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Modeling the diffusion of residential photovoltaic systems in Italy: An agent-based simulation

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Abstract

We propose an agent-based model to simulate the diffusion of small PV systems among single- or two-family homes in Italy over the 2006-2026 period. To this end,we explicitly model the geographical distribution of the agents in order to account for regional differences across the country. The adoption decision is assumed to be influenced predominantly by (1) the payback period of the investment, (2) its environmental benefit, (3) the household's income, and (4) the influence of communication with other agents. For the estimation of the payback period, the model considers investment costs, local irradiation levels, governmental support, earnings from using self-produced electricity vs. buying electricity from the grid, as well as various administrative fees and maintenance costs. The environmental benefit is estimated by a proxy for the CO_2 emissions saved. The level of the household income is associated with the specific economic conditions of the region where the agent is located, as well as the agent's socio-economic group (age group, level of education, household type). Finally, the influence of communication is measured by the number of links with other households that have already adopted a PV system. In each simulation step, the program dynamically updates the social system and the communication network, while the evolution of the PV system's investment costs depend on a one-factor experience curve model that is based on the exogeneous development of the global installed PV capacity. Our results show that Italy's domestic PV installations are already beyond an initial stage of rapid growth and, though likely to spread further, they will do so at a significantly slower rate of diffusion.

Keywords: PV, Technological diffusion, Agent-based modeling, Italy

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1 Introduction

Following the introduction of a governmental incentive program, the Italian photovoltaics (PV) market has experienced a remarkable growth. Electricity generated by PV systems increased from 35 GWh in 2006 to 10,796 GWh in 2011, an astounding increment (GSE, 2012a; see also Figure 1 and Table 1). Italy has thus become one of the world's leading PV markets, accounting for about 18% of the global installed PV capacity in 2011 (EPIA, 2012).

Nevertheless, the diffusion of PV across Italy has followed a rather peculiar pattern. The number of installed PV systems is much higher in the north, although the irradiation level is lower there compared to other regions of the country. In addition, most of the installed systems in the north belong to private households and are thus characterized by a small rated power. However, while small-scale PV systems up to 20 kW are overwhelming in number (88% of the total, as of 2011), they account for only 15.5% of Italy's installed PV power (GSE, 2012c, , see also Figure 1). Furthermore, the share of small PV systems with respect to installed capacity has fallen steadily (from 66% in 2006 to 15.5% in 2011) due to the more recent installation of large PV farms (mostly located in Central and Southern Italy), a trend that strongly contributed to the PV boom in Italy (GSE, 2012c). As a result, the number, size and electricity generation of PV systems in Italy are rather unevenly spread across the country.

It is thus relevant to investigate whether the residential PV market will grow further, or whether the Italian PV market will be dominated in the future by large PV farms. The objective of this article is to simulate the future diffusion of small residential PV systems under different conditions. Due to the multitude of factors influencing a household's investment decision in favor of an innovative energy technology such as PV, we designed and implemented an agent-based simulation model (ABM). ABMs provide a suitable framework to explicitly model the adoption decision process of the members (agents) of a heterogeneous social system based on their individual preferences, behavioral rules, and interactions/communications within a social network.

We explicitly model the geographical distribution of the agents in order to account for the regional differences that have strongly influenced the PV diffusion in Italy. The investment in a PV system is assumed to depend mainly on (1) the payback period, (2) the environmental benefit of the investment, (3) the household's income, and (4) the influence of communication with other agents. For the estimation of the payback period, the model considers investment costs, local irradiation levels, feed-in tariffs, earnings from using self-generated electricity vs. buying electricity from the grid, as well as various administrative fees and maintenance costs. The environmental benefit of the PV system is estimated via a proxy for the amount of CO_2 saved. The level of the household income is associated with the specific economic conditions of the region where the agent is located, as well

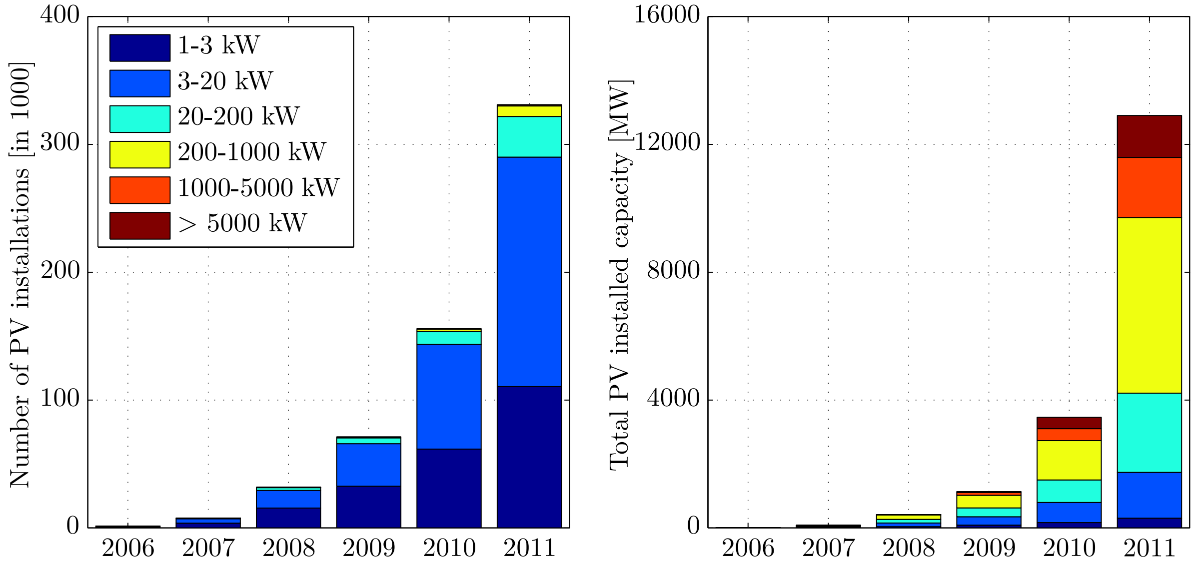

Figure 1: Evolution of Italy's PV market, 2006–2011

Source: GSE (2012c)

Table 1: Evolution of Italy's electricity generation, 2006–2011

		2006	2007	2008	2009	2010	2011
Total electricity generation	[TWh]	352.7	354.5	353.6	333.3	342.9	346.4
thereof PV el. generation	[GWh]	35	39	193	676	1,906	10,796
Share of RES in total electricity generation	[%]	15.9	16.0	16.6	18.8	20.1	23.5
Share of PV in total electricity generation	[%]	0.01	0.01	0.05	0.20	0.56	3.12

Source: GSE (2012a)

as the agent's socio-economic group (age group, level of education, and household type). Finally, the influence of communication is measured by the number of links with other households that have already adopted a PV system. It is assumed that each adopter communicates predominantly, but not uniquely, with other households that belong to the same socio-economic group. Furthermore, the likelihood that different groups interact with each other varies across the categories of agents considered.

Following Schwarz and Ernst (2009), an important contribution to the current literature on PV adoption and diffusion simulations is the inclusion of adaptive socio-economic categories to represent heterogeneous household groups with distinctive attitudes toward adoptions and innovations. The socio-economic groups considered here are based on the Sinus-Milieus® categorization developed by the Sinus-Institut (2011).[1] In particular, the

[1]The Sinus-Milieus® are a registered commercial product of a marketing company that does not disclose the rules or the questionnaires used to generate these socio-economic characterizations. We

Table 2: Date of issue, support cap, and reasons for revision of the Conto Energia 1–5

Conto Energia	Issue	Cap on cumulative PV installed capacity	Reason for update
1	08/2005	100 MW, updated to 500 MW by 2015	Adjustments
2	04/2007	1,200 MW, updated to 3000 MW by 2015	Adjustments
3	01/2011	8,000 MW by 2020	Cap reached
4	06/2011	23,000 MW by 2016, registration required	Cap almost reached
5	09/2012	Max + 3,000 MW/a, registration required	Still in place

Source: MSE (2005, 2007, 2010, 2011, 2012)

Sinus-Milieu® paradigm is most relevant for the distribution of the households' income and the determination of group-specific social communication networks. In each simulation step, the social system and the communication network are updated dynamically in order to account for demographic changes and new adopters among the population of agents.

The remainder of the paper is structured as follows. Section 2 provides a brief introduction to the current Italian PV support policy. Section 3 gives an overview of the relevant literature concerning the adoption of new technologies, its modeling via agent-based simulation frameworks, and the inclusion of a social system in the modeling architecture. Section 4 presents in detail the structure of the ABM. Section 5 describes the model's calibration, while section 6 discusses the policy scenarios and the simulation results. Finally, section 7 delivers the conclusions of the article and highlights strengths and weaknesses of our analysis.

2 The Italian support scheme for PV systems

The current legal framework for the support of PV systems in Italy is called "Conto Energia" (CE). The first CE has been issued in August 2005. Since then, the incentive scheme has been renewed five times with a series of adjustments and changes. An important characteristic of the CE is that support is granted up to a given amount of total installed PV power, as shown in Table 2 (MSE, 2005, 2007, 2010, 2011, 2012).[2]

Each CE guarantees contracts with fixed conditions for 20 years for grid-connected PV systems with at least 1 kW of peak power. Local electricity providers are required by law to buy the electricity that is generated by PV systems. Furthermore, governmental incentives are tax-free. Beginning with CE 2, the government has also reduced the purchase tax from 20% to 10%.

discuss this aspect in more detail in the conclusion (see section 7).

[2]Note that in our model we do not account for the PV installation caps, as we consider only a sub-group of potential adopters and PV systems.

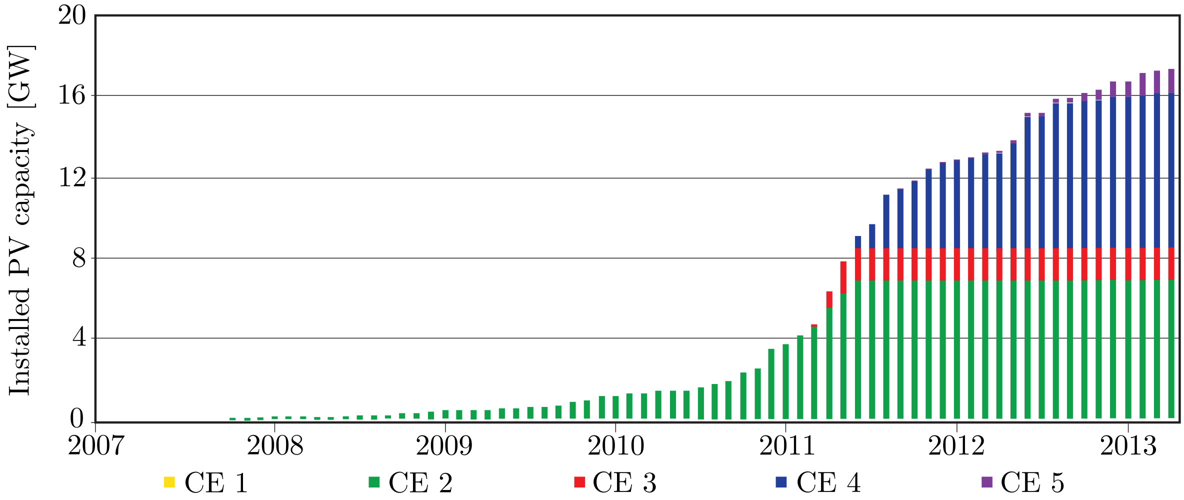

Figure 2: Stages of the Conto Energia by installed PV installed capacity, 2007–2013

Source: Own illustration, based on GSE (2013b)

Table 3: Incentives paid by the Conto Energia, 2006–2012

Year	2006	2007	2008	2009	2010	2011	2012[a]
Incentives [million €/a]	1	19	91	304	743	3,835	4,565
Total incentives [million €]	1	20	111	415	1,158	4,993	9,558

[a] Jan.–Sept. 2012

Source: GSE (2012c)

The CE considers two different support schemes. The first scheme is a net metering plan ("scambio sul posto") designed for small PV systems.[3] The plan is meant to favor the direct use of self-produced electricity. Besides a payment for each produced kWh of electricity, the consumer receives additional rewards for directly consuming the self-generated energy. With the introduction of CE 4, direct consumption is rewarded financially, whereas before 2011 consumers received an energy credit. Importantly, energy that is fed into the grid is bought by the local electricity provider at conditions that are less advantageous than direct self-consumption.

The second support scheme is available to all PV systems, but it is designed for larger plants with no or limited direct electricity self-consumption. The electricity produced is sold to the local energy supplier, for which the CE guarantees an additional feed-in payment.

In general, the incentives granted are higher for small PV systems. The Feed-in Tariffs (FiT) increase further for PV systems that are based on innovative technologies or systems that are integrated into the building. Additional payments or bonuses can also

[3]The first two versions of the CE limited the maximum peak power for this plan to 20 kW. Beginning with CE 3, systems up to 200 kW are also accepted.

be received in the following cases[4]: the adopter owns an energy-saving home; the adopter renews his/her roofs because of asbestos; the adopter lives in a small village with up to 5,000 inhabitants; the PV system was produced in Europe; the PV system is located on a municipal building, in an old industrial area, or in an old garbage dump.

It is important to mention that in each new version of the CE, the FiT were decreased. Since CE 1 was first issued in 2005, the basic support level has been curtailed from approximately 0.45 €/kWh in 2006 to 0.20 €/kWh in 2012.[5] Besides a reduction in tax revenues due to cuts in the PV purchase tax and the expenses associated with administrative tasks, the Italian government has spent €9,558 million for PV incentives from 2006 to September 2012 (see Table 3). Due to the high costs, Italy introduced a register for new PV systems with the implementation of CE 4. The register is meant to put a cap on the amount of support granted to PV systems for each year, whereby small PV systems (< 20 kW) still enjoy register priority. Similarly, the latest version of the support scheme (i.e. CE 5) aims at quickly decreasing the level of the feed-in payments, since grid parity was reached around 2011 and the costs of the support program are high. The FiT in CE 5 are set to decrease further by approximately 10% every 6 months for 2.5 years, starting in September 2012. Afterwards, the FiT will be reduced every 6 months by 15%. Figure 2 and Table 3 show the different stages of the CE with respect to the installed PV capacity and the incentives paid per year.

