [CHF/kWh] for various systems in the "High investment cost" scenario.

Investment costs [CHF/kW]	2015	2020	2030	2040	2050
2 kW	2'472	2'341	2'100	1'738	1'440
3 kW	2'308	2'185	1'960	1'623	1'344
5kW	2'275	2'154	1'932	1'599	1'324
7 kW	2'119	2'007	1'800	1'490	1'234
10 kW	1'978	1'873	1'680	1'391	1'152
20 kW	1'889	1'789	1'604	1'328	1'100

Change relative to baseline [%]	+1.98	+10.03	+20.00	+20.00	+20.00

Table 17: Future investment costs [CHF/kWh] for various systems in the "Low investment cost" scenario.

Investment costs [CHF/kW]	**2015**	**2020**	**2030**	**2040**	**2050**
2 kW	2'411	2'011	1'400	1'159	960
3 kW	2'250	1'877	1'306	1'082	896
5kW	2'218	1'850	1'288	1'066	883
7 kW	2'065	1'724	1'200	993	822
10 kW	1'928	1'609	1'120	927	768
20 kW	1'842	1'536	1'096	885	733
Change relative to baseline [%]	-0.58	-5.49	-20.00	-20.00	-20.00

Both scenarios (Figure 42) create changes in the diffusion process. The total number of adopters in 2050 is 332'400 (i.e. 3.7% higher than the "Baseline") in the "Low investment cost" scenario and 298'228 (i.e. 7% lower than the "Baseline") in the "High investment cost" scenario. The increase in the number of adopters in the "Low investment cost" scenario is caused by the increase of the economic and communication utility. Lower investment costs improve the payback period and provoke higher adoption rates. In turn, the more agents are adopting the PV technology the more influential is the social network.

However, the difference in the cumulative number of adopters is not as significant as the difference in the evolution of the diffusion process in respect to time. The time in which a system gains its momentum is a very important factor, especially when specific targets have to be reached within a certain time frame. Lower investment costs act recto-actively, resulting in more adopters backwards in time. In the contrary, higher investment costs procrastinate the diffusion process and result in less adopters forward in time, when investment costs are low enough to attract investors. However, although the cumulative curve in the "Baseline" and "Low investment cost" scenarios reaches its saturation point in 2050 the "High investment cost" scenario shows a rather evolving process. This means that the period from 2014 to 2050 is not sufficient for the diffusion to reach its maximum.

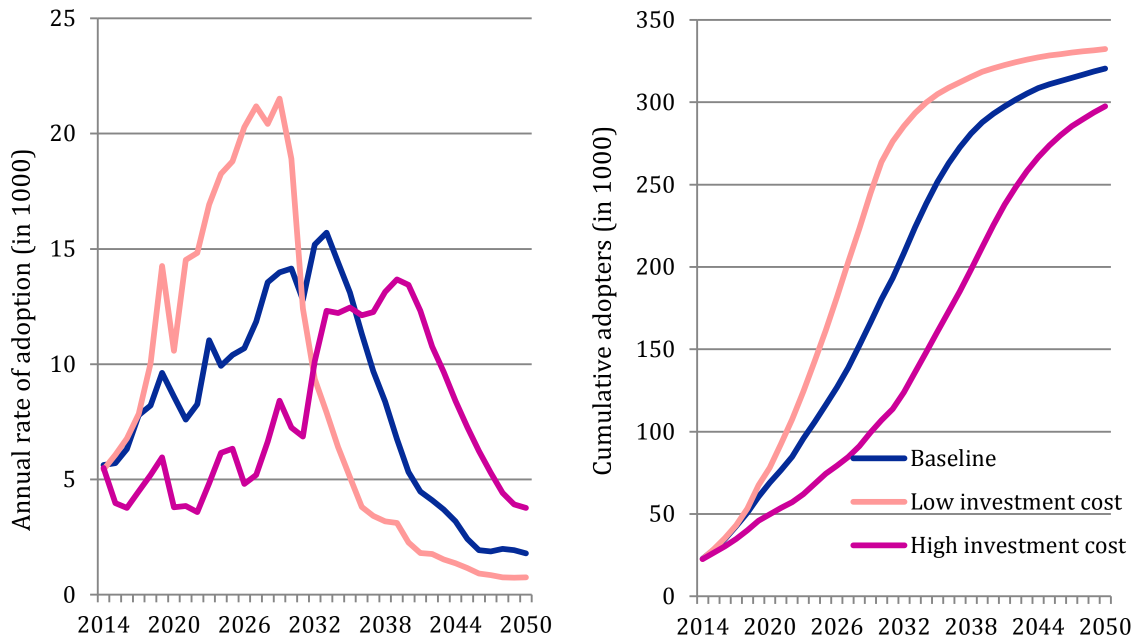

Figure 42: Annual rate of adoption and cumulative adopters in the "High investment cost" and "Low investment cost" scenarios (2014-2050).

7.3. Scenarios of different governmental policy

Two alternative scenarios of financial incentive policy were examined, including the "Continuation policy" scenario and the "Weaker policy" scenario. The former considers a constant feed-in tariff from 2014 until 2050 as shown in Figure 43 for the case of large residential producers (≥10kW). Similarly, it is assumed that small producers (<10 kW) will have a constant one-off payment covering 30% of the initial investment cost from 2014 to 2050. On the other hand, the "Weaker policy" scenario assumes a sharper decline in the feed-in tariff until 2018, and no financial incentives thereafter.

