Supplementary information to

Responsive adjustments to keep deployment policies effective and cost-efficient as technology prices fall

1. Extended model description

This extended description of the model follows the ODD protocol (i.e. overview, design concepts, details) for structuring the information on our agent-based model.[1,2]

1.1. Overview

This section provides a concise explanation of the purpose, variables and processes in the model.

1.1.1. Purpose

Our agent-based model aims to represent the processes of adoption of solar photovoltaics in Germany between 1992 and 2016 in order to explore how different designs of a feed-in tariff policy can achieve its policy targets while being effective and cost-efficient.

1.1.2. Entities, state variables and scales

Model entities

There are two entities in the model: the observer and potential adopters. The observer is a system-level entity responsible for timekeeping, updating the global variables, and adjusting the policy and technology prices. Potential adopters are individual, heterogeneous agents representing the population of electricity consumers in Germany.

State variables

We model three categories of potential adopters: residential, commercial, and industrial, and utility-scale agents. According to their category, agents would install PV systems within a different size range, consume different shares of their solar electricity generation, pay different electricity prices, employ different discount rates, and receive different incentives (see Table A - 1).

Table A - 1. Main category-dependent variables for agents in the model.

Type of adopter	**Number of agents**[a]	**System size**[b]	**Solar self-consumption rate**[c]	**Electricity rate**	**Discount rate**[d]	**Incentive**[e]
Residential	16891049[f]	0-10 kWp	30%[i]	Historical rates[j]	Historical rates[k]	100%
Commercial and Industrial	3853103[g]	10-40 kWp	20%[i]	Historical rates[j]	Historical rates[k]	90%
Utility-scale	85086[h]	40-10,000 kWp	40%[i]	Historical rates[j]	Historical rates[k]	70%

(a) Average number of firms over several years are used to account for the variation in their populations during the years under study. **(b)** See section 8. **(c)** Solar self-consumption rate is the fraction of electricity generated from the solar PV system that is consumed by the adopter. **(d)** The historical lending rate for each adopter type is added to the individual discount rate of each agent. **(e)** Fraction of the feed-in tariff received by each adopter type based on the historical ratios between the feed-in tariffs for large and small installations in Germany.[3] **(f)** Number of owner-occupied households in Germany.[4] **(g)** Average number of firms, except insurance activities of holdings, electricity and finance firms, from 2008 to 2014 and average number of farms between 2000 and 2010 in Germany.[5,6] **(h)** Average number of electricity, financial and insurance firms between 2008 and 2014 in Germany.[5] **(i)** The self-consumption rate of each agent is randomly assigned from a truncated normal distribution between zero and one, with the above mean, an assumed standard deviation of 0.05.[7] **(j)** See section 10. **(k)** See section 11.

Table A - 2. State variables for agents.

Entity	State variables	Description	Value range	Unit	Source
Adopters (independent of category)	Category	Determines the type of electricity consumer of the agent	[household, commercial and industrial, utility-scale]	[-]	Model parameter
	Solar adopter	Indicates if the agent owns a solar PV system or not	[Boolean]	[-]	Simulation
	Location	Determines where the agent is located	[-]	[-]	Historical[4] (see Scales subsection)
	PV orientation	Represents the impacts of the solar PV system orientation, shading, and others	N(0.9, 0.2)[a]	[1:1]	Assumption
	Personal discount rate	Discount rate applied by the agent in addition to the corresponding to its category	N(0, 100)[a]	[% p.a.]	Assumption
	Environmental awareness	Represents the behavioural motivation of the agent to adopt environmental innovations	N(0.5, 0.2)[a] truncated to [0, 1]	[-]	Assumption
Adopters (dependent on category)	Solar PV system size	Size of the potential solar PV system the agent would install	[0.5, 5,000]	[kWp]	Historical[3] (see section 8)
	Self-consumption rate	Fraction of the solar electricity generated that is consumed by the agent	[0, 1]	[1:1]	Historical[7]
	Electricity price	Electricity tariff paid by the agent, including levies and taxes	[0.0878, 0.3000]	[€/kWh]	Historical[8,9] (see section 10)
	Discount rate	Discount rate applied by the agent	[1.40, 9.90]	[% p.a.]	Historical[10] (see section 11)

[a]N(μ, σ) stands for normal distribution of mean μ and standard deviation σ.

Table A - 3. State variables for the policy adjustment mechanism.