3 Literature overview

The modeling and forecasting of technology diffusion has been the focus of theoretical and empirical research since the works of Fourt and Woodlock (1960), Mansfield (1961), Rogers (1962), Chow (1967), and Bass (1969). The adoption and diffusion of innovations is determined by four core elements: the characteristics of the innovation, the structure of the social system where the adoption and diffusion takes place, the communication channels within the social system, and the time-frame of the innovation-decision process (Rogers, 2003). A variety of models focusing on one or more of these elements have been applied to a multitude of research fields and technologies. For an overview, see for instance Mahajan et al. (2000) and Meade and Islam (2006).

In recent years, agent-based simulation models (ABM) have been widely used to simulate the inherent complexity of the adoption and diffusion process (Dawid, 2006; Kiesling et al., 2012). In particular, ABM frameworks replicate the micro-based behavior of economic actors in order to evaluate and explain meso- and macro-level phenomena. They enable modelers to ascribe specific characteristics to the agents, who independently

[4] The individual bonuses lead to an increase in the FiT that may range from 5% to 30%. Note that the requirements for the award of a bonus have changed over time (MSE, 2005, 2007, 2010, 2011, 2012).

[5] Here we are referring to the basic FiT for small roof-top PV systems.

interact within their environment and among each other according to determined rules (Bonabeau, 2002).

ABM have also been applied to investigate the adoption of various energy technologies (e.g., Schwoon, 2006; Cantono and Silverberg, 2009; Faber et al., 2010; Zhang and Nuttall, 2011; Zhang et al., 2011; Sorda et al., 2013). However, to the best of our knowledge, in the recent literature only Zhao et al. (2011) implement an ABM to simulate the diffusion of PV systems. They evaluate the impact of different governmental incentives, including the impact of investment credit taxes and feed-in tariffs, on the PV diffusion process in two regions in the US.

Nevertheless, the factors influencing PV adoption and their modeling have been the subject of several publications. These can be grouped into three categories: survey-based analyses (Jager, 2006; Faiers and Neame, 2005; Faiers et al., 2007; Yuan et al., 2011; Zhai and Williams, 2012), PV diffusion and forecasting models other than ABM (Guidolin and Mortarino, 2010; Gallo and De Bonis, 2013), and PV grid parity studies (Ayompe et al., 2010; Yang, 2010; Breyer and Gerlach, 2013).

One may suspect that the fast-decreasing installation costs of PV systems and the prospect of grid parity PV electricity generation provide strong incentives for the investment in photovoltaic technology by homeowners. However, the adoption decision is still strongly influenced by the perceived attributes of the innovation, such as installation costs, maintenance, complexity, and environmental concerns (Zhai and Williams, 2012). In addition, the adopter characteristics[6] (Faiers and Neame, 2005; Faiers et al., 2007) as well as the communication network play an important role in the actual diffusion process (Jager, 2006).

In our model, we try to incorporate these three considerations: the specific attributes of the PV technology, the attitudes and preferences of the adopters according to their respective socio-economic groups, as well as the influence of communication among agents.

4 Model description

In our model, we consider small grid-connected PV systems in the 1–20 kW range powered by crystalline silicon solar cells (silicon solar cells had a 93% share of the Italian market in 2011; GSE, 2012b). Furthermore, it is assumed that the PV systems are installed on the roofs of single- or two-family houses[7]. The ABM framework simultaneously accounts for the attributes of the PV systems, the attitude of specific adopter groups, and the

[6]In their study of the adoption of residential PV systems in the UK, Faiers and Neame (2005) and Faiers et al. (2007) based their questionnaires on Rogers' (2003) adopter categories with respect to innovativeness and product characteristics.

[7]Small PV systems could also be installed on the roofs of larger multi-flat building blocks. However, the adoption decision would become much more complicated to replicate, as often several house-owners or groups of families cooperatively decide to make a PV investment.

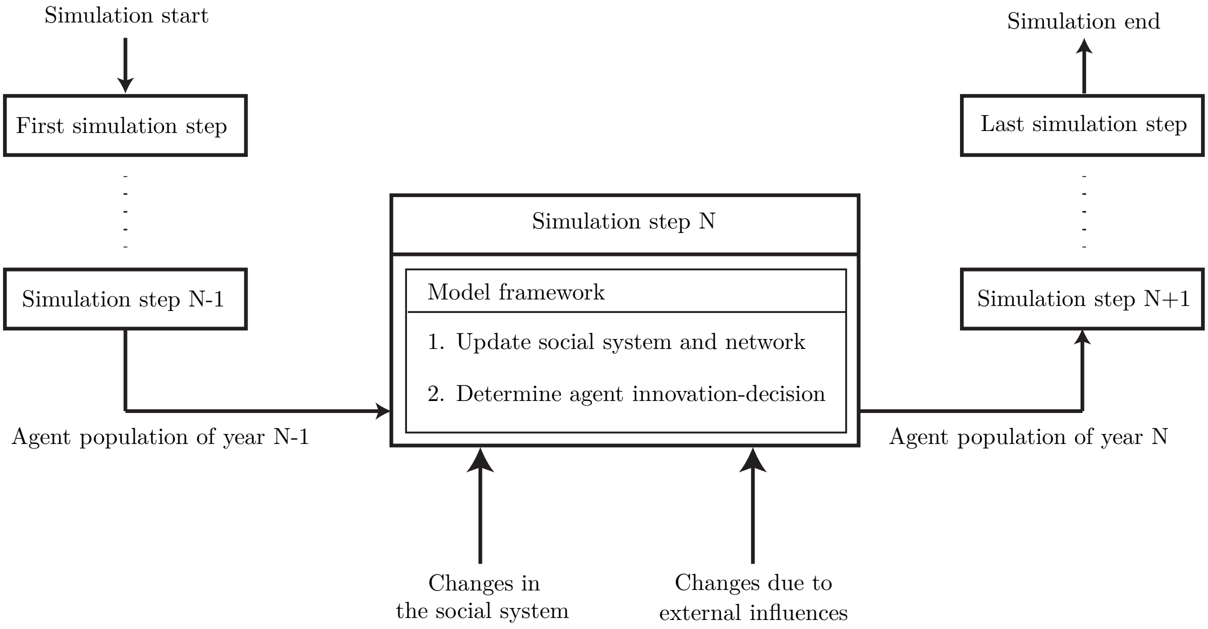

Figure 3: Schematic diagram of the step-wise simulation process

Source: Own illustration

communication network thanks to a multi-attribute utility function (Zhao et al., 2011) weighted by adopter preferences according to different socio-economic classes (Schwarz and Ernst, 2009).

The ABM has been programmed in MATLAB and simulates the PV diffusion process on a step-wise yearly basis. Two key components constitute the core structure of the framework: the agent's adoption decision and the representation of Italy's social system. The decision to invest in a PV system depends on static functions fed with data that, in some cases, account for changes in the underlying social structure and communication network. As a result, specific model parameters are updated after each simulation step, as highlighted in Figure 3. Next, we present in more detail the formulation of the agent's behavioral rules (section 4.1), the modeling of socio-economic attributes in Italy (section 4.2), and the agent's communication network (section 4.3).

4.1 Agent's adoption behavior

An agent represents a household living in a single- or two-family house. The decision to invest in a PV system takes place when the utility of the potential adopter surpasses a certain threshold level. The threshold is determined by comparing the simulation results with the actual diffusion of the PV system during the calibration of the model (see section 5 for more details). The utility of agent j equals the sum of four weighted partial utilities

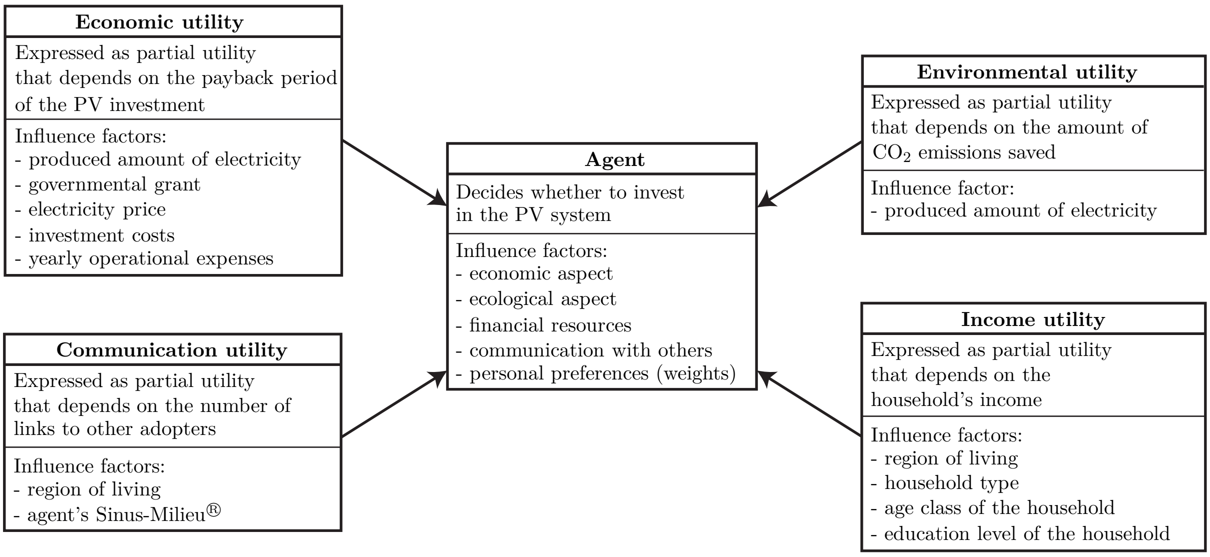

Figure 4: Factors influencing the agent's adoption-decision process and their representation in the model

Source: Own illustration

and is calculated as follows:

$$
\begin{aligned}
U(j) \quad = \quad & w_{pp}(sm_j) \cdot u_{pp}(j) + w_{env}(sm_j) \cdot u_{env}(j) \\
& + w_{inc}(sm_j) \cdot u_{inc}(j) + w_{com}(sm_j) \cdot u_{com}(j),
\end{aligned} \tag{1}
$$

where

$$\sum_k w_k(sm_j) = 1 \text{ for } k \in K : \{pp, env, inc, com\} \qquad \text{and} \qquad w_k(sm_j),\, U(j) \in [0{,}1].$$

The partial utilities $u(\cdot)$ account for the payback period of the investment (u_{pp}), the environmental benefit of investing in a PV system (u_{env}), the household's income (u_{inc}), and the influence of communication with other agents (u_{com}). Each partial utility is calculated on the basis of specific influence factors (see Figure 4) and is normalized[8] in order to lie within the [0,1] interval. The weights $w(\cdot)$ assigned to each partial utility vary according to the agent's Sinus-Milieu® (sm_j) and are determined in the model's calibration. Next, we illustrate how each partial utility is calculated.

4.1.1 Economic utility

The estimation of the economic utility of adoption is based on the expected payback period pp of a specific PV system for agent j. The payback period is then converted into a linear utility function whose value ranges between 0 and 1. The utility function is

[8] The total utility of an adopter is defined within the [0,1] interval. As a result, all partial utilities need to be normalized. In accordance with Zhao et al. (2011), the utility of the payback period is programmed as a linear function, while all other partial utility functions follow an S-shaped curve, also within the [0,1] interval.

calculated as follows:

$$u_{pp}(j) = \frac{max(pp) - pp(j)}{max(pp) - min(pp)} = \frac{21 - pp(j)}{20}. \tag{2}$$

In order to ensure that the partial utility arising from the payback period lies within the [0,1] interval, and given that the payback period is calculated over 20 years (i.e. the expected useful life of the PV system), the values corresponding to the minimum ($min(pp)$) and maximum ($max(pp)$) payback periods are 1 and 21 years, respectively.

The payback period is determined by the year in which the net present value (NPV) of the PV system turns from negative to positive. The NPV is defined as the sum of the discounted cash flows ($R(t)$) of the PV system, given the initial investment costs (I_0) and the interest rate (i):

$$\text{NPV} = -I_0 + \sum_{t=1}^{20} \frac{R(t)}{(1+i)^t}. \tag{3}$$

The investment costs are the product of the maximum peak power (P_{MMP}) and the price per installed kW of the PV system (p_{PV}), such that:

$$I_0 = P_{MMP} \cdot p_{PV}(t_0) \tag{4}$$

$$P_{MMP} = G_{STC} \cdot A_{PV} \cdot \eta_{SC} \cdot \eta_{PV}. \tag{5}$$

The peak power of the PV system is computed by the available rooftop area for PV modules (A_{PV}), the efficiency of the solar cells (η_{SC}), the PV system efficiency (η_{PV}), and the irradiation at standard conditions (G_{STC}), which is assumed to equal 1 kW/m^2. The estimation of the system's NPV at a given time period assumes that the price and efficiency of the PV system remain constant. Note, however, that in each simulation step the price per installed kW of the PV system and the cell's efficiency are exogenously updated (see also section 6.1) . In addition, the available roof area for PV modules depends on the type of housing. All other values are kept constant throughout the simulation.

As shown in eq. (6) below, the cash flow $R(t)$ is composed of five factors. The term $R_{Save}(t, CE)$ includes all earnings that are generated by directly using the produced electricity instead of buying it from or selling it to the grid provider. The terms $R_{Gov}(t, CE)$, $R_{Adm}(CE)$, $R_{Main}(t)$, and $R_{Deprec}(t)$ indicate cash flows due to governmental support, administrative fees, maintenance and upfront costs, and depreciation allowance payments, respectively.

$$R(t) = R_{Save}(t, CE) + R_{Gov}(t, CE) - R_{Adm}(CE) - R_{Main}(t) - R_{Deprec}(t). \tag{6}$$

The explicit estimation of the revenues due to electricity savings[9] ($R_{Save}(t, CE)$) is a function of time t and of the governmental policy in place. As a result, the calculation of $R_{Save}(t, CE)$ varies across the different formulations of the Conto Energia (CE). For the CEs 1-4, the savings are computed by considering the electricity grid as a storage component of the PV system. From the introduction of CE 5 onwards, $R_{Save}(t, CE)$ is calculated as:

$$\begin{aligned} R_{Save}(t, CE\ 5) &= E_{PV}(t) \cdot [x_{DC} \cdot p_{elec,buy} \cdot (1 + \tau_{elec,buy})^{t-1} \\ &\quad +(1 - x_{DC}) \cdot p_{elec,sell} \cdot (1 + \tau_{elec,sell})^{t-1}]. \end{aligned} \tag{7}$$

The estimated savings are a function of the produced amount of electricity ($E_{PV}(t)$), the share of direct electricity consumption (x_{DC}), and the price of electricity, which varies depending on whether the consumer is selling it to ($p_{elec,sell}$) or buying it from the grid provider ($p_{elec,buy}$).[10] In addition, electricity prices are assumed to grow geometrically at constant rates ($\tau_{elec,sell}$ and $\tau_{elec,buy}$).[11] The first right-hand side term in eq. (7) describes the cost savings due to direct consumption of the PV-generated electricity. The second term describes the earnings from selling PV electricity to the local energy provider.[12]

Importantly, the amount of electricity E_{PV} generated by the system is a function of the level of irradiation (E_{Sun}), of the installed nominal maximum peak power (P_{MPP}), and of the predicted PV module abrasion[13] ($\xi_{Abrasion}$). Furthermore, the level of irradiation depends on the region where the house is located, such that:

$$E_{PV}(t) = E_{Sun} \cdot P_{MPP} \cdot (1 - \xi_{Abrasion})^{t-1}. \tag{8}$$

Besides energy savings, an additional positive cash flow is generated by governmental support ($R_{Gov}(t, CE)$), which is based on the FiT given by the CE. The amount of the support is calculated as the sum of three components: a basic payment for the production of electricity ($FiT_{Prod}(CE)$), an incentive for direct PV electricity consumption ($FiT_{DC}(CE)$), and, if applicable, additional bonuses ($FiT_{Bon}(CE)$) that accrue in special circumstances[14]. The cash flows associated with governmental support are then

[9] Electricity may be directly consumed by the owner of the PV system, thus saving part of his/her electricity bill. The owner then sells to the utility provider the surplus PV electricity that is not used for self-consumption.