The "Continuation policy" scenario behaves similarly to the "Low investment cost" scenario, showing an increasing trend in the rate of adoption taking place earlier in time (Figure 44). Nevertheless, the cumulative number of adopters in this case is 5.2% higher in comparison to the "Baseline" scenario. The "Weaker policy" scenario presents a decline in the number of adopters until 2021 with the sharpest drop of -80% taking place in the years 2015 and 2016 (compared to the "Baseline" scenario). Thereafter, the situation is reversed. In the period between 2021 and 2032, the rate of adoption exceeds the rate of adoption in the "Baseline" scenario. This results in having the same cumulative number of adopters for both scenarios by the end of 2050. A further investigation shows that the agents which become adopters in both scenarios are identical, with the year of adoption being different. In other words, given that the feed-in tariff is relatively low in the "Baseline" scenario", a lower feed-in tariff changes neither the total number nor the identity of the adopters but only postpones slightly the adoption time.

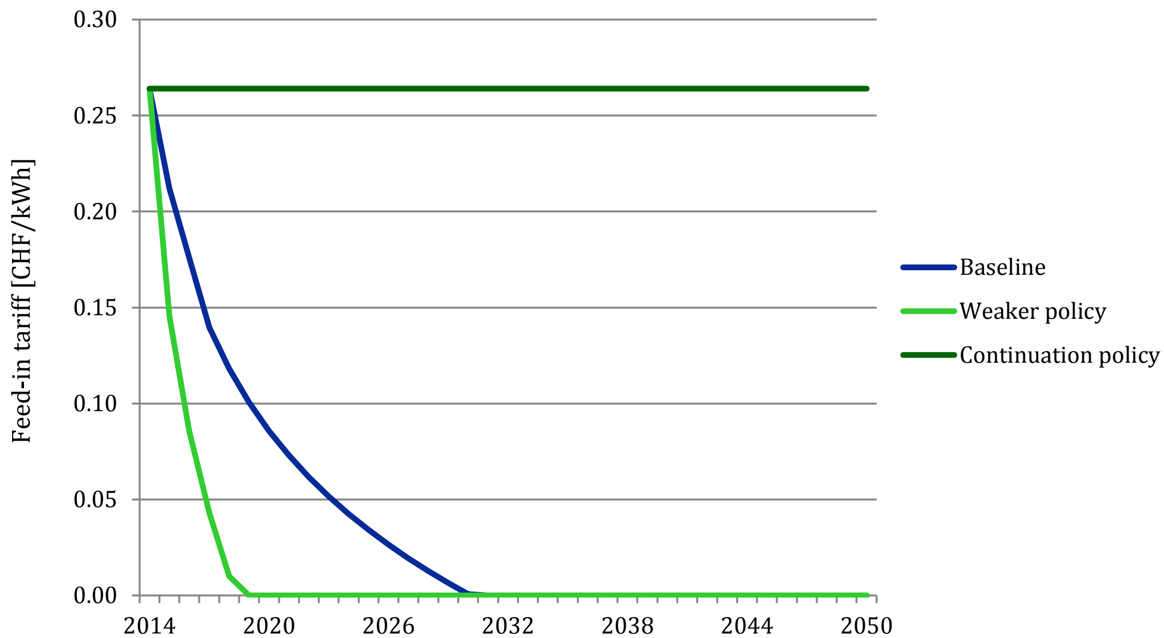

Figure 43: Financial incentives in different governmental policy scenarios.

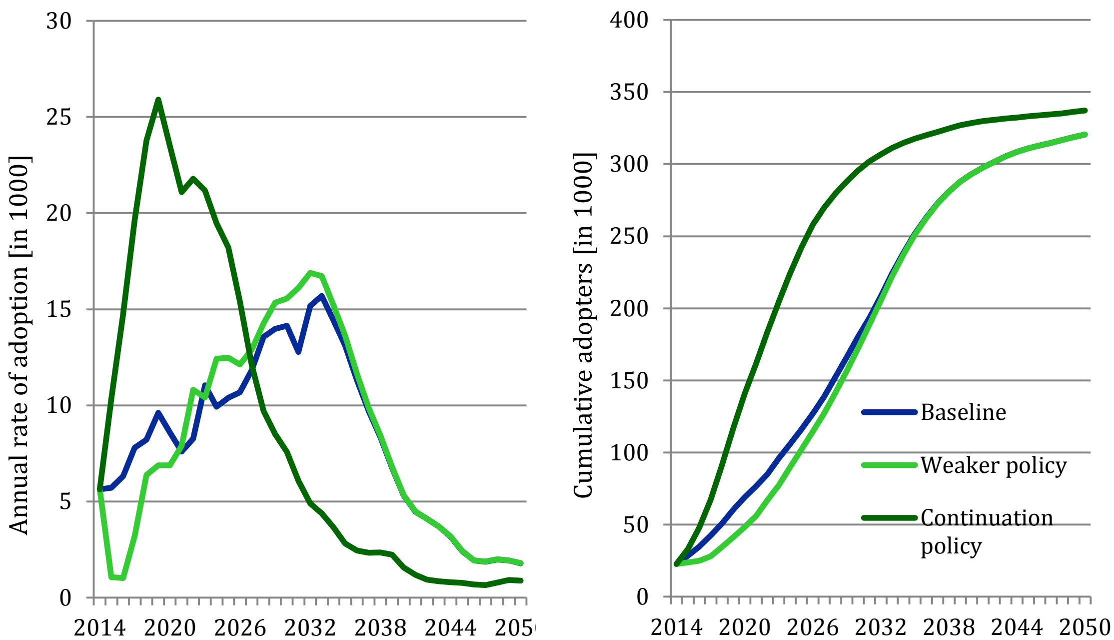

Figure 44: Annual rate of adoption and cumulative adopters in the "Continuation policy" and "Weaker policy" scenarios (2014-2050).

7.4. Scenarios of different electricity price

Two more scenarios were developed in order to test the model's behavior in respect of electricity prices. The first scenario considers a 10% higher electricity price compared to the "Baseline" for all the years and the second a 10% lower price. As can be seen in Figure

45, the cumulative number of adopters in the "Baseline" scenario coincides with that of the "Higher electricity price" scenario. The "Baseline" scenario acts similarly to the "Weaker policy" scenario described in Chapter 7.3, moving the same adopters forward in time. The model seems to show a higher sensitivity in lower electricity prices, resulting in a lower number of adopters by the end of 2050.