Entity	State variables	Description	Value range	Unit	Source
Observer (policy-adjustment)	Adjustment mechanism	Determines how the policy incentives are adjusted	[historical, PID-algorithm]	[-]	Design parameter
	PID parameters	Define the weights of the proportional, integrative and derivative corrections in the PID-algorithm mechanism	[0, +∞]	[depends on the parameter and policy target definition]	PID calibration
	Policy start year	Defines the year the policy begins	2000	[-]	Historical[11]
	Policy end year	Defines the last year the policy is active	2016	[-]	Historical[12]
	Policy start month	Defines the month of the year the policy begins	April	[-]	Historical[11]
	Initial feed-in tariff	Defines the first value of the incentives	0.5062	[€/kWh]	Historical[11]
	Type of policy goal	Defines the policy variable the adjustment mechanism is responsive to	[deployment, policy-cost, profitability]	[-]	Design parameter
	Overall policy target	Defines the cumulative policy target	[0, +∞]	[depends on policy goal type]	Design parameter
	Temporal distribution of targets	Defines how the cumulative policy target is distributed throughout the months of active policy	[linear, bell-shaped]	[-]	Design parameter
	Bell-curve month peak	Defines the month that monthly policy targets peak when distributed using a bell-shaped curve.	142 [April 2012]	[-]	Design parameter
	Bell-curve steepness	Defines the steepness of the cumulative policy target	0.07	[-]	Design parameter

Table A - 4. State variables related to the technology and technological learning.

Entity	State variables	Description	Value range	Unit	Source
Observer (technology variables)	PV performance ratio	Defines the effectiveness of the solar PV system in converting solar power into AC power	0.85	[-]	Literature[7]
	Maintenance and operation cost	Defines the annual costs of using the solar PV system	1.5% of system cost	[€/year]	Literature[13]
	PV module price	Indicates the cost of a solar module	[0.76, 10.59]	[€/Wp]	Simulation (see section 9)
	Non-module price	Indicates the cost of non-module elements of a solar PV system	[0.85, 4.38]	[€/Wp]	Simulation (see section 9)
	Solar PV module learning rate	Determines the cost reduction per doubling of cumulative installed capacity in the World	20.3	[%]	Historical (see section 9)
	Non-module components learning rate	Determines the cost reduction per doubling of cumulative installed capacity in Germany	10.2	[%]	Historical (see section 9)
	Scale effect	Determines the economies of scale for larger solar PV systems	[see section 0]	[-]	Literature[14] (see section 0)
	Price random fraction	Determines the allowed variations around the price determined by the experience curve	5	[%]	Model parameter
	Average irradiation in Germany	Defines the average level of irradiation in Germany for the calculation of the internal return rate for an average household	950	[kWh/m^2/year]	Literature[7]

Table A - 5. Other and time-keeping variables in the model.

Entity	State variables	Description	Value range	Unit	Source
Observer (other variables)	Wholesale electricity price	Price paid to solar electricity generators	[0.0207, 0.0687]	[€/kWh]	Historical[15] (see section 10)
	Interest rate for government	Discount rate for future payments used by the government	[-0.15, 8.90]	[% p.a.]	Historical[16] (see section 11)
	Information about solar PV	Represents the available information about the technology to the agents	[0, 1]	[-]	Historical[17] (see section 12)
	Peer-effect radius	Determines the distance within which the agent observes if other agents have installed solar photovoltaics	2	[km]	Model calibration
	Ideation step weights	Determine the weight of each ideation variable in the adoption decision-making process of the agents	[see section 1.3.3]	[-]	Model calibration
	High-awareness threshold	Determines the environmental awareness required from an agent so that it can skip the economic evaluation step	0.92	[-]	Model calibration
	Installed capacity out of Germany	Determines the monthly cumulative installed capacity out of Germany	[44.3, 261,888.9]	[MWp]	Historical[18]
	Population resize	Determines the population scaling in the model	0.001	[-]	Model parameter
Observer (time-keeping)	Year	Year of the simulation	[1992, 2016]	[-]	Simulation
	Month (1 time step in the model)	Month of the simulation	[0, 301]	[-]	Simulation
	Calendar month	Month of the year of the simulation	[1, 12]	[-]	Simulation
	Real month	Corresponding month if the simulation started in January 1991 (used for retrieving historical data)	[0, 313]	[-]	Simulation
	Policy month	Month since the policy started	[0, 201]	[-]	Simulation
	Control derivative	Indicates if there are enough data points to calculate the derivative correction	[Boolean]	[-]	Simulation
	Start year	Year the simulation starts	1992	[-]	Simulation
	End year	Last year in the simulation	2016	[-]	Simulation

Table A - 6. Variables of the geographical patches in the model.