[10] In general, the amount of money paid by local energy providers is only a fraction of the electricity price they charge consumers for electricity consumption.

[11] Since there is no price increase for $t = 1$, the electricity price grows by the power of $t - 1$.

[12] Note that the second term is independent from and additional to the governmental feed-in tariffs.

[13] Similar to the electricity price, the abrasion increases over time by the power of $t - 1$.

[14] For instance, a bonus is paid if the roof of the house is renewed due to asbestos, if the PV system is located in a village with less than 5,000 inhabitants, or if the PV system consists of components that were produced in Europe. The individual bonuses lead to increments in the FiT that range from 5% to 30%. In the model, bonuses are assumed to increase the basic FiT by about 5% on average.

expressed as follows:

$$R_{Gov}(t, CE) = E_{PV}(t) \cdot (FiT_{Prod}(CE) + FiT_{DC}(CE) + FiT_{Bon}(CE)) \,. \tag{9}$$

The adoption of a PV system also entails a series of negative cash flows. Administrative fees ($R_{Adm}(CE)$) have to be paid to the provider of the electricity grid and depend on the specific CE considered, such that:

$$R_{Adm}(CE) = \begin{cases} 30 \ \dfrac{€}{year} & \text{for CE 1-3} \\ \\ 3 \ \dfrac{€}{kW \cdot year} & \text{for CE 4-5.} \end{cases} \tag{10}$$

Maintenance and upfront costs ($R_{Main}(t)$) must also be considered. Upfront costs (e.g., the consultation of a PV expert/adviser) are paid in the first year of the investment, while maintenance costs occur yearly. Both expenditures are estimated to be a fraction of the initial investment costs:

$$R_{Main}(t) = \begin{cases} (\alpha_{upfront} + \alpha_{Main}) \cdot I_0 & \text{if } t = 1 \\ \alpha_{Main} \cdot I_0 & \text{otherwise} \end{cases} \tag{11}$$

Finally, the cash flow includes depreciation allowance payments of the PV system ($R_{Deprec}(t)$). The depreciation allowance amounts to a fixed outflow taking place at the end of every year for 20 years, at which point the remaining value of the fixed asset at the end of its useful lifetime is zero.

4.1.2 Environmental utility

The partial utility $u_{env}(j)$ in eq. (1) is meant to capture an agent's attitude toward the environmental/ecological advantages associated with the adoption of a PV system. These attributes could be measured by the amount of CO_2 emissions saved; however, for reasons of simplicity, the partial utility considers only the expected amount of energy generated by the PV system. In line with Marheineke (2002), we assume that the energy required to produce a PV system is small in comparison to the amount of "green" energy it generates. The actual output of the PV system depends on its location and technical attributes, and the estimated environmental utility is assumed to follow an S-shaped function, where $E_{PV,tot,j}$ is the expected amount of electricity generated over 20 years by the PV system of agent j, and $\bar{E}_{PV,tot}$ is the expected average amount of electricity

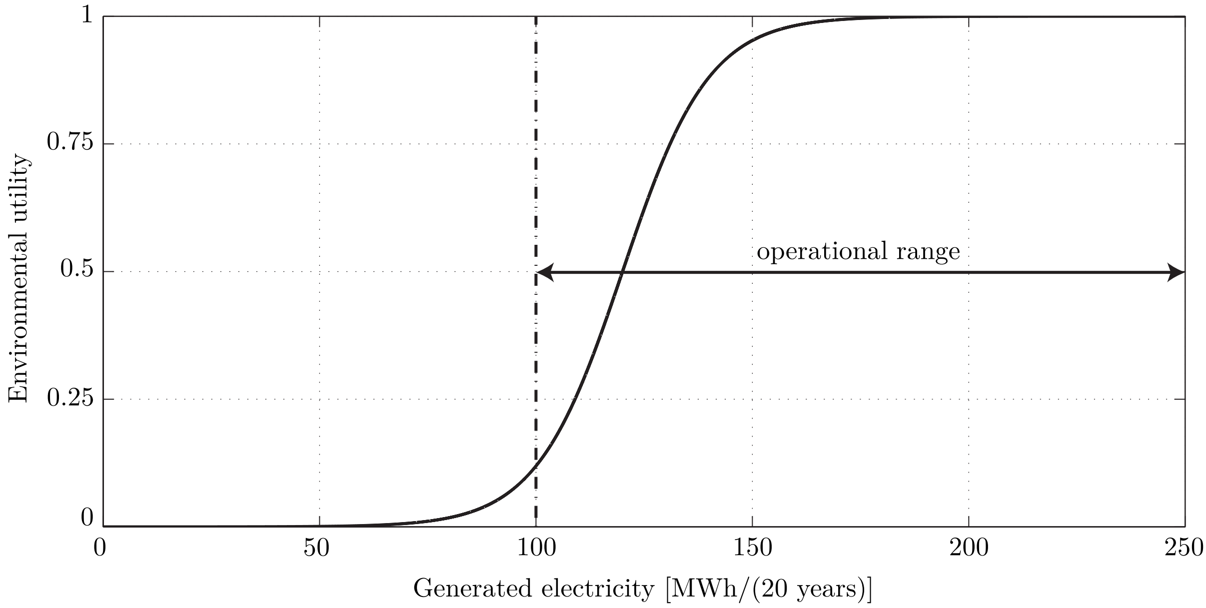

Figure 5: Utility function of the environmental benefits associated with the adoption of a PV system

Source: Own illustration

generated over 20 years by all PV systems, such that:

$$u_{env}(j) = \frac{\exp\left(\dfrac{E_{PV,tot,j} - \bar{E}_{PV,tot}}{1 \cdot 10^4}\right)}{1 + \exp\left(\dfrac{E_{PV,tot,j} - \bar{E}_{PV,tot}}{1 \cdot 10^4}\right)}. \tag{12}$$

Figure 5 shows the environmental utility function curve and its operational range. The figure indicates that the environmental utility does not have its minimum at zero. This is due to the fact that PV systems always save energy when operating. However, the curve also implies that the agent becomes less responsive to CO_2 savings as the amount of expected electricity generation increases.

4.1.3 Income utility

The partial utility $u_{inc}(j)$ is based on the household's income, which in turn is determined by the agent's region and his/her socio-demographic attributes. In general, it is assumed that agents with an above-average income are more likely to invest in a PV system. This consideration is accounted for in the functional representation of an agent's income utility, whose S-shaped curve depends on agent j's income (N_j) and the average income of all agents in the model ($\bar{N}$), such that:

$$u_{inc}(j) = \frac{\exp\left(\frac{N_j - \bar{N}}{1 \cdot 10^3}\right)}{1 + \exp\left(\frac{N_j - \bar{N}}{1 \cdot 10^3}\right)}. \tag{13}$$

4.1.4 Communication utility

Finally, the influence of the social communication network on the adoption decision is represented by the partial utility $u_{com}(j)$. In the model it is expressed as a function of agent j's total number of communication links ($L_{j,tot}$) and in relation to the number of links with actual adopters ($L_{j,adopter}$). Since there are no or only a few adopters in the social system at the beginning of the diffusion process, communication hardly plays a role initially. The S-shaped communication utility function therefore starts with a value of about zero and increases as the diffusion process takes place. The partial utility is estimated by the following expression:

$$u_{com}(j) = \frac{\exp\left(\frac{L_{j,adopter} - 0.5 \cdot L_{j,tot}}{0.8}\right)}{1 + exp\left(\frac{L_{j,adopter} - 0.5 \cdot L_{j,tot}}{0.8}\right)}. \tag{14}$$

In the model, it is assumed that the total number of links (to both adopters and non-adopters) varies according to the Sinus-Milieu® of the agent (see Figure 6). The resulting array of functions represented by eq. (14) nonetheless guarantees that each agent, independently of his/her Sinus-Milieu®, has an equal response to a proportional increase in the number of links to other adopters.[15] For a more detailed explanation of the communication network see also section 4.3.

4.2 Modeling socio-economic attributes in the PV diffusion process

Investments in a new technology are related not only to economic considerations, but also to specific attitudes towards a technology's attributes (Rogers, 2003). These attitudes are the product, among other things, of an agent's socio-economic background and his/her lifestyle choices.

In the model, the social system is represented by different socio-economic categories. Each category identifies groups of individuals displaying similarities in their socio-economic

[15]For instance, consider an agent with six links, three of those links being links to other adopters. The resulting communication utility is 0.5. An agent with ten links, five of which are to adopters, also has a communication utility of 0.5.

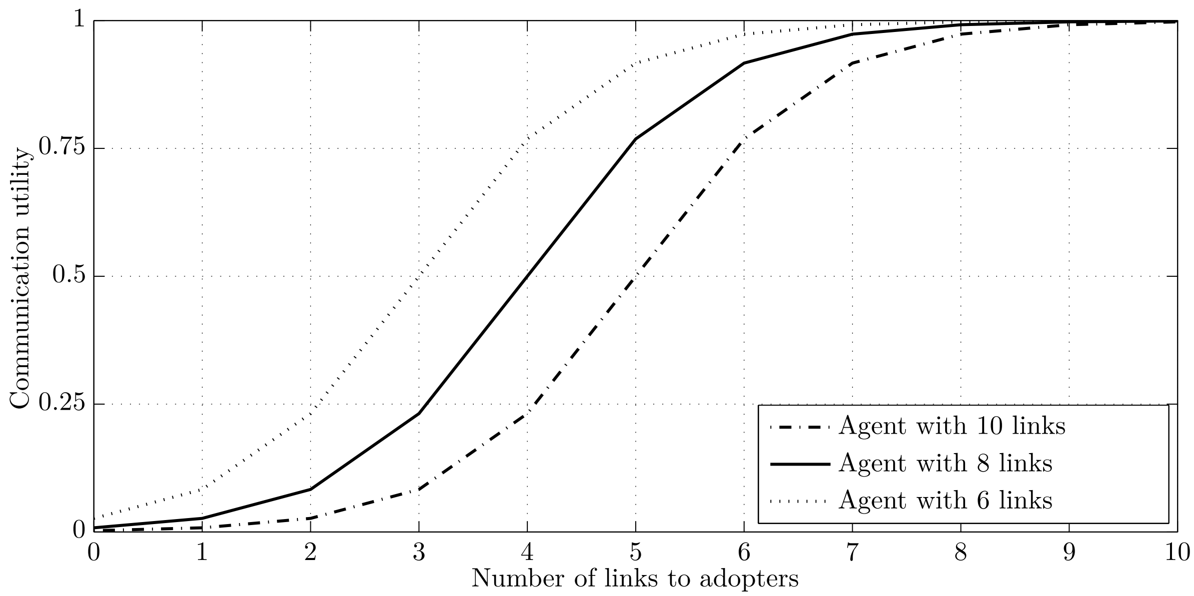

Figure 6: Response of the communication utility in relation to different communication network configurations

Source: Own illustration

behavior and consumption patterns. The social system is thereby characterized by subgroups that have common values and attitudes toward work, family, leisure, money, and consumption. Following Schwarz (2007) and Schwarz and Ernst (2009), we incorporate these socio-economic groups and their attitudes toward innovative technologies in the model by referring to Sinus-Milieus®.

The Sinus-Milieus® include a wide array of social categories that range from the enlightened middle-class ("Borgehsia Illuminata") to consumers-materialists ("Consumisti Precari"). Figure 7 shows the eight Sinus-Milieus® modeled in our study and displays them as a function of social status and basic values. The model uses freely available Sinus-Milieu® data for Italy from 2003 provided by For Sale Italia Advertising Agency (2004). In addition, the milieus are also associated to the adopter categories defined by Rogers (2003), as illustrated in Table 4.

The Sinus-Milieu® structure of the model is created during an initialization phase that proceeds the first simulation period. In the initialization, the agents/households are allocated to the different Italian regions and assigned to various categories. Following the available census statistics (ISTAT, 2012), these categories include six household types, five age classes and five education levels.[16] The model then restricts its focus to agents living in single- or two-family houses (see Figure 8). At this point, four attributes are assigned

[16] There is a total of 150 categories spread across the 20 regions considered. Each single category is formally represented in the model by an object in an array, which makes them easily accessible from a programming point of view. The individual agents that are assigned to each category are saved as vectors, which guarantees high computational speed when calculating, for instance, the NPV.