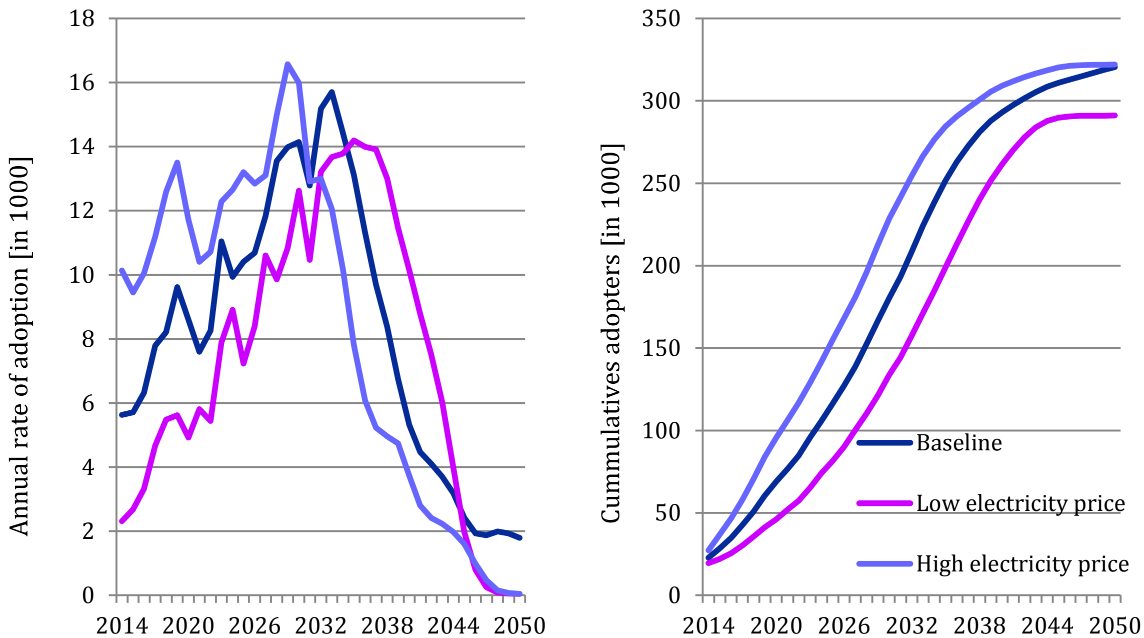

Figure 45: Annual rate of adoption and cumulative adopters in the "High electricity price" and "Low electriciy price" scenarios (2014-2050).

7.5. Alternative discount rate scenario

In addition to the described scenarios, the "High discount rate" scenario is developed, assuming a constant rate of 12.5% in all time horizons. The "High discount rate" behaves as the "High investment cost" scenario, postponing the adoption process and cumulating less adopters by the end of 2050. The discount rate describes one's perception of the value of money at a given time; high discount rates correspond to high payback periods which discourage investors intuitively. Only when the investment costs and in turn the payback periods will become low enough, the investment seems to become more attractive.

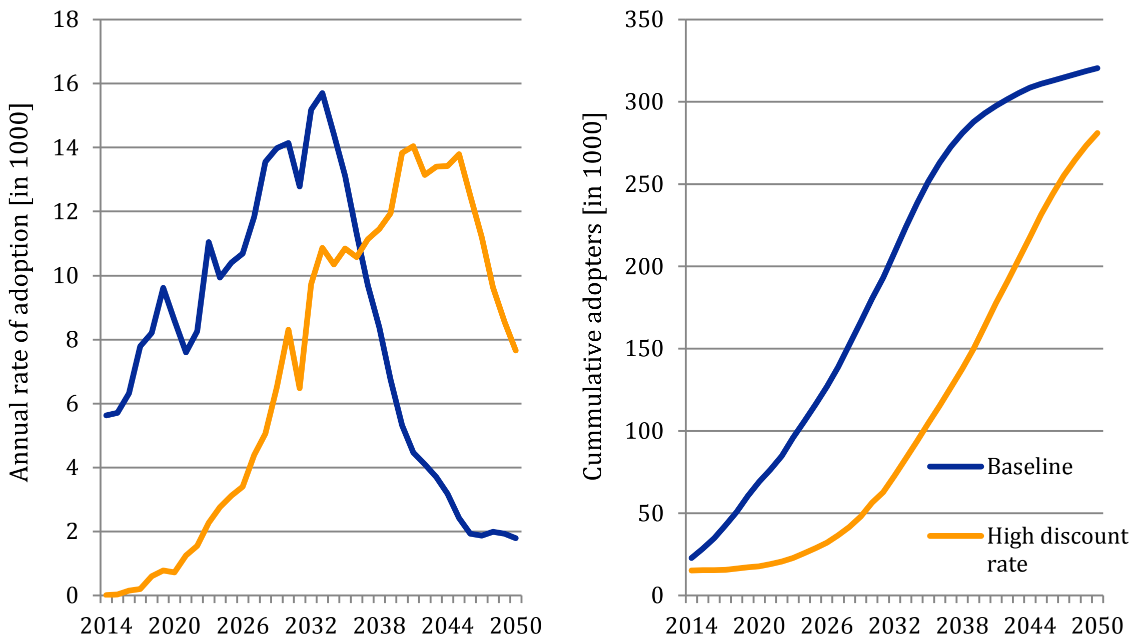

Figure 46: Annual rate of adoption and cumulative adopters in the “High discount scenario (2014-2050).