Entity	State variables	Description	Value range	Unit	Source
Geographical patches 10x10km	States boundaries	Defines the location of the boundaries between states in Germany	[-]	[-]	Historical
	States	List of German states	[all German states]	[-]	Historical
	Building density	Density of residential buildings in each German state	[17, 356]	[building/km^2]	Historical[4]
	Irradiation	Average global solar irradiation on a horizontal surface received in the patch during one year	[967, 1,230]	[kWh/m^2/year]	Historical[19]

Scales

Due to computational power constraints, the population of agents had to be scaled down by a factor of 1:1000 (i.e. for each residential household in the model, there were one thousand in reality) leading to a model population of 20,893 agents. The simulation runs from January, 1992 to December, 2016 on a monthly basis. The population of agents is distributed across Germany on geographical patches of 10 per 10 kilometers and according to the density of residential buildings.

1.1.3. Process overview and scheduling

The model has three modules: (A) policy adjustment – which modifies the feed-in tariff, (B) adoption decision-making – in which individual agents determine if they install or not, and (C) technological learning – which dictates the evolution of PV system prices (see Figure A - 1).

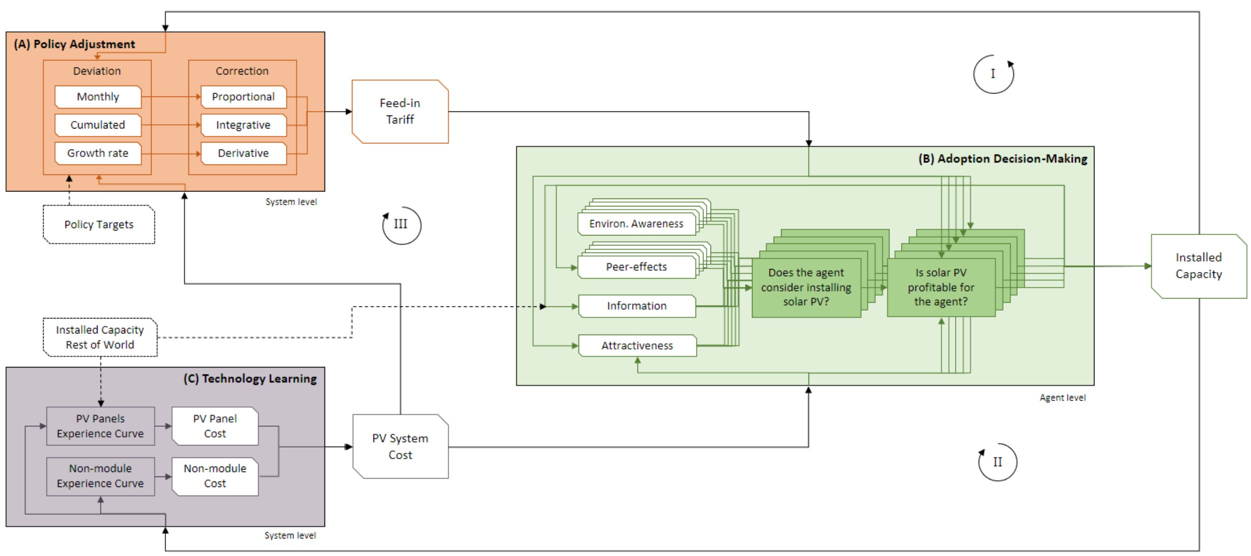

Figure A - 1. Schematic representation of the modules in the model and their main components.

The modules interact according to the following schedule every time step (i.e. month). First, the adjustment mechanism (PID algorithm) calculates a correction of incentives that tries to simultaneously reduce: (i) the deviation from the target of the previous month (i.e. proportional correction), (ii) the cumulated deviation since the policy started (i.e. integrative correction) and (iii) the growth of the deviation in the following month (i.e. derivative correction). In the historical scenario, the incentives are adjusted according to the historical mechanism in force at each point in time.

Second, the agents decide whether to install a solar photovoltaic system or not. Agents first need to develop the idea of installing solar PV, which depends on the weighted sum of four variables (i) peer-effects, (ii) available information on the technology, (iii) the agent's environmental awareness, and (iv) the attractiveness of investing in solar PV. Once developed the idea, an agent installs a solar system if the net present value is non-negative or if the agent is exceptionally environmentally aware.