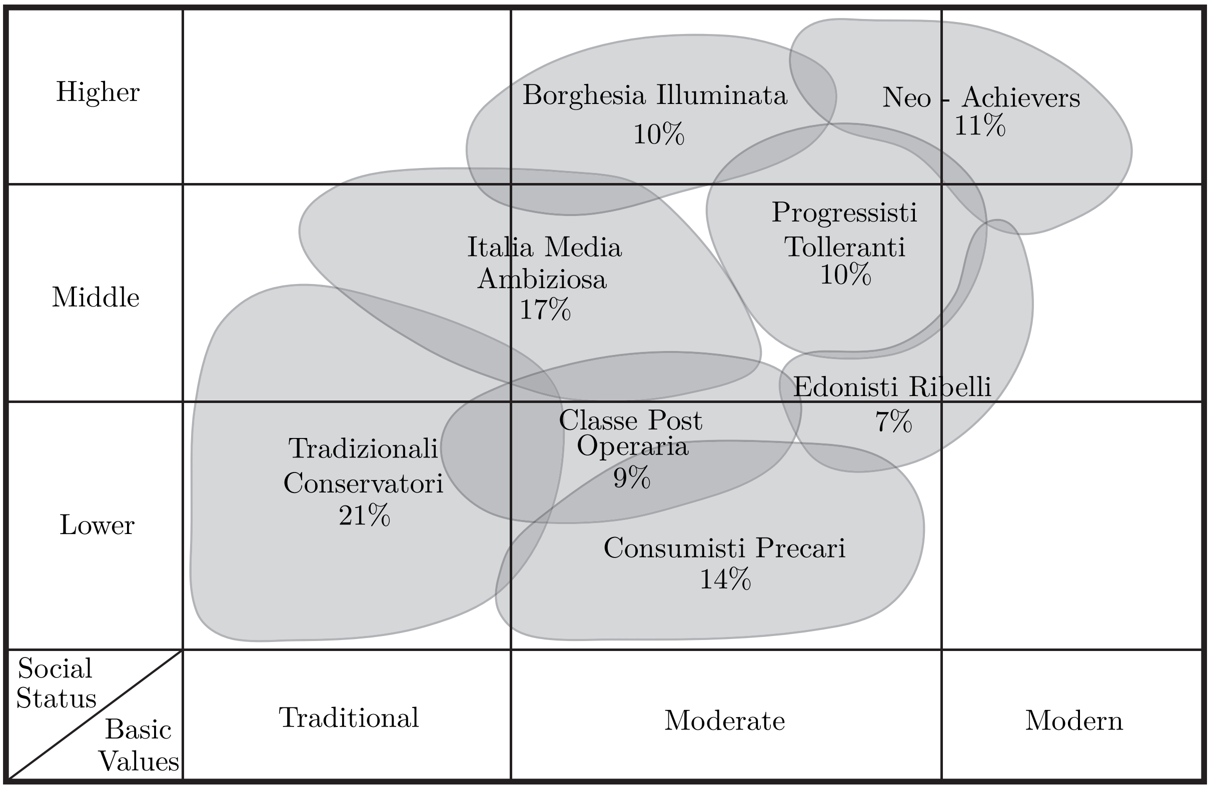

Figure 7: Share of population by Sinus-Milieus® in Italy, 2003

Source: Own illustration, based on For Sale Italia Advertising Agency (2004)

to each household: the Sinus-Milieu®, the average income, the electricity consumption level, and the type of housing (see Figure 9).

The household income is correlated to the agent's household type, age class, education level, and region. It is assumed that the average household income can be described by a logarithmic probability distribution (Statistisches Bundesamt, 2012), whose standard deviation depends on Italy's Gini coefficient, which is about 0.337 (OECD, 2011)[17].

The energy consumption of an agent depends on the number of household members, which, in turn, is also associated to the household type. The average number of Italian household members, as well as the average energy consumption per household, is based on statistical data (ISTAT, 2012). In contrast, the average number of household members in each Sinus-Milieu® rests on own assumptions.

Finally, the housing type is linked to the household's income. According to Eurostat (2012), the likelihood that an agent lives in a single-family house is significantly higher if his income exceeds the Italian median by 60%. The probability increases even further for

[17]The Gini coefficient is a measure of income inequality within a country. It ranges from 0 (perfect equality) to 1 (perfect inequality). The Gini coefficient presented here is based on disposable household income, corrected for household size and deflated by the consumer price index (CPI). Italy displays an intermediate level of income inequality in comparison to other developed countries. The OECD average is 0.314 (OECD, 2011), a value between those of Norway (0.256) or Germany (0.295), and those of the USA (0.378) and Mexico (0.476).

Table 4: Sinus-Milieus® and adopter categories in Italy

Sinus-Milieu®	Adopter categories	Reason for assignment
Borghesia Illuminata *Enlightened Middle Class*	Innovators, Early Adopters	Highest income, rational-economical thinking
Neo-Achievers *Neo-Achievers*	Innovators, Early Adopters	Environmental thinking, high income, high knowledge, take risks
Progressisti Tolleranti *Tolerant Progressists*	Early Adopters, Early Majority	Intellectuals, basic ecological and economic thinking
Italia Media Ambiziosa *Average Middle Class*	Early Majority, Late Majority	Consider social norms, influenced by mass media communication
Tradizionali Conservatori *Traditional Conservatives*	Late Majority, Laggards	Do not take risks, adopt only when everyone does
Classe Post Operaria *Working Class*	Early Majority, Late Majority	Consider social norms, strongly influenced by communication
Edonisti Ribelli *Hedonists*	Early Adopters, Early Majority	See the potential of PV systems but do not have money
Consumisti Precari *Precarious Consumerists*	Early Majority, Late Majority	Strongly influenced by peer-to-peer communication

Source: Own assumptions and illustration, based on For Sale Italia Advertising Agency (2004) and Rogers' (2003) adopter categories

agents living in two-family homes. It is important to differentiate between housing types, as they are associated with different roof areas[18], which pose a limit to the maximum peak power of the PV system. Since the average household income is higher in Northern Italy, more agents live in single-family houses, resulting in a higher than average PV power per adopter. In Southern Italy there is a higher level of irradiation, but the median income is lower and fewer people live in single-family houses, so that the average PV system is smaller. Importantly, by accounting for two housing types the model has more control over simulation results, thus improving the model's calibration across the different regions.

After its creation in the model's initialization, the social structure is recursively updated at the end of each simulation period. Updating the social structure involves, on the one hand, the model's calibration over the 2006–2010 period and, on the other hand, the implementation of various assumptions about future demographic developments. The latter include forecasts for the Italian population growth and the number of household members. The size of each milieu varies over time in accordance with the changes in the social system. However, the model assumes that the share of each Sinus-Milieu® relative

[18] A household in a single-family house has, on average, a larger roof area available for PV modules than a household living in a two-family house.

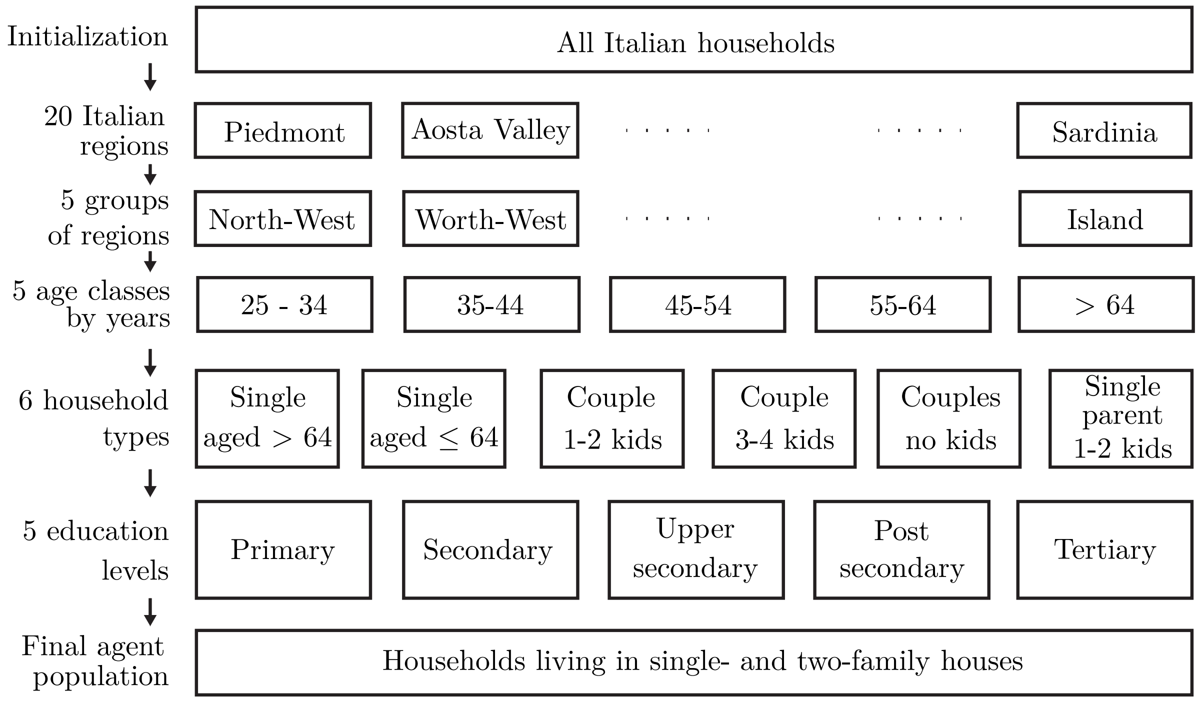

Figure 8: Initialization and structure of the social system in the model

Source: Own illustration

to the total agent populations remains constant from 2010 onwards.[19]

One last remark must be made before the next section is introduced. Once the social system is initialized, the model includes about 10 million Italian households as possible adopters[20]. Since each agent has several attributes and needs to perform a series of operations during the innovation-decision process, the model requires a relatively large computer storage capacity and the simulation time can be long. In order to reduce the computational effort, the model includes the option to scale the number of agents[21], i.e. one agent may represent several households simultaneously, thereby reducing the number of potential adopters and speeding up the simulation process. This process may have implications for the accuracy of the estimations and is discussed in more detail during the model calibration stage described in section 5.

[19] While the total number of agents in each milieu may grow, the relative share of each Sinus-Milieu® remains constant. This simplification results from a lack of forecasts concerning the future evolution of Sinus-Milieus® and is justified by the fact that their share remains almost unvaried during the model's calibration over the 2006–2010 period.

[20] In 2006, Italy had a population of about 59.1 million inhabitants and a total of about 23.9 million households, 10 million of which are living in one- or two-family houses.

[21] Each agent has 20 attribute values, and each attribute value requires about 8 bytes of hard-drive memory. If there are 10 million agents, one simulation step requires about 1.5 GB and the whole simulation needs about 30 GB hard-drive storage capacity. As a result, the simulation lasts longer than 12 hours.

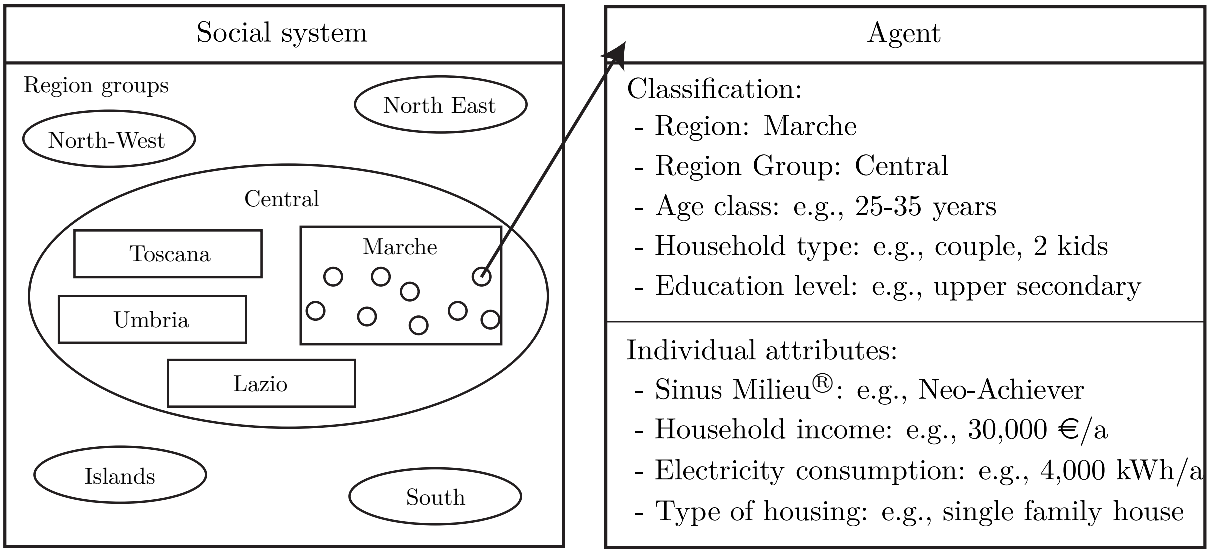

Figure 9: Attributes of a representative agent in the model's social structure

Source: Own illustration

4.3 The communication network

The model's social structure also affects the communication among agents, which in turn influences the adoption decision. As done by Schwarz and Ernst (2009), communication channels between agents are assigned according to the Small-World-Network (SWN) algorithm, which was originally created by Watts and Strogatz (1998). SWNs are based on the idea that every individual is connected to anyone else through no more than six degrees of separation (Barabási and Bonabeau, 2003). In addition, SWNs are characterized by a high density of connections with short path-lengths, features also shared with actual social communities. Empirical studies have shown a strong correlation between the number of contacts in a SWN and the agents' gender, age, education, and income (Schwarz, 2007; Zheng et al., 2006).

In the model, the number of communication channels depends on the Sinus-Milieu® of the agent. Furthermore, the SWN algorithm has been adjusted in order to account for the structure of the social system considered. All possible adopters are situated across the 20 regions and have primarily "localite" links to other agents from the same region. In addition, most of the communication channels are modeled to take place between agents belonging to the same socio-economic group (see Table 5). The remaining links are almost uniquely with agents from bordering Sinus-Milieus® (see Figure 7). Note that the network structure (i.e. the links across specific agents) is created in the initialization of the model and maintained throughout the simulations. However, in order to create an element of uncertainty, there is a small probability in each simulation run that an agent will break up a link and randomly reconnect to another agent (see Table 6).[22]

[22]For instance, for any of the 6 links to other agents of a Neo-Achiever, there is a 1% chance that the

Table 5: Probabilities to connect to other agents in own and other Sinus-Milieus® [%]

Sinus-Milieu®	Borghesia Illuminata	Neo-Achievers	Progressisti Tolleranti	Italia Media Ambiziosa	Tradizionali Conservatori	Classe Post Operaria	Edonisti Ribelli	Consumisti Precari
Borghesia Illuminata	85	10	5	0	0	0	0	0
Neo-Achievers	10	75	10	5	0	0	0	0
Progressisti Tolleranti	5	10	70	10	5	0	0	0
Italia Media Ambiziosa	0	5	10	70	10	5	0	0
Tradizionali Conservatori	0	0	5	10	70	10	5	0
Classe Post Operaria	0	0	0	5	10	70	10	5
Edonisti Ribelli	0	0	0	0	5	10	75	10
Consumisti Precari	0	0	0	0	0	5	10	85

Source: Own assumptions, based on Schwarz (2007)

Table 6: Number of communication channels and probability to randomly reconnect

Sinus-Milieu®	Borghesia Illuminata	Neo-Achievers	Progressisti Tolleranti	Italia Media Ambiziosa	Tradizionali Conservatori	Classe Post Operaria	Edonisti Ribelli	Consumisti Precari
Number of links	7	6	7	8	6	8	9	10
Probability to reconnect [%]	0.5	1.0	1.0	0.75	0.25	0.5	1.0	0.25

Source: Own assumptions, based on Schwarz (2007)

5 Model calibration

We calibrate the model with respect to the total number of adopters, the rate of adoption, the installed PV power, and the PV system characteristics over the 2006–2011 period. We target a close resemblance of the simulation results with the actual PV diffusion process at the national level. As adjusting the model in order to fit the PV adoption dynamics of

link will be broken and a new connection will be created with another agent.