7.6. Comparison of all the scenarios

Figure 47, Figure 48 and Figure 49 summarize the simulation results of all the scenarios. The comparison of all scenarios, shows that the “Continuation policy” scenario gives the highest cumulative number of adopters and the highest cumulative capacity in 2050 (337’043 agents will have installed 1.634GW) followed by the “Low investment cost” scenario (332’379 agents will have installed 1.631GW). In fact, the “Continuation policy” scenario shows the earliest adoption growth, reaching its maximum annual rate of adoption in 2019, whilst the “Low investment cost” in 2029. The “Baseline”, “High electricity price” and “Weaker policy” scenarios result in almost the same number of adopters and cumulative capacity by the end of 2050 (approximately 320’500 adopters will have installed 1.593GW in all three scenarios). The “High discount rate” scenario results in the lowest rate of adoption in 2050 (only 281’004 agents will have installed 1.481GW).

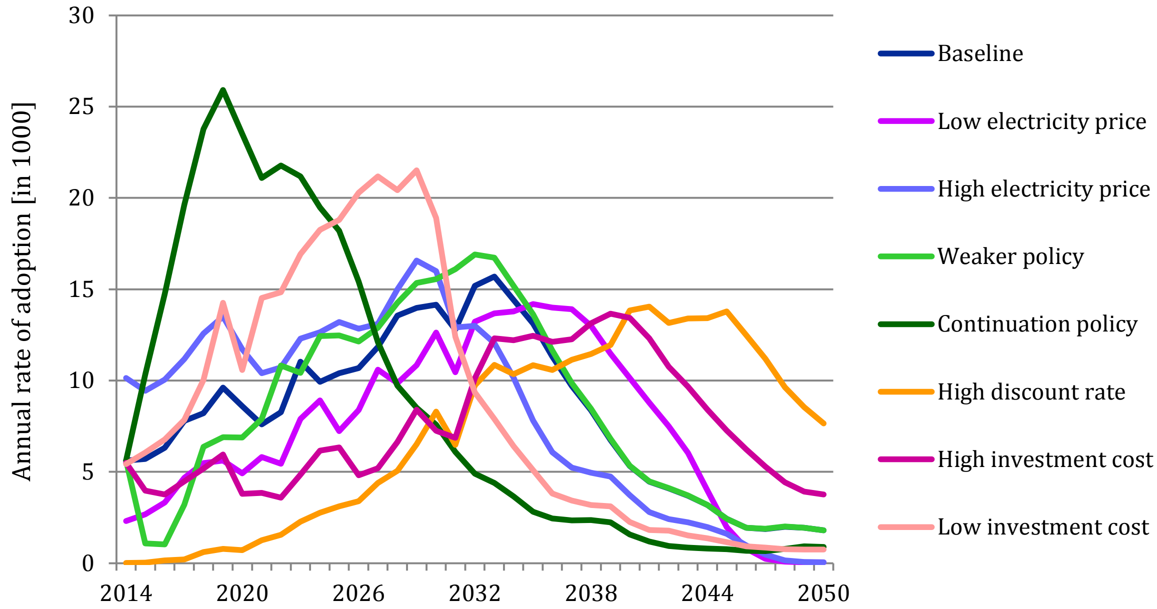

Figure 47: Annual rate of adoption in all scenarios (2014-2050).

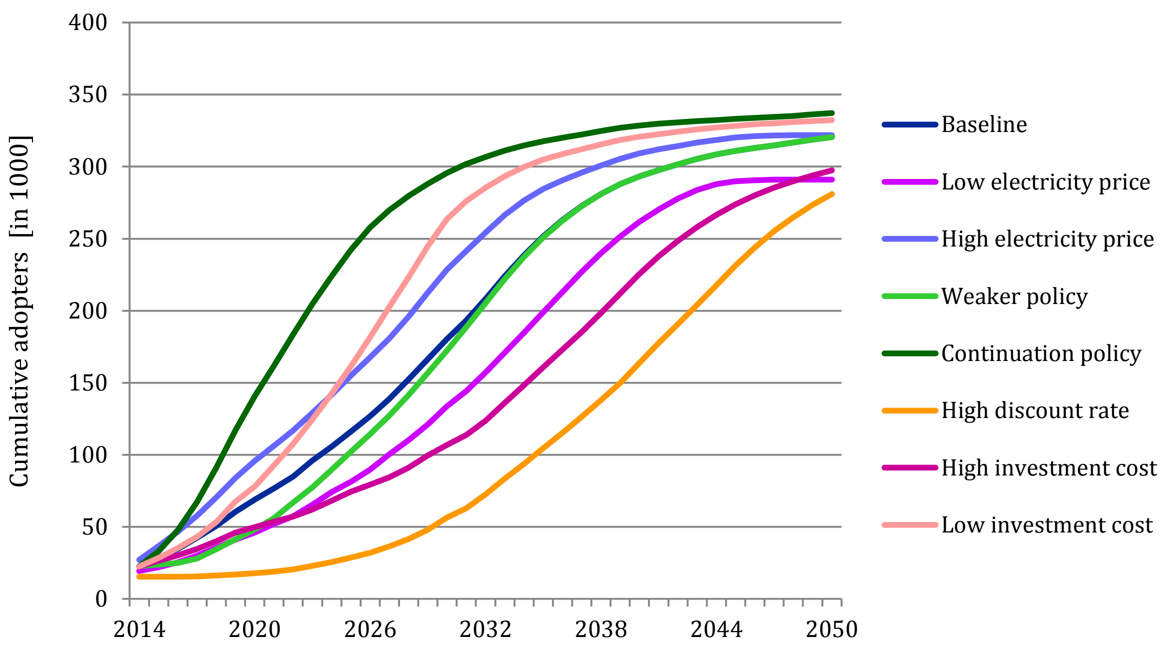

Figure 48: Cumulative adopters in all scenarios (2014-2050).