Third, solar photovoltaic prices progress down the technology's experience curves according to the capacity installed by adopters. Our model employs a global experience curve for solar modules, and a national one for the non-module components of a solar system (e.g., balance of system, installation services). Solar modules are a global product whose technological learning depends on global deployment, while prices of non-module elements evolve through regional learning processes.

1.2. Design concepts

This section describes the main design concepts employed in the construction of this model, following the design concepts listed by Grimm and colleagues (2010).[2] We omit those concepts not contained in this model such as objectives for the agents, learning or prediction. The agents in our model lack a predefined objective (i.e. other than saving money if possible by installing a solar PV system) and do not learn, remember, or predict the evolution of prices or the policy.

1.2.1. Basic principles

The principles behind the model representing the behavior of individuals considering the installation of a solar PV system is loosely based on the theory of planned behavior.[20] This theory of behavior has been widely applied in studying and modelling the diffusion of innovations, including solar photovoltaics.[21,22]

According to the theory of planned behavior, decisions such as the acquisition of a solar PV system, which involve a substantial economic commitment, are influenced by three elements. (1) The attitude toward the behavior (e.g., the perceived environmental and personal gains from adopting solar PV). We represent this in the ideation step with the environmental awareness and attractiveness of the investment. (2) the subjective norms (e.g., the social perception of solar PV adopters among the individual's community). We represent this element with the effect of peers that have adopted the technology near the agent. (3) The perceived behavioral control (e.g., the perceived ability to install a solar PV system). We represent this element with the available information about the technology. These three factors determine the intention of an individual towards the behavior.[20] Finally, the behavior (e.g., adoption of solar PV) takes place as a result of a positive intention and perceived behavioral control. We represent this by using a two-step process: (1) ideation, when the agent develops or not the intention to adopt, and (2) economic evaluation, when the agent analyses whether it is economically sensible to adopt (i.e. if the agent is able to adopt a solar PV system from an economic perspective).

1.2.2. Emergence

Our model contains two emergent phenomena: (1) the adoption patterns of the agents – which impact deployment, policy costs and the evolution of technology prices – and (2) the evolution of the incentives as determined by the responsive nature of policy adjustments. Incentives, then, follow different paths in each individual simulation run depending on the behavior of the agents, see section 3, which would be impossible to predict beforehand.

The influence of peer-effects, by which local adoption rates encourages further adoption in nearby agents, is the main emergent behavior in our model. We observe how installations evolve in clusters where peer-effects play a large role. These clusters are influenced by the number and location of early adopters, as well as by the timing of the installation by these early adopters. In turn, this has a major impact on the evolution of deployment and policy costs, see section 4.

1.2.3. Sensing

The behavior of the agents in the model is influenced by environmental variables and other agents' decisions. The environmental variables perceived by the agents are: (1) solar PV system price, (2) feed-in tariff, (3) electricity prices, (4) interest rates for loans, (5) available information, (6) attractiveness of adoption. Other agents' decisions influence the behavior of agents directly through peer-effects.

The internal variables that agents are supposed to sense (or act upon) are (1) environmental awareness, and (2) economic evaluation of the investment (e.g., the net present value of installing a solar PV system). Within the economic evaluation, the agent is assumed to consider the following variables: (1) PV system size, (2) external and internal discount rate, (3) electricity price, (4) PV system price, (5) self-consumption rate, (6) irradiation, (7) scale effects, (8) performance ratio, (9) orientation ratio. Please, see the section of state variables for a description of these elements.

1.2.4. Interaction

The agents only interact with each other through peer-effects.

1.2.5. Stochasticity

There are several sources of stochasticity in our model that allow a more realistic representation of the uncertainties surrounding the evolution of deployment of a new technology.

Several attributes of the agents are distributed randomly. (1) The solar PV system size an agent would install is distributed randomly using an empirical distribution for each agent category, see section 8. (2) The environmental awareness of each agent is assigned randomly from an assumed normal distribution. (3) The personal discount rate of each agent is assigned randomly from an assumed normal distribution. (4) The losses or gains from the orientation, shading and other factors in the installation of each solar PV system are represented by assigning a factor randomly to each agent from an assumed normal distribution. (5) The self-consumption rate of each agent is randomly assigned from an assumed normal distribution around the mean self-consumption rate for each category. (5) The location of each agent, though proportional to the residential buildings density in Germany, can change from one simulation run to another. This influences several variables in the model such as irradiation or peer-effects. (6) Prices of solar PV systems are allowed to oscillate slightly around the evolution determined by the experience curves to represent noise in technology prices.