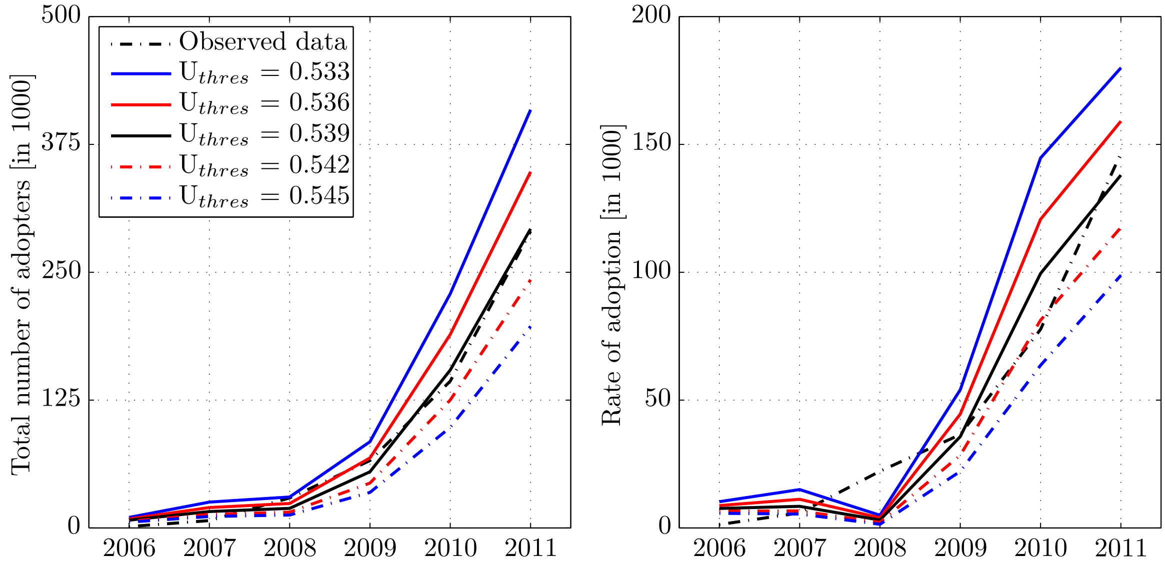

Figure 10: Outcome of the calibration for different threshold levels, 2006-2011

Source: Own illustration, based on calibration results

each individual region is particularly difficult, each region is individually calibrated once the model matches the general national PV diffusion trends.

The calibration is performed by adjusting the values of the utility threshold and the weights of the partial utilities across the various socio-economic adopter categories. Changes to the partial utility weights of a specific socio-economic group influence the slope of the adopter curves of that given agent's category, thereby affecting their specific attitude towards the innovation. Changes to the utility threshold, in contrast, shape the whole level/slope of the curves without affecting specific adopter categories.

Figure 10 shows the results of the calibration for the total number of adopters and the rate of adoption at the national level. The diagrams illustrate the actual PV market data and various simulation runs with different thresholds, while all other parameters are kept constant. The model displays a good fit to the actual number of adopters. The best results are obtained with a threshold value of 0.539. However, the simulations also turn out to be rather sensitive to variations in the threshold level. A threshold change of ± 0.03 causes a difference in the number of adopters of about $\pm 18\%$, whereas a change of ± 0.06 leads to fluctuations in the $\pm 35\%$ range.

The simulated rate of adoption is less accurate in matching the actual PV statistics. This is primarily due to the year 2008. In 2008, investment costs were still relatively high and the introduction of the CE 2, which brought a first reduction in support payments and led to a fall in the NPV of the PV system as well as a longer payback period. In the model, PV systems were not as economically appealing as before, which led to a lower

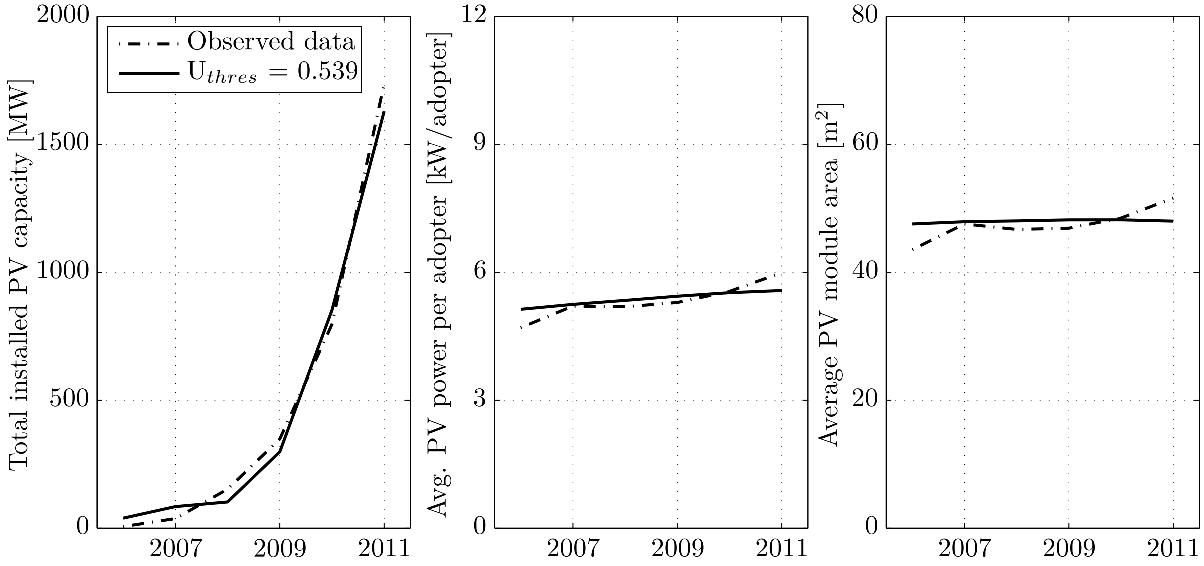

Figure 11: Calibration of the installed PV capacity, 2006–2011

Source: Own illustration, based on calibration results

number of adopters and a lower adoption rate than displayed in the the actual market.[23] Nevertheless, the rate of adoption better resembles the actual values in the following years (i.e. 2009–2011), thus still capturing a key trend to be picked up for the successful prediction of the PV market's future development.

Figure 11 shows the calibration of the total installed PV capacity, the average PV power per adopter, and the average roof surface area of the PV systems. The achieved fit is acceptable for all three parameters. Note that the average roof-surface area of PV systems is assumed to be constant in the model. However, the slightly increasing average installed PV power per adopter is guaranteed thanks to improving PV module efficiency over time.

The partial utility weights implemented in the model are shown in Table 7. They have been determined by trial and error in response to the simulation results during the calibration. Obviously, there may be other value combinations that could help achieve similar or better calibration results. Nevertheless, the chosen values lead to a good fit for most of the Italian regions. Still, it should be explicitly mentioned that the model responds unevenly to changes to different weights. In particular, the weight of the payback period has, due to the linear formulation of its partial utility, a stronger impact on the diffusion process than the other weights. Therefore, the weight coefficients should not be directly compared to each other and their value should be interpreted as their relative importance in the adoption decision process.

In addition, the weights have been assigned so as to replicate the allocation of the

[23]Note that attempts to overcome this issue by altering the weights of the partial utilities across different adopter categories did not produce significant improvements.

Table 7: Calibrated weights by Sinus-Milieus®

Weights	w_{pp}	w_{env}	w_{inc}	w_{com}
Borghesia Illuminata	0.060	0.350	0.300	0.290
Neo-Achievers	0.070	0.350	0.310	0.270
Progressisti Tolleranti	0.150	0.310	0.265	0.275
Italia Media Ambiziosa	0.150	0.310	0.260	0.280
Tradizionali Conservatori	0.140	0.290	0.260	0.310
Classe Post Operaria	0.140	0.310	0.270	0.280
Edonisti Ribelli	0.135	0.310	0.280	0.275
Consumisti Precari	0.125	0.320	0.280	0.275

Source: Calibration results

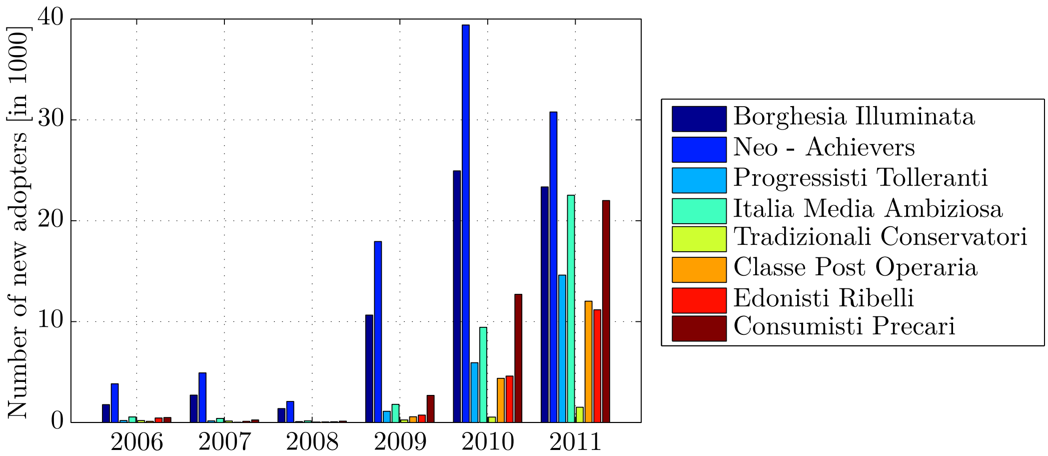

Figure 12: Number of adopters by Sinus-Milieu®, 2006–2011

Source: Own illustration, based on calibration results

Sinus-Milieus® with respect to Rogers' (2003) adopter categories presented in Table 4. Figure 12 shows the number of new adopters in each Sinus-Milieu® between 2006 and 2011. Initially, the diffusion process is driven mainly by innovators and early adopters (2006–2008). Later, as the rate of adoption increases, also the average middle class is participating in the adoption process (2009–2011). As a result, innovators and early adopters are characterized by higher coefficients for the income and environment weight. Small coefficients for the payback period weight indicate that innovators are willing to take more risk. Later adopters are characterized by higher coefficients for the weight of the payback period, thus stressing their need for financial security.

Figure 13 shows the distribution of the Sinus-Milieus® over time, regardless of the adoption status. The calibrated distribution of the socio-economic groups fits almost perfectly to the reference values observed in real world data, which is given as a share of households. The milieus are slightly different across the regions and depend on local socio-demographics. The distribution of the Sinus-Milieus® changes slightly between

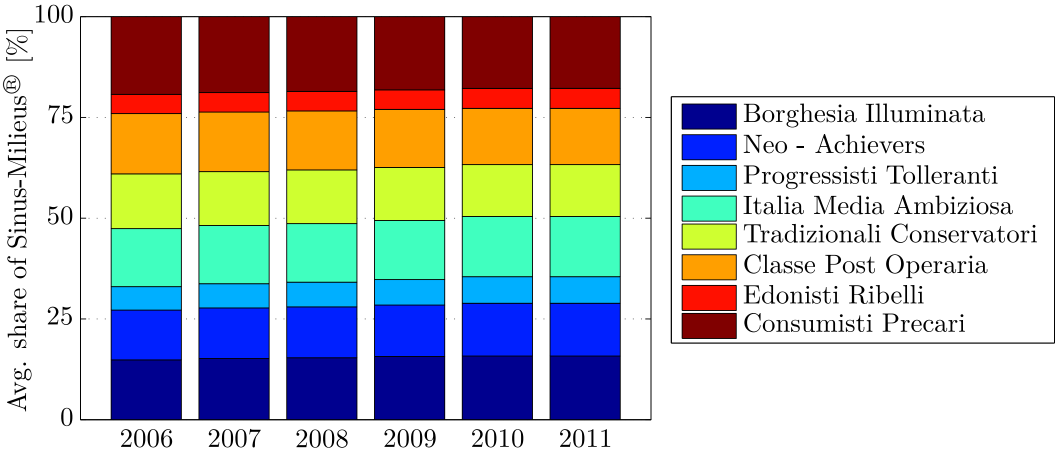

Figure 13: Distribution of households according to the Sinus-Milieus®, 2006–2011

Source: Own illustration, based on calibration results

2006 and 2011, but no further changes are assumed to take place in the social system (see section 4.2).

Finally, it is important to have a closer look at the option to scale the number of agents implemented in this model and already mentioned in section 4.2. The option works well for rather large regions of Italy with many inhabitants, for example Veneto (see Figure 14a). For these regions, the agent scale may be increased up to 80 without significant effects on the results of the model. In contrast, the fit of the calibration is more problematic for smaller regions with only few inhabitants, e.g. Molise, when the agent scale is large (see Figure 14b). The calibration issue arises as the agent scale approaches or even surpasses the number of agents in one or more categories of the regional social system.

During the calibration, and in the further scenarios of the model, an agent scale of 15 is used. This value keeps the simulation duration and the required computational memory small while limiting the calibration error in small regions to a minimum (see Table 8). As a matter of fact, when focusing on the calibration of the model at the national level, the "agent scale-error" in the small regions has a negligible influence, since the number of adopters is comparably small.