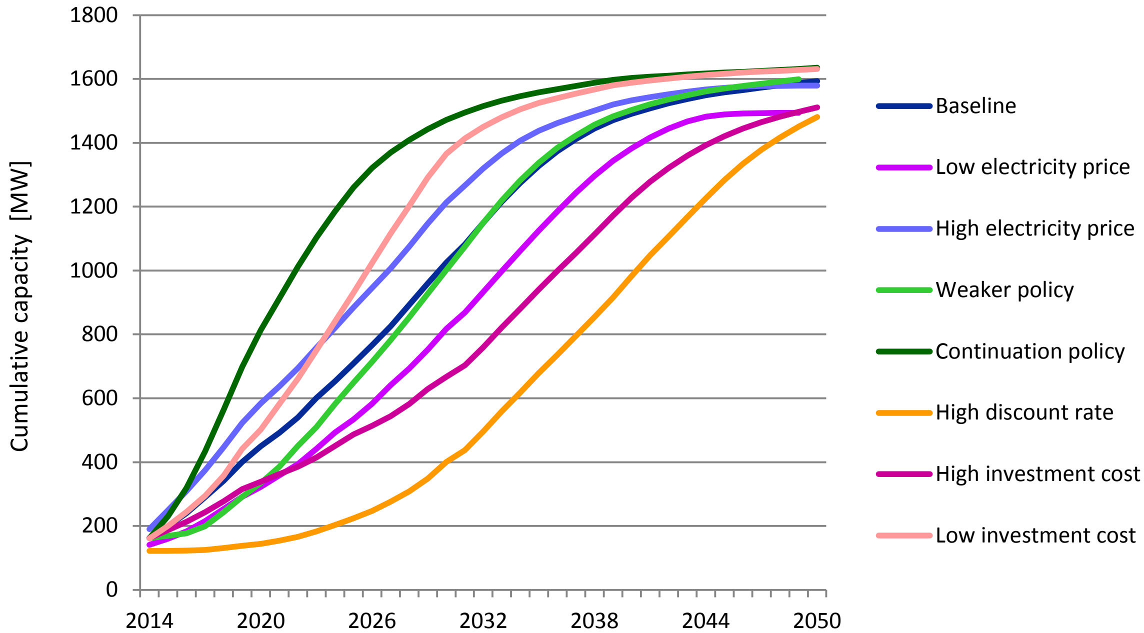

Figure 49: Cumulative capacity in all scenarios (2014-2050).

Lastly, we present the cumulative rate of adoption for the "Baseline" scenario in years 2014, 2030 and 2050 for all cantons. The cantons that show the highest potential are the cantons of Zurich, Bern, Aargau, Vaud and Ticino. Despite differences in electricity prices and wages, the adoption rate by canton is almost proportional to the number of single-family houses in each canton. In addition, the southern cantons (e.g. Vaud, Ticino) benefit from higher solar irradiation levels that compensate for the lower population compared to the northern cantons (e.g. Zurich, Bern, Aargau).

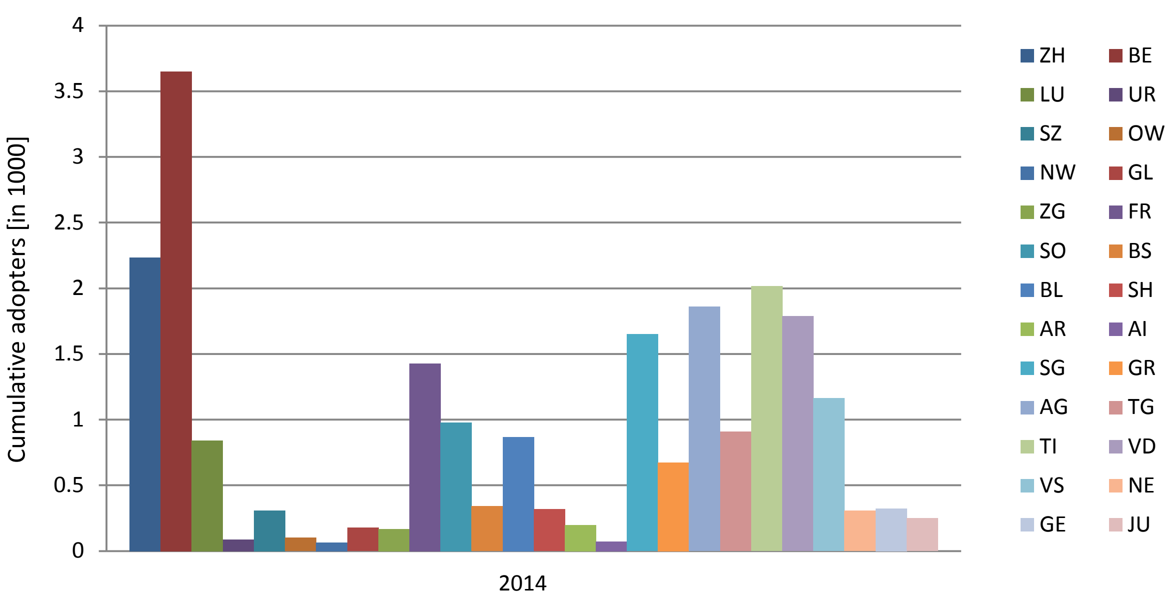

Figure 50: Cumulative adopters by canton in 2014.