1.2.6. Collectives

The agents are classified in three categories: residential, commercial and industrial, and utility-scale. Each category establishes different values for self-consumption rates or electricity prices, among others. However, the categories cannot be seen as collective since agents do not form any ties with members of the same or other categories that would influence their behaviors.

1.2.7. Observation

The observer is able to measure several variables in the model. (1) The capacity of installations by the agents every month. (2) The policy costs incurred in inducing each adopter to install. (3) The subsidies distributed to each adopter above those needed to induce it to install (i.e. windfall profits). (4) The price of solar PV systems. (5) Installations outside of Germany. These five variables are used by the observer for (1) the adjustment of the policy incentives, and (2) the adjustment of technology prices.

1.3. Detailed process description

This section contains an in-detail description of the main processes in the model.

1.3.1. Initialization

The model is initialized to a month previous to the beginning of the policy (in April 2000). In particular, to December 1991. This ensures all state variables evolve correctly before the entry in force of the policy.

The initialization of the model contains the creation of the geographical patches, and the assignment of their state variables (e.g., irradiation level). This is the same for all simulation runs and based on historical data.

The initialization of the agents contains the creation of the agents, and the assignment of their state variables, which may vary from one simulation run to another. According to historical data and the scaling factor of 1:1000, 16,891 residential consumers, 3,853 commercial and industrial consumers, and 85 utility-scale consumers are created. Each agent is then randomly assigned a solar PV system size using the empirical distributions for each category derived from historical installations in Germany, see section 8. The agent's self-consumption is also randomly assigned following a normal distribution with a mean that depends on the agent's category and an assumed standard deviation of 0.05. The means for each distribution are based on historical data.[7]

Independently of their category, each agent is then assigned a discount rate, PV orientation, and environmental awareness. The agent's discount rate is taken randomly from an assumed normal distribution of mean zero and standard deviation 1. In order to account for the heterogeneity of solar installations (e.g., orientation, tilt, shading), each agent has a production factor randomly assigned from an assumed normal distribution of mean 0.9 and standard deviation 0.2. Each agent has an environmental awareness between zero and one, following an assumed, truncated normal distribution of mean 0.5 and standard deviation 0.2. One out of 10,000 agents is assumed to already have a solar PV system installed (around 2 agents per simulation). This was done to allow some early adopters though its impact on the results is negligible.

Each agent is then placed in a different part of Germany distributed according to the residential buildings' density, where it receives an annual irradiation based on its location.[4,19]

Prices of solar PV systems are initialized by calculating the price of solar PV modules and non-module components based on the cumulative installations in Germany and the rest of the World in December 1991, see section 9. These values are always the same for all simulation runs. The price of electricity or the discount rates are based on historical data and always the same across simulation runs.

Except for the historical scenario, in which feed-in tariff values linked to the electricity prices are used – in accordance to the Electricity Feed-in Act of 1990[23], policy incentives do not exist at the beginning of the simulation. Therefore, all policy-related variables are initialized at zero (e.g., policy costs, windfall profits).

1.3.2. Input

During the simulations, the model uses historical data to represent the evolution over time of several variables. (1) Installations of solar photovoltaics out of Germany. The cumulative installed capacity at a monthly resolution is used to update the price of solar PV modules and the available information to agents, see sections 8 and 12. (2) Electricity prices for consumers and for solar producers, see section 10. (3) Discount rates for agents' categories and for the government, see section 11.

The historical data employed for these variables comes from public sources detailed in each section.

1.3.3. Sub-models

This section describes in detail the main sub-models in our model, as well as key remaining concepts such as the model outputs.

Model outputs

The model outputs are the deployment of the technology, the policy costs and the windfall profits, which allow us to evaluate to what extent each adjustment mechanism ensures the policy is (1) effective and (2) cost-efficient, and (3) whether and to which extent the mechanism prevents windfall profits.