6 Scenario analysis and results

After the agent-based diffusion model has been calibrated, it can be used to predict the future Italian PV market under various scenarios. Three simulation scenarios have been tested to consider the sensitivity and validity of the model: a Baseline scenario with the most likely development of the PV market, a scenario with different PV investment costs (Scenario II), and a policy-driven scenario with varying degrees of future governmental

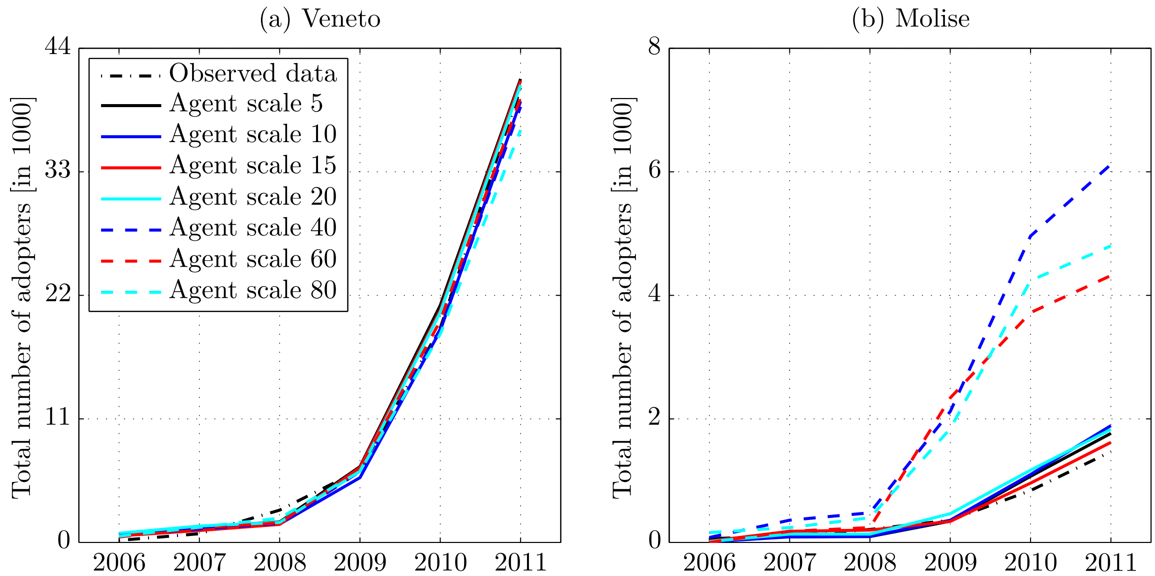

Figure 14: Influence of the agent scale on the number of adopters, 2006–2011

Source: Own illustration, calibration results

Table 8: Influence of the agent scale on the duration[a] of the simulation [s], 2006–2011

Agent scale	5	10	15	20	40	60	80
Veneto[b]	681	342	230	174	91	64	50
Molise[c]	26	18	16	15	13	12	11

[a] Simulations performed with a utility adoption threshold of 0.539
[b] Veneto has about 1.9 to 2.0 million households.
[c] Molise has about 300 to 320 thousand households.
Source: Calibration results

PV support (Scenario III). All three scenarios build on the parametrization obtained from the initial calibration.

6.1 Baseline scenario

6.1.1 Description Baseline scenario

The Baseline scenario considers the most likely development of the Italian PV market from 2012 to 2026. Governmental support is modeled on the current CE 5. The Italian government has planned to maintain the CE 5 scheme until the end of 2014. Afterwards, the model assumes that incentives will decrease by 15% every six months. Figure 15 shows the development of the incentive scheme over time.[24]

[24]Figure 15 shows the average incentive for PV-generated electricity from systems with an installed capacity of up to 20 kW of peak power. Extra payments and payments for direct energy consumption are not included.

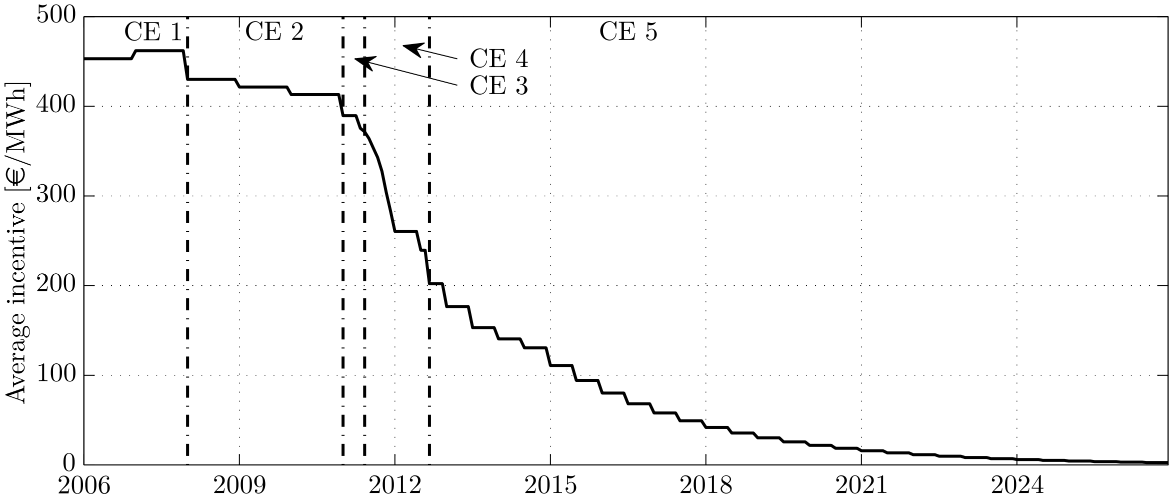

Figure 15: Incentive scheme in the Baseline scenario, 2006–2026

Source: Own illustration, based on MSE (2005, 2007, 2010, 2011, 2012) and own assumptions

Table 9: Cumulative global installed PV power and PV system price developments, 2012–2026

Year	2012	2013	2014	2015	2020	2026
PV power [GW]	77	88	100	125	345	760
System price[a] [€/kW]	1,904	1,824	1,750	1,626	1,543	1,021

[a] VAT excluded. Prices refer to small-scale (1–20 kW) PV systems

Source: EPIA (2011) and own calculations

Besides governmental support, investment costs are probably the second most important factor for the future development of the PV market. They play an important role in the estimation of the "Levelized Cost of Electricity"(LCOE) generation, a measure of the value of electricity self-generation. The LCOE of a PV system depends on its investment costs (I_0), yearly running costs (R_t), financing conditions (i.e. the interest rate i), energy output (E_{PV}), and economic lifetime (n) of the technology (Kost et al., 2012). The LCOE for new PV systems equals the ratio of the total costs of a PV system to the total energy produced over the lifetime of the PV system, measured as:

$$LCOE = \frac{I_0 + \sum\limits_{t=1}^{n} \frac{R_t}{(1+i)^t}}{\sum\limits_{t=1}^{n} \frac{E_{PV}}{(1+i)^t}} \tag{15}$$

Usually, the dominant component of the LCOE of a PV system are its investment costs. About half of the investment costs of a PV system are due to the modules' price, the other half is due to the inverter, cables, monitoring systems, and the installation costs (Wirth, 2012).[25] The reduction in PV system prices over time can be ascribed to economies of scale as well as learning effects and improvements in efficiency due to research and development activities (Wirth, 2012; EPIA, 2011). Their cost evolution has often been modeled via experience curves (for a literature overview, see van Sark et al., 2010). Here, we also model the evolution of the PV system price (I_t) at time t by forecasting the price per installed kW power of the system ($p_{PV}(t)$) with a one-factor experience curve (see also eqs. (3)–(5)). More specifically, it is assumed that $p_{PV}(t)$ is a function of the global cumulative PV power ($ACC(t)$), the experience parameter ($-b$), the price of the system in the base year ($p_{PV}(t_0)$) and the global cumulative installed capacity in the base year ($ACC(t_0)$). The price of the system per installed kW power at the time t is then given by:

$$p_{PV}(t) = p_{PV}(t_0) \cdot \left(\frac{ACC(t)}{ACC(t_0)}\right)^{-b} \tag{16}$$

$$LR = 1 - 2^{-b} \tag{17}$$

The model implements a learning rate (LR) of 20% until 2020, followed by a reduced rate of 18% until 2026 (EPIA, 2011). Data for the global cumulative installed PV capacity until 2026 are taken from EPIA (2011). The associated PV system price evolution and the cumulative installed capacity are given in Table 6.1.1.

Besides the price per kW, additional assumptions are necessary to estimate changes in the LCOE of a PV system over time. According to Kost et al. (2012), the maintenance cost of a photovoltaic system increases every year by about 2%, with a starting value of circa 1.3% of the initial investment. The intertemporal value of money is discounted at an interest rate of 6% (i in eqs. (3) and (15)). In addition, the PV investment is financed by borrowing 70% of the required capital at an interest of 5%. The energy output depends on the region where the PV system is located. Degradation of the PV system is also taken into account and amounts to about 0.3% per year (Kost et al., 2012). In addition, the efficiency of the PV panels is assumed to improve with linear increments by 1.5% per year, which leads to an efficiency increase from 13.5% in 2013 to 16.9% in 2026. Similarly, electricity prices are growing linearly by about 2% per year (Kost et al., 2012).

6.1.2 Results Baseline scenario

The Baseline scenario indicates a stagnation of the diffusion process in all regions. The inflection point of the diffusion process is very distinct and takes place in 2012 (Figure 16). After the rate of adoption reaches its maximum, the number of new adopters decreases quickly from about 280,000 in 2012 to about 6,500 in 2021.

This outcome seems to be consistent with real-world data. According to the latest

[25] Also known as Balance of System (BOS) components.

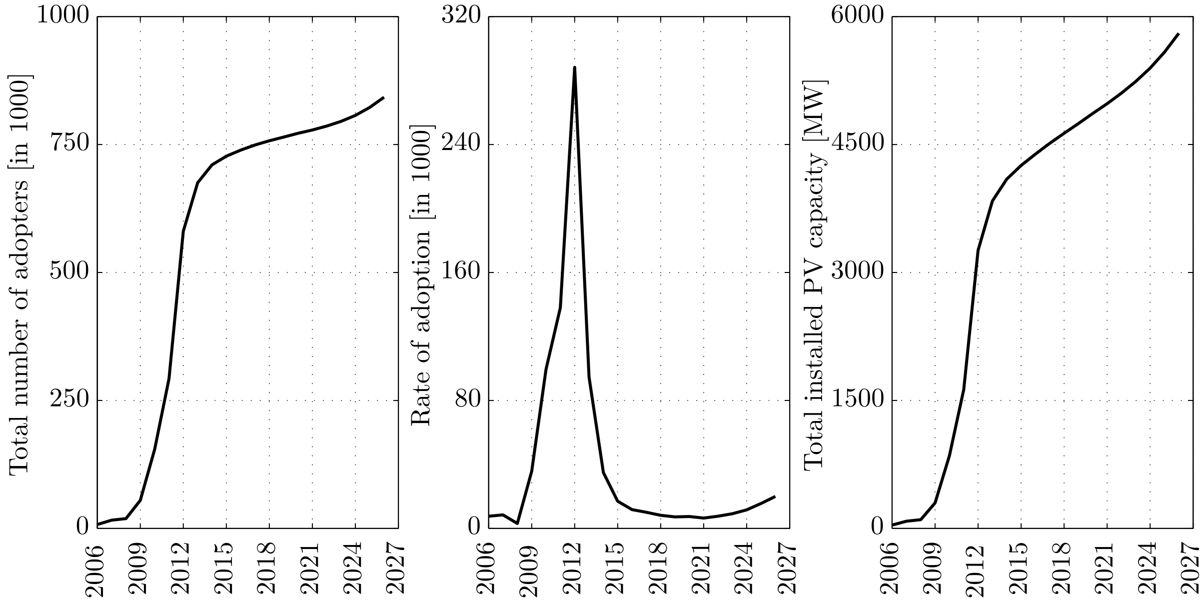

Figure 16: PV diffusion in the Baseline scenario, 2006-2026

Source: Own illustration, based on simulation results

PV report (GSE, 2013a), the cumulative adoption of PV systems is still growing, but it is slowing down. Between 2007 and 2011, the number of PV installations more than doubled every year. In 2012, for the first time, the total number of new installations was lower than in the previous year. Installed capacity, while still increasing, has also been growing at a slower pace. Between 2010 and 2011, installed capacity grew by 269%, with a marked increase in the average PV system size from 22 to 38.7 kW. Between 2011 and 2012, installed capacity grew by 29%. Similarly, the average size of newly installed PV systems steadily increased between 2007 and 2011[26], while in 2012 this indicator dropped to values lower than those of 2010. While our simulation results might overestimate the decrease in PV diffusion, the model still seems to capture the recent slow-down of the investments and trend that, also due to the currently unfavorable economic conditions, may be persistent.

The simulation results can be better contextualized with the help of the prediction scenarios proposed by other studies. EPIA (2012), for instance, estimates[27] a cumulative installed PV capacity in Italy of 23,000 MW by 2016. Our model estimates the cumulative installed capacity of small PV systems at about 4,400 MW in 2016, which corresponds to a share of about 19.0% of the total in that year. This number is consistent with the actual share of 15.5% in 2011.[28]

[26]Note that there was a jump in the average size of newly installed plants in 2011. This change is probably also due to the activation of several large-scale PV plants.

[27]We refer to their "moderate scenario". In their "policy-driven" scenario, EPIA (2012) estimate a total installed capacity of 30,800 MW in 2016.

[28]If we used EPIA's (2012) "policy-driven" scenario, the actual share of domestic installed PV capacity drops to 14.3%.