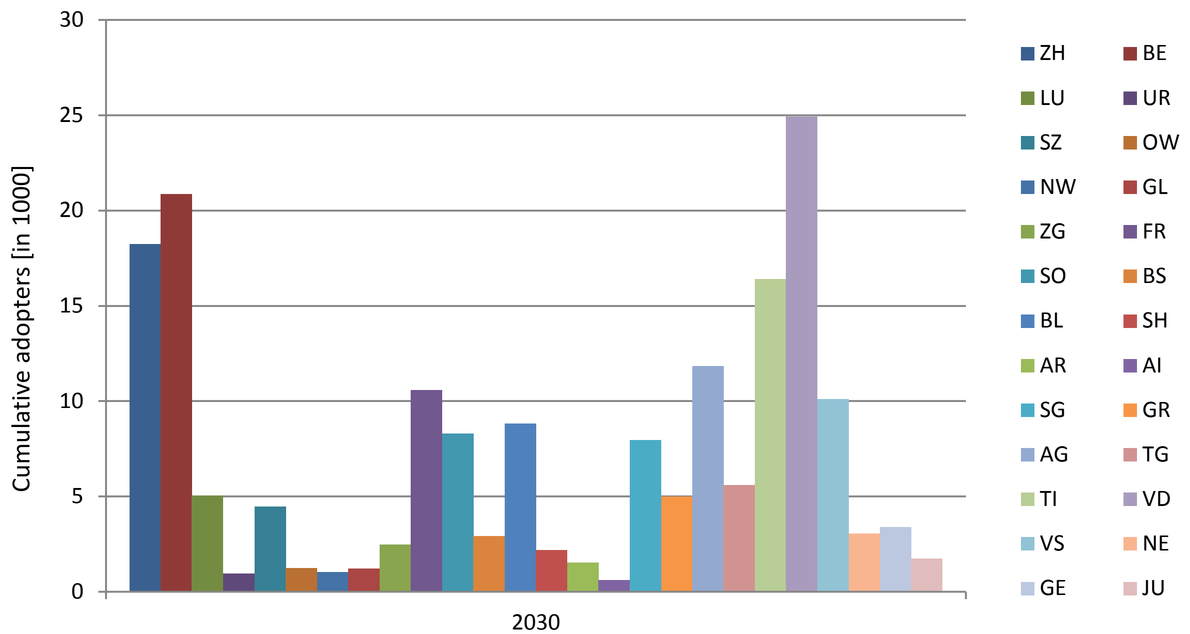

Figure 51: Cumulative adopters by canton in 2030.

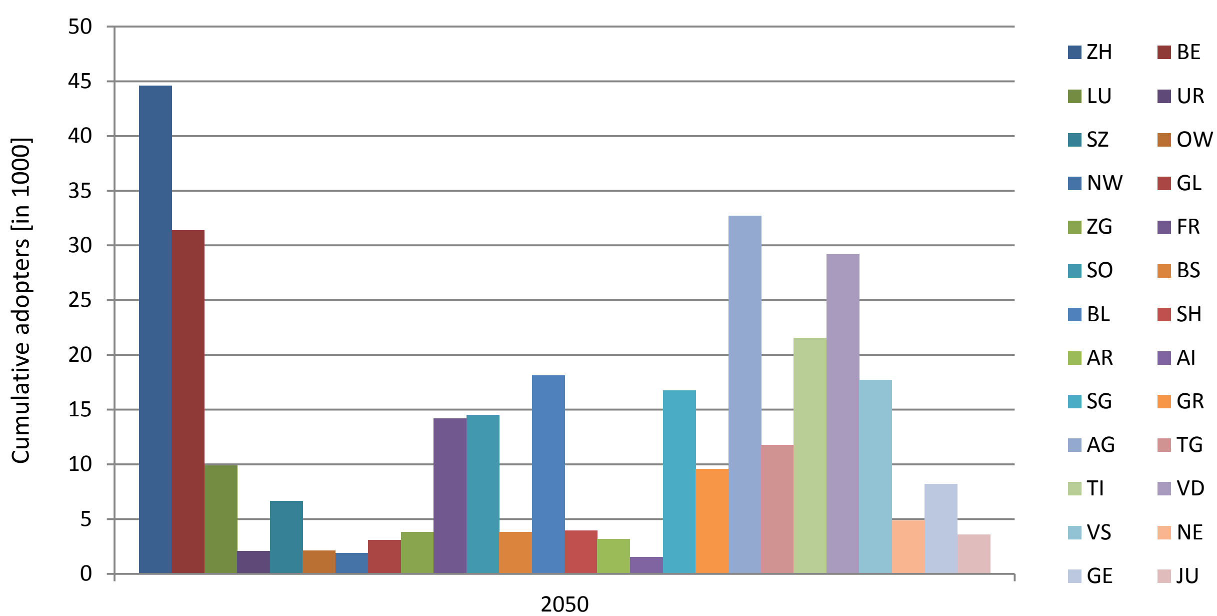

Figure 52: Cumulative adopters by canton in 2050.

8. Conclusion and extensions

Switzerland is now facing a new energy challenge with its decision to gradually phase out nuclear energy and instead increase the share of non-hydro based renewable energy in the electricity mix. To this scope, our study focuses on the diffusion of solar PV technology, which shows a significant potential and high social acceptance in Switzerland. More specifically, we study the future PV market growth in single-family houses that have currently the largest share of the domestic residential PV market.

An agent-based model is developed to forecast the future PV deployment in single-family houses in Switzerland in the period of 2014 to 2050. The model incorporates four main factors that affect an agent's decision to adopt PV technology. These are: the economic profitability of the investment, the agent's environmental friendliness, the household income and the impact of communication networks (neighboring effect). To create social networks, the agents are classified in different demographic categories according to Sinus-Milieus. We construct six different synthetic populations of agents, with unique characteristics derived from joint probability distributions by applying Monte Carlo simulation.

The model was calibrated using historical data for the period 2010-2013. The calibration presented a good fit to the annual rate of adopters and the cumulative number of adopters but less accuracy in the installed capacity per adopter. In fact, the model did not capture the recent trend of increasing the installed capacity per adopter but it showed a rather constant trend during the years of calibration and a decreasing trend thereafter.

According to the "Baseline" scenario that represents the most likely future PV deployment in single family houses, 320'502 houses (i.e. 30.4 % of the total agent population) will install 1.593 GW by the end of 2050. This cumulative capacity is in general in-line with the Swiss Energy Strategy 2050. According to the results, the diffusion process is initially driven by the most innovative agents, the adoption rate of which is constantly increasing. By the time they have by majority become adopters, more technologically immature agents start adopting, however at a decreasing annual adoption rate. This turning point corresponds to the saturation point of the diffusion process. Throughout the time length of the diffusion process the factors affecting most the adoption decision are the income level and the payback period of the investment.

Several scenarios, including alternative future trends in investment costs, governmental policies and electricity prices were developed in order to examine the validity and sensitivity of the model in dynamically changing factors. The results showed that between the worst and the best scenarios the difference in the number of adopters is not as significant as is the difference in the evolution of the diffusion process with respect to time. This implies that the system has gained its momentum but evolves rather slowly. Stronger governmental policy and lower investment costs will accelerate the diffusion process, bringing the investments forward in time. On the contrary, high investment costs will decelerate the diffusion process such as the respective timeframe will not be sufficient for the diffusion to reach its maximum.

There are certain recommendations to be made in the scope of future studies on the PV penetration rate. At first, this work should expand to all potential adopters including as agents multi-family houses, industrial facilities and commercial buildings. Furthermore, it would be important to conduct surveys in order to evaluate people's perception about the factors affecting their adoption decision. This would allow us to better define the utility functions and their corresponding weights.

A third enhancement of the model is to increase its spatial resolution below the cantonal level, for example at the level of a city or a village. This could provide more insights regarding the decision process of an agent and it could potentially demonstrate in a better way the social and neighboring effects.

Another improvement of the model is the differentiation of the discount rate according to the socio-economic categories of the agents. This will capture the cost of capital and the risk perception of the agents with respect to their annual incomes and access to financing.

The implicit assumption of renewing the investment after its lifetime could also be lifted considering a probability function in deciding whether the agent will re-install the solar photovoltaic system immediately or it will be re-considered as a potential adopter.

Finally, in order to quantify the uncertainty surrounding the decision mechanism of the agent, more than six synthetic populations have to be taken into account. These populations will be generated with the same stochastic process described in Chapter 4.1.

9. References

[1] EnergyMarketPrice, "Switzerland Energy Statistics," Jan-2013.
[2] P. Huesser and N. Farrag, "National Survey Report of PV Power Applications in Switzerland 2013," International Energy Agency, 2013.
[3] "Swiss Federal Office of Energy (SFOE): Press releases." [Online]. Available: http://www.bfe.admin.ch/energie/00588/00589/index.html?lang=en. [Accessed: 26-Aug-2015].
[4] D. Weibel, "The Swiss Feed-in Tariff System," Energy Economics and Policy, ETH Zurich, Jun. 2011.
[5] J. Grätz and D. Möckli, "Swiss nuclear phaseout: energy supply challenges," Center for Security Studies (CSS), ETH Zurich, 2012.
[6] "Fiche d'information: Rétribution unique et consommation propre pour les petites installations photovoltaïques," Swiss Federal Office of Energy (SFOE), Nov. 2014.
[7] "Ordonnance sur l'energie: Modification du 2014." Swiss Federal Office of Energy (SFOE).
[8] "Fiche d'information: RPC pour installations photovoltaïques," Swiss Federal Office of Energy (SFOE), Mar. 2015.
[9] E. Bonabeau, "Agent-based modeling: Methods and techniques for simulating human systems," *Proc. Natl. Acad. Sci.*, vol. 99, no. suppl 3, pp. 7280–7287, 2002.
[10] D. Helbing and S. Balietti, "How to do agent-based simulations in the future: From modeling social mechanisms to emergent phenomena and interactive systems design," *Chapter Agent-Based Model. Book Soc. Self-Organ. Dirk Helbing Springer Berl. 2012*, pp. 25–70, 2013.
[11] G. Wurzer, K. Kowarik, and H. Reschreiter, *Agent-based Modeling and Simulation in Archaeology*. Springer, 2015.
[12] A. Bazghandi, "Techniques, advantages and problems of agent based modeling for traffic simulation," *Int J Comput Sci*, vol. 9, no. 1, pp. 115–119, 2012.
[13] E. Kiesling, M. Günther, C. Stummer, and L. M. Wakolbinger, "Agent-based simulation of innovation diffusion: a review," *Cent. Eur. J. Oper. Res.*, vol. 20, no. 2, pp. 183–230, 2012.
[14] J. Zhao, E. Mazhari, N. Celik, and Y.-J. Son, "Hybrid agent-based simulation for policy evaluation of solar power generation systems," *Simul. Model. Pract. Theory*, vol. 19, no. 10, pp. 2189–2205, 2011.
[15] J. Palmer, G. Sorda, and R. Madlener, "Modeling the diffusion of residential photovoltaic systems in italy: An agent-based simulation," 2013.
[16] S. A. Robinson, M. Stringer, V. Rai, and A. Tondon, "GIS-integrated agent-based model of residential solar pv diffusion," in *32nd USAEE/IAEE North American Conference*, 2013, pp. 28–31.
[17] W. Jager, "Stimulating the diffusion of photovoltaic systems: A behavioural perspective," *Energy Policy*, vol. 34, no. 14, pp. 1935–1943, 2006.
[18] A. Faiers, C. Neame, and M. Cook, "The adoption of domestic solar-power systems: Do consumers assess product attributes in a stepwise process?," *Energy Policy*, vol. 35, no. 6, pp. 3418–3423, 2007.
[19] M. Guidolin and C. Mortarino, "Cross-country diffusion of photovoltaic systems: modelling choices and forecasts for national adoption patterns," *Technol. Forecast. Soc. Change*, vol. 77, no. 2, pp. 279–296, 2010.