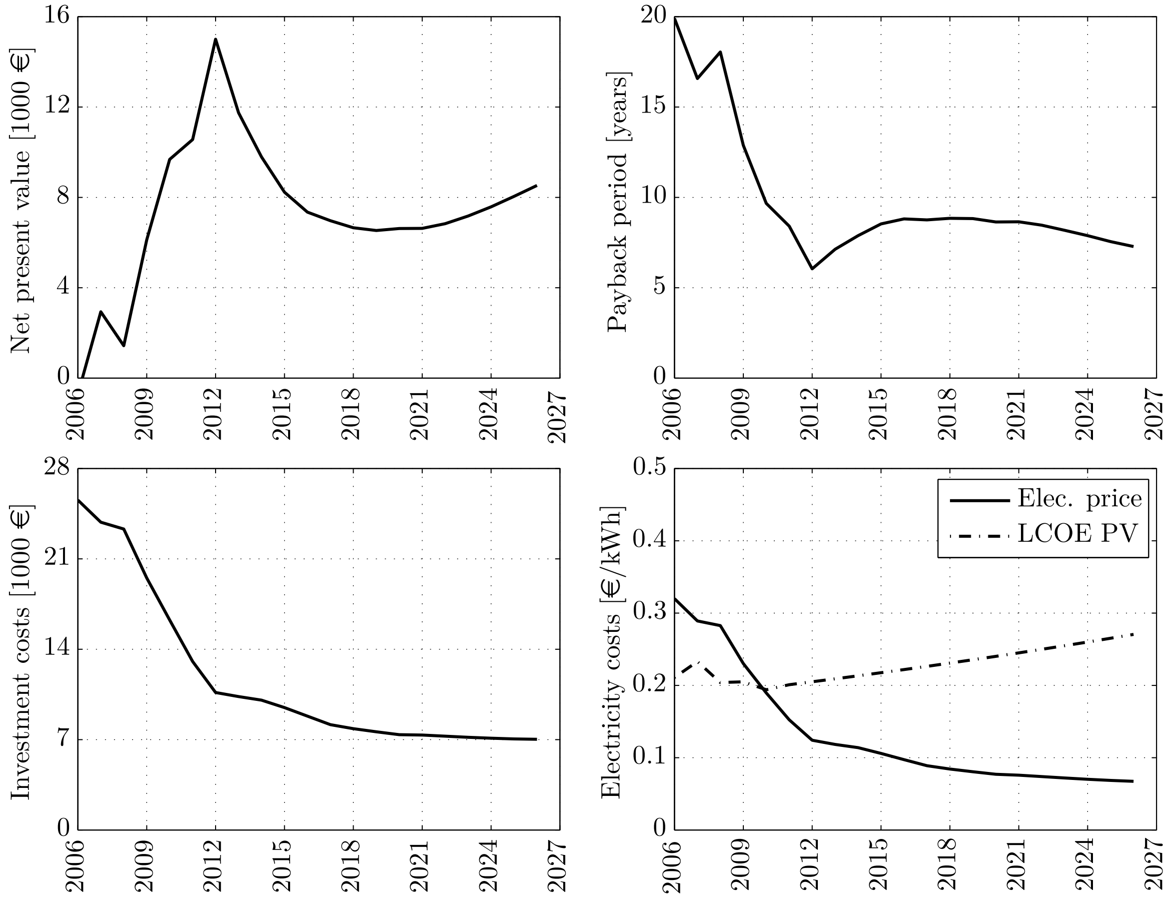

Figure 17: Average values of key economic indicators in the Baseline scenario, 2006–2026

Source: Own illustration, based on simulation results

A more detailed analysis of the simulated average NPV values of the PV system helps to better explain the results of the model (see Figure 17). At the beginning of 2006, PV systems were not profitable. Thanks to the introduction of government support and decreasing investment costs, the average NPV of photovoltaics grew steadily until 2012, when it reached a value of about €15,000.[29] However, starting already in 2011, the incentive scheme has been reduced dramatically. As a consequence, the average NPV decreases to €6,534 by 2019. Moreover, the CE 5 has changed the calculation method for the clearance balance[30] of direct PV electricity consumption. According to TIS Innovation Park (2012), the Italian government made this change on purpose, in order to support direct electricity consumption more strongly. As a result of the support scheme changes, the PV system owner needs an electricity storage component for his PV system to receive the benefit payments. The model, however, does not simulate any such components.[31]

[29]We always refer to small PV systems up to 20 kW of peak power.

[30]Refers to the savings summand ($R_{save}(t, CE)$) in the PV systems' cash flow (see eq. 6).

[31]The inclusion of a storage capacity would significantly alter the NPV valuation of the system. In addition, it would complicate the decision as to when to consume and when to feed-in the self-generated electricity.

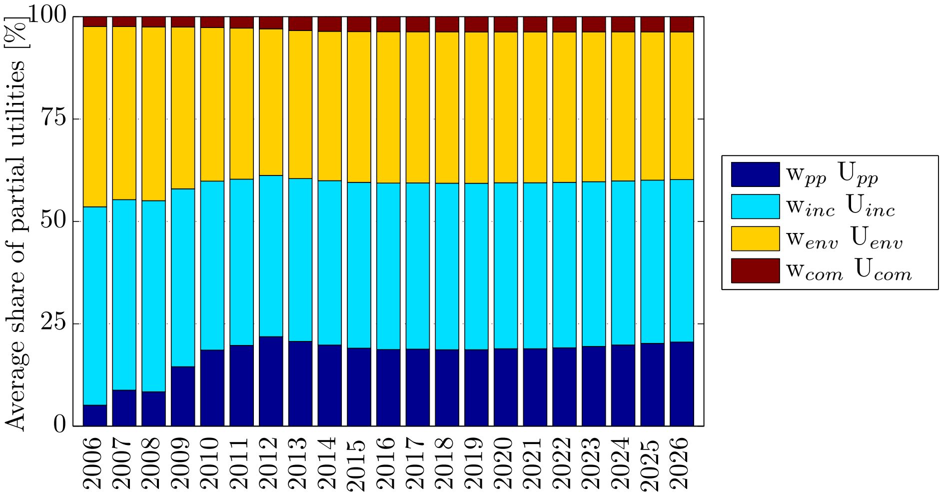

Figure 18: Influence of the different weighted partial utilities in the Baseline scenario

Source: Simulation results

Interestingly, the rate of adoption and the NPV of the system increase again from 2021 to 2026. The decline in investment costs eventually makes the PV system economically profitable again, despite the small remaining governmental support[32]. The average investment costs, which depend on the given PV system price (Table 6.1.1), are the most important component for the estimation of the production costs of the self-generated electricity. As shown in Figure 17, the model predicts grid parity [33] in 2010. This result corresponds to the actual point in time when residential grid parity was achieved in Italy (Breyer and Gerlach, 2013), thus confirming the good parametrization of the model. After grid parity is reached, the model predicts further reductions in PV electricity production costs, which is in accordance with the assumed decrease in the investment costs and the values forecasted by Breyer and Gerlach (2013).

Understanding the results of the Baseline scenario requires also a closer look at the innovation-decision process of the model. Figure 18 displays the average share of weighted partial utilities of the calibrated model as a function of time. The diagram includes all agents' utilities, regardless of whether they are adopters or not. As one can see, the influence of the communication network is negligible during the calibration phase and increases only marginally from 2010 to 2013. Afterwards, the influence of communication remains constant. The influence of the households' income and the importance of environmental concerns decrease as PV diffusion expands until 2011. In contrast, the share of weight of the payback period increases between 2006-2012, which can be explained by its linear influence on the partial utility, as well as by the strong increase in the NPV in the first years of the simulation.

[32]The average payback period follows a curve that is the inverse of the NPV curve, and thus its shape and evolution over time may be explained in a similar way.

[33]Grid parity takes place when electricity from the grid and self-generated PV electricity (i.e., LCOE) have equal production costs.

Overall, the model leads to stable and reproducible simulation results, which nevertheless may be questioned. Especially the influence of each partial utility could have been designed in a different way. However, it seems reasonable that communication networks have a rather small influence on the adoption decision, since the share of adopters to the total agent population remains small across the entire simulation period (max. of 6.6% in 2026). Increasing the weight of the communication utility has little to no influence on the outcome of the model. Communication is therefore not likely to be the driving force behind the diffusion process. Since environmental and income effects do not change much over time, they are also not likely to play a leading role for a potential increment in the diffusion process. The only aspect that may lead to and maintain a high rate of adoption is the economic profitability of the PV system. In order to analyze the model's response to different NPV valuations, the following two scenarios further elaborate on governmental PV support and the price of the PV system.

6.2 Scenario II - Changes to the Support Policy

6.2.1 Description Scenario II

In this scenario, two alternative governmental incentive schemes are implemented. The Baseline scenario is used as a reference for comparisons. Changes to the support scheme take place from 2015 onwards. While the Baseline scenario considers a decrease in incentives of 15% every six months, here in Scenario II the incentives are reduced by 5% and 25%, respectively. The reduction in the incentive payments leads to an end of governmental support before the last simulation year. The alternative with stronger incentives, instead, guarantees governmental support until 2026 and beyond. Figure 19 displays the alternative support schemes simulated.

6.2.2 Results Scenario II

The gradual reductions in the incentive scheme by only 5% increase the number of adopters. Cutting back the incentives by 25% does not contribute to significant differences in the results compared to the Baseline scenario. Both the Baseline scenario and the "weaker incentive" alternative hardly have new adopters between 2015 and 2026. In contrast, the "stronger incentive" program leads to 36% more adopters by the end of 2026 (1,145,900 households) compared to the reference case. Similarly, the cumulative installed PV power increases to 7,900 MW, compared to 4,400 MW in the baseline case.[34] Higher incentives secure a shorter payback period of the investment and incentivizes, from 2015 onwards, at least 31,000 new adopters per year. Nevertheless, the "PV boom" that characterized the 2009–2012 period could not be replicated.

[34] The individual regions show similar characteristics as the whole nation and are not further analyzed.

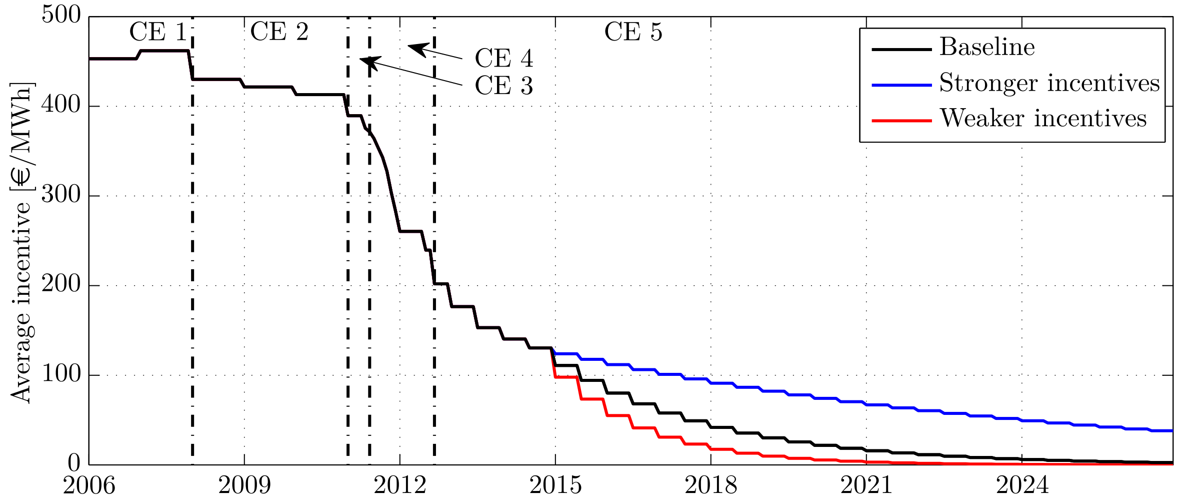

Figure 19: Alternative incentives for the future PV support scheme in Scenario II, 2006–2026

Source: Own assumptions and illustration, based on Conto Energia 5

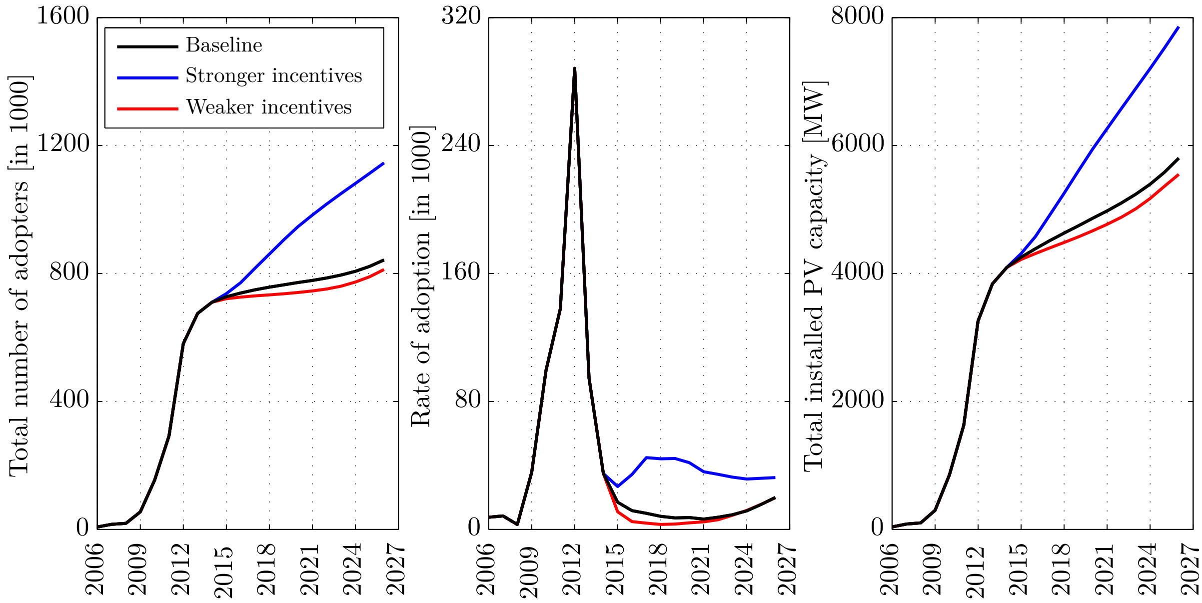

Figure 20: PV diffusion results in Scenario II, 2006–2026

Source: Own illustration, based on simulation results

The two alternative incentive schemes have a strong impact on the NPV and the payback time of the PV system (see Figure 21). Lower incentives contribute to a drop in the NPV value, which decreases to €5,240 in 2018, and then increases again till the end of the simulation period. By 2026, the reduced governmental support scenario shows almost the same NPV as the Baseline scenario. The NPV growth after 2018 is due to decreasing PV investment costs, as it is the case for the baseline simulation. Since in the reference case and in the low incentive alternative the monetary incentives are small and

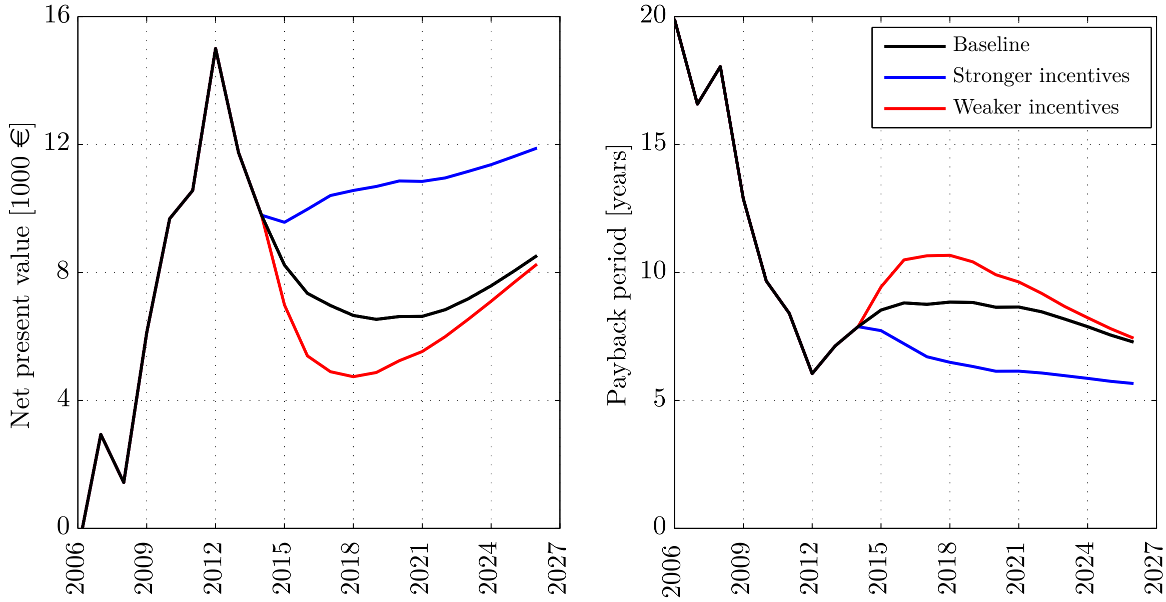

Figure 21: Average values of key economic indicators in Scenario II, 2006–2026

Source: Own illustration, based on simulation results

decreasing, the PV price has a stronger influence on the NPV value[35]. On the contrary, the stronger incentive scheme leads to an almost linearly increasing NPV from 2015 till the end of the simulation period. The final NPV in 2026 is about €11,890.