[20] H. Turton Ramachandran,Kannan, "Cost of ad-hoc nuclear policy uncertainties in the evolution of the Swiss electricity system." .
[21] "Swissgrid - Startseite." [Online]. Available: https://www.swissgrid.ch/swissgrid/de/home.html. [Accessed: 26-Aug-2015].
[22] "publisuisse. Wir machen Marken." [Online]. Available: http://www.publisuisse.ch/106996. [Accessed: 26-Aug-2015].
[23] "Eidgenössische Steuerverwaltung ESTV: Direkte Bundessteuer - Natürliche Personen - Kantone - Steuerjahr 2011." [Online]. Available: http://www.estv.admin.ch/dokumentation/00075/00076/00701/01685/index.html?lang=de. [Accessed: 26-Aug-2015].
[24] "Swiss Federal Statistical Office: Population size and population composition - Permanent population by age, canton district and commune (2010-2013)." [Online]. Available: http://www.bfs.admin.ch/bfs/portal/en/index/themen/01/02/blank/key/bevoelkerungsstand.html. [Accessed: 26-Aug-2015].
[25] "Swiss Federal Statistical Office: Gross monthly wage by age - Private and public (Confederation) sectors-Switzerland." [Online]. Available: http://www.bfs.admin.ch/bfs/portal/en/index/themen/03/04/blank/data/01/06_01.html. [Accessed: 26-Aug-2015].
[26] "Strompreis-Webseite der ElCom: Vergleichen Sie Ihren Strompreis." [Online]. Available: https://www.strompreis.elcom.admin.ch/ShowCat.aspx?placeNumber=3513&OpID=527&Period=2012&lang=de. [Accessed: 26-Aug-2015].
[27] "Bundesamt für Statistik: Energiebereich - Gebäude nach Kanton, Gebäudekategorie, Heizungsart, Warmwasserversorgung, Energieträger und Bauperiode." [Online]. Available: https://www.pxweb.bfs.admin.ch/Selection.aspx?px_language=de&px_db=px-x-0902010000_102&px_tableid=px-x-0902010000_102\px-x-0902010000_102.px&px_type=PX. [Accessed: 26-Aug-2015].
[28] "Solstis Photovoltaique: Installations de référence." [Online]. Available: http://www.solstis.ch/en/references/installations-reference?cck=installations_de_reference&type_dinstallation=14&systme_de_montage=L%27appos%C3%A9%20/%20sur%20tuiles&pays=Suisse&boxchecked=0&search=liste_des_installations&task=search&start=150. [Accessed: 26-Aug-2015].
[29] "Viessmann: Richtpreisofferte Photovoltaik (solare Stromerzeugung) für Klein - und Mittelanlagen." [Online]. Available: http://www.viessmann.ch/content/dam/internet-ch/pl_2014/pv_kuzofferte_072014.pdf. [Accessed: 26-Aug-2015].
[30] "Oracle Crystal Ball User's Guide." [Online]. Available: http://docs.oracle.com/cd/E17236_01/epm.1112/cb_user/frameset.htm?apas04.html. [Accessed: 26-Aug-2015].
[31] "Bundesamt für Statistik: Bau- und Wohnungswesen - Gebäude und Wohnungsstatistik 2013." [Online]. Available: http://www.bfs.admin.ch/bfs/portal/de/index/themen/09/01/new.html. [Accessed: 26-Aug-2015].
[32] A. G. Prognos, "Die Energieperspektiven für die Schweiz bis 2050," *Bundesamt Für Energ. BFE Tech Rep*, 2012.
[33] "Bundesamt für Energie BFE: Kostendeckende Einspeisevergütung - Listen aller KEV-Bezüger in den Jahren 2011-2014." [Online]. Available: http://www.bfe.admin.ch/themen/00612/02073/index.html?dossier_id=02166&lang=de. [Accessed: 26-Aug-2015].

[34] "PV potential estimation utility." [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php. [Accessed: 26-Aug-2015].
[35] Goodpal, "Solar PV Power Plants: Major Causes of Performance Degradation," *Solar Power for Ordinary People*. .
[36] "Degradation and Failure Modes | PVEducation." [Online]. Available: http://pveducation.org/pvcdrom/modules/degradation-and-failure-modes. [Accessed: 26-Aug-2015].
[37] G. Makrides, B. Zinsser, G. E. Georghiou, M. Schubert, and J. H. Werner, "Degradation of different photovoltaic technologies under field conditions," in *Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE*, 2010, pp. 002332–002337.
[38] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates—an analytical review," *Prog. Photovolt. Res. Appl.*, vol. 21, no. 1, pp. 12–29, 2013.
[39] D. C. Jordan, J. H. Wohlgemuth, and S. R. Kurtz, "Technology and climate trends in PV module degradation," in *Proceedings of the 27th European Photovoltaic Solar Energy Conference*, 2012.
[40] L.-L. Richter and others, "Social Effects in the Diffusion of solar Photovoltaic Technology in the UK," Faculty of Economics, University of Cambridge, 2013.
[41] B. Bollinger and K. Gillingham, "Environmental preferences and peer effects in the diffusion of solar photovoltaic panels," *Unpubl. Manuscr.*, 2010.
[42] "IEA - Investment Costs." [Online]. Available: http://www.worldenergyoutlook.org/weomodel/investmentcosts/. [Accessed: 27-Aug-2015].
[43] "Site Internet de l'Elcom concernant les prix de l'électricité: Comparez le prix de votre courant." [Online]. Available: https://www.strompreis.elcom.admin.ch/ShowCat.aspx?placeNumber=3513&OpID=527&Period=2012&lang=fr. [Accessed: 26-Aug-2015].
[44] M. Densing, S. Hirschberg, and H. Turton, "Review of Swiss Electricity Scenarios 2050," 2014.
[45] "KEV-Vergütungssätze gültig für neue Bescheide." [Online]. Available: http://www.swissolar.ch/fileadmin/user_upload/Swissolar/Unsere_Dossiers/KEV-Tarife_de.pdf. [Accessed: 27-Aug-2015].
[46] E. P. I. Association and others, "Global market outlook for photovoltaics 2014–2018," *EPIA Rep.*, 2014.