Besides the two alternative incentive schemes presented here, other governmental support programs have been tested to explore the "boundary behavior" of the model. Cutting off the incentives totally in January 2013 leads to a result similar to the one obtained with weaker incentives. Maintaining the governmental payments of December 2012 throughout the remaining simulation runs also leads to a similar turning point in the rate of adoption as the one obtained with the "higher incentive" scheme, though the NPV in 2026 is higher. In general, the simulations show that the adoption behavior of the agents can be strongly influenced by the incentive scheme adopted by the government. Small to no incentives lead to a stagnation of the diffusion process. Strong incentive programs, in contrast, rapidly accelerate the diffusion dynamics.

6.3 Scenario III - Changes to the Investment Costs

6.3.1 Description Scenario III

The third scenario simulates two alternative PV system price developments. Both alternatives are derived from the experience curve model adopted for the PV system price forecast (see eqs. (16)–(17)). The learning rates are kept constant for different estimates

[35] As shown in eq. (3), investment costs in the NPV calculation correspond to a single down payment, while the cash flows (including the support incentives) are discounted over time. As a result, the investment costs have a much stronger direct influence on the final value of the NPV estimation.

Table 10: Forecasted investment costs in Scenario III, 2012–2026

Year		2012	2013	2014	2015	2020	2026
Low PV price	[€/kW]	1,904	1,736	1,615	1,524	967	842
Change relative to baseline	[%]	0	-4.8	-7.7	-6.2	-17.6	-17.6
High PV price	[€/kW]	1,904	1,833	1,784	1,749	1,543	1,342
Change relative to baseline	[%]	0	+0.5	+1.9	+7.6	+31.4	+31.4

Source: EPIA (2011)

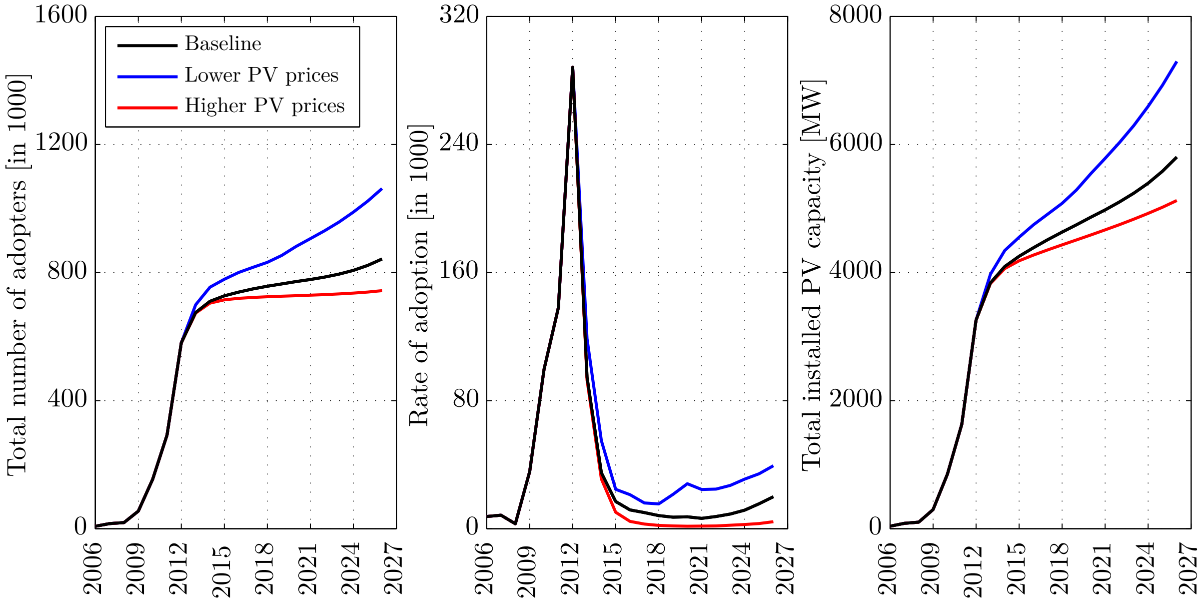

Figure 22: PV diffusion results in Scenario III, 2006–2026

Source: Own illustration, based on simulation results

of cumulative global installed PV capacity. For the prediction of the cumulative installed PV capacity, EPIA (2011) provides two additional scenarios based on an optimistic or a pessimistic outlook regarding future PV market development. Table 10 lists these investment cost projections as “low” and “high” PV system price alternatives. Moreover, the table shows the percentage change in relation to the original baseline investment costs.

6.3.2 Results Scenario III

The results indicate clear differences relative to the Baseline scenario. An incremental reduction in the investment costs of up to 17.6% by 2026 leads to an increase in the total number of adopters by 26.1% to about 1,062,540 households. The share of adopters corresponds to about 8.3% of the total agent population. The higher number of adopters also raises the total installed PV capacity to 7,300 MW. In contrast, the pessimistic scenario regarding investment costs stops the diffusion process. The rate of adoption becomes almost zero and the number of total adopters remains constant from 2013 onwards.

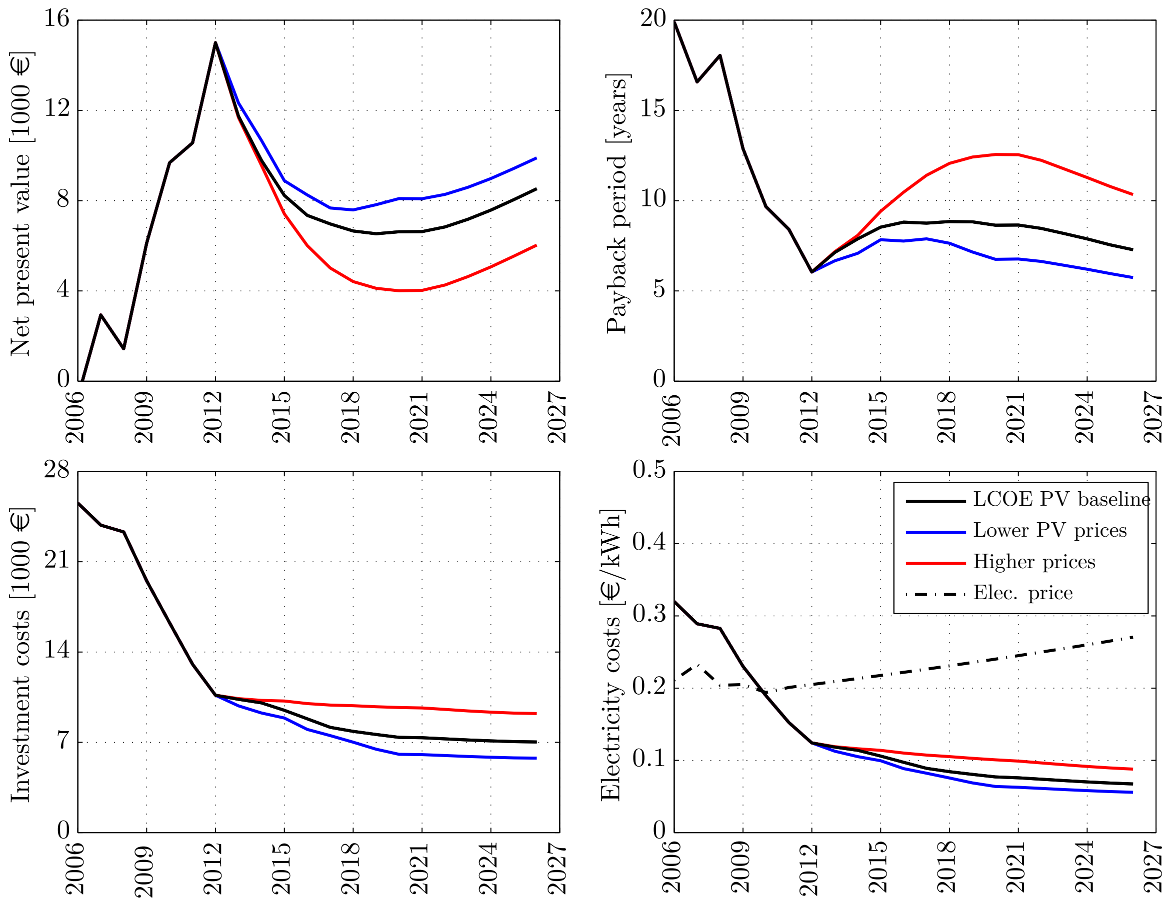

Figure 23: Average values of key economic indicators in Scenario III, 2006–2026

Source: Own simulation, based on simulation results

Compared to the Baseline scenario, this alternative has 11.7% less adopters in 2026 and a total PV power of only 5,100 MW.[36]

The simulation outcome may be explained by looking at the relevant economic parameters that drive the diffusion process of the PV system (Figure 23). Higher investment costs bring about a decrease in the NPV by 29.3% until 2026. A decrease in the PV price by 17.6%, in contrast, increases the NPV by 16.0% at the end of the simulation. The payback period of the PV system and the cost of self-produced electricity follow similar paths.

By comparing the results of Scenario II and Scenario III, it may be argued that both governmental incentives and the evolution of the PV system price have a significant influence on the adoption process. Based on the simulations' outcome, the scenario with the highest incentive scheme obtained the largest technology adoption. Obviously, a one-to-one comparison of the two scenarios is hindered by the many assumptions made. In particular, the PV system price is assumed to depend on the success of PV adoption at a global scale, not forgetting the imputed economies of scale and learning effects

[36]For both alternatives, the individual regions show similar characteristics and are not further analyzed.

of the experience curve model. In contrast, incentives can be used more flexibly, as they are directly determined by government policy. As a result, though more expensive to taxpayers, they are a better controllable option to accelerate the diffusion of PV technology.

7 Conclusion

While the expansion of large PV sytems may continue, Italy's domestic[37] PV installations have already surpassed an initial phase of rapid growth and, although likely to spread further, they are expected to do so at a significantly slower rate. According to the simulation results, the number of new households adopting photovoltaic technology stagnates under the current support scheme.

In an attempt to adequately account for the complexity of the actual diffusion process of the PV technology, we implement an agent-based model that incorporates four elements influencing the adoption decision: the economic profitability of the investment, environmental considerations, a household's income, and the impact of communication networks. To do so, the model structures the social system into socio-economic classes (Sinus-Milieus®). In total, 150 categories across 20 regions have been implemented by distinguishing between age classes, the level of education, and the household type.

Despite the multiple factors interacting simultaneously, the model simulates reproducible and reasonable results that are in line with observed data over the 2006–2011 period. Overall, the calibration of the model proved to be relatively easy to handle by varying the weights of the innovation-decision process and the utility threshold. The projected diffusion can therefore be evaluated by altering key parameters driving the outcome of the model.

As one might expect, it has been shown that the economic profitability of the investment is the most influential criterion in the adoption decision. As a result, we examined in greater detail the two parameters that most influence it: alternative governmental support schemes and variations in the PV system's investment costs. Compared to the Baseline scenario, a steeper reduction in the support payments would stop the diffusion process at once. On the contrary, a more gentle step-wise decline in the incentive scheme would ensure a greater diffusion of the PV technology. Nevetherless, in the simulation results, the adoption rate that characterized the initial diffusion is never replicated under the latest support policy scheme. A similar outcome is obtained with variations in the expected evolution of the PV investment costs. In general, it may be argued that direct governmental support is more costly to taxpayers, but it is a relatively safe option to ensure a speedier diffusion of photovoltaic technology among private homeowners.

[37] In the model, the agent population contains only households living in single- or two-family houses; hence, only the diffusion of small residential PV systems of up to 20 kW power is considered.

Interestingly, the model managed to accurately predict when grid parity is reached in the Italian market. The model also indicates that self-produced electricity becomes increasingly more advantageous over time. However, Italy witnessed a boom in PV adoption under the influence of strong governmental incentives. Relatively high NPV values were associated with the fast diffusion of the technology. As a result, despite the decline in investment costs and the increasing benefits associated with PV electricity self-generation and direct consumption, the agents do not manage to replicate the profitability levels witnessed during the initial PV boom due the significant reduction in support granted by the government. Under the assumption that the preferences of investors will not significantly change over time, the lower profitability of PV systems ultimately explains the reduction in new adoption following the introduction of the new support scheme. Environmental concerns and communication also play an important role, but they are not nearly as significant as economic considerations.

Obviously, the model is built on a number of simplifications and assumptions that fundamentally put into question the validity of its predictions. In particular, as already mentioned, the model is suspiciously sensible to changes in the utility threshold parameter. Small changes in values contribute to strong changes in the diffusion process. In addition, the categorization according to Sinus-Milieus® is an effective way to represent the multi-faceted aspects of the current social structure. However, its parametrization in the model was rather *ad-hoc* and not substantiated by verifiable empirical research. While keeping these points in mind, which are shared by many forecasting frameworks, the model's ability to match the actual diffusion of PV systems in Italy at both the national and regional level are encouraging signs of its potential. Furthermore, the applicability of the proposed framework to other countries and, with small changes, to other renewable energy technologies, calls for future implementations with an improved set of underlying parameters.

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