The deployment of the technology is measured by the installed capacity of solar photovoltaics [in Watt peak]. Policy costs are calculated as the support costs of feed-in tariff payments over the duration of the contract with each adopter, allocated to the month of installation, see equation (A.1).

$$\text{Policy costs [bn EUR]} = \sum_{\text{year}=1}^{20} \frac{\left(\text{Feed-in tariff}_0 \text{ - Wholesale electricity market price}_{\text{year}}\right) \cdot \text{Solar generation} \cdot (1\text{-Self-consumption})}{(1 + \text{Government discount rate})^{\text{year}}} \tag{A.1}$$

Policy cost derives from paying to adopters the difference between the feed-in tariff and the wholesale electricity market price. Simulating the complex price-formation mechanisms of Germany's wholesale electricity prices exceeded the scope of our model. Instead, we rely on historical annual prices until 2016, after which we assume yearly 1.5% increases (see supplementary information).[24] The government's discount rate for the month of installation is represented by the historical interest rates of German bonds.[16] Our accounting procedure includes future payments, which prevents a direct comparison with historical data that reports annual payments, but enables a more comprehensive evaluation of the cost of the policy.[25]

Windfall profits are the sum of subsidies paid to each adopter above what was required to induce it to invest. Since the agents only require a non-negative net present value (NPV) to invest in solar PV, any incentives inducing a positive NPV – or increasing an already positive NPV – are windfall profits for adopters and unnecessary costs for policymakers, see equation (A.2). Policy costs include both windfall profits and subsidies required to motivate adoption.

$$\text{Windfall profits [bn EUR]} = \begin{Bmatrix} \text{if NPV}_{\text{no-policy}} > 0, & \text{NPV - NPV}_{\text{no-policy}} \\ \text{if NPV}_{\text{no-policy}} \leq 0, & \text{NPV} \end{Bmatrix} \tag{A.2}$$

Modules

After updating the monitoring and time-keeping variables, the model proceeds through its three modules in the following order. (1) Policy adjustment – incentives are modified attending to the deviation from policy targets. (2) Adoption decision-making – the individual agents determine if they install or not. (3) Technological learning – the price of solar PV systems decreases according to cumulative installations in Germany and the rest of the world.

Simulations run from January 1992 to December 2016, while the policy is active between April 2000 to December 2016, the same period as the feed-in tariff for solar photovoltaics in Germany's Renewable Energy Sources Act.[11,26]

1) Policy adjustment

We evaluate three novel adjustment mechanisms that automatically modify policy incentives each month according to how much deployment, policy costs or profitability for adopters deviates from the policy targets.

The three mechanisms apply the same PID algorithm but respond to different variables depending on the formulation of the policy targets. (1) **Deployment targets** set a desired cumulative installed capacity at the end of the policy. (2) **Policy cost targets** establish a total budget for support costs, including future payments, to be spent before the end of the policy. (3) **Profitability targets** determine a desired internal return rate for an average adopter, which is operationalized as the average household in Germany. Average values for residential agents and an annual solar yield of 950 kWh/kWp are used to estimate the internal rate of return.[7]

For deployment and policy cost targets, a linear and an approximately normal, bell-shaped distribution define two different temporal allocations of monthly targets. Profitability targets are kept the same for every month. Distributing deployment and policy costs targets uniformly was discarded based on early results that suggested very low cost-efficiencies.

The linear distribution increases monthly targets by the same amount every month, creating higher targets in later years in an attempt to benefit from lower technology costs. The steepness of the ramp-up depends on the overall policy target and active period of the policy (e.g., 201 months between April, 2000 and December, 2016), see equation (A.3).

$$\text{Policy target}_{\#\text{month}}\ [\text{MWp or m EUR}] = \#\text{month} \cdot \frac{\text{Overall policy target [MWp or m EUR]}}{\sum_0^{201} \#\text{month}} \tag{A.3}$$

The bell-shaped distribution intends to exploit the typical pattern of the diffusion of innovations by setting monthly targets that generate an s-shaped cumulative adoption curve.[27] Monthly targets are calculated from the cumulative adoption curve using a logistic function as the difference between one month and the following, see equation (A.4).

$$\text{Cumulative policy target}_{\#\text{month}}\ [\text{MWp or m EUR}] = \frac{\text{Overall policy target [MWp or m EUR]}}{(1 + \exp(-k \cdot (\#\text{month} - \text{month}_{\text{peak}}))} \tag{A.4}$$

To limit the influence of timing policy targets differently, $\text{month}_{\text{peak}}$ is set to 142 (i.e. February 2012) so that the linear and the bell-shaped distributions reach half their cumulative targets at the same time. Moreover, the steepness of the cumulative s-curve k is set to 0.07 so that it mirrors that of the historical cumulative installations curve in Germany.

The mechanisms calculate a correction of the incentives each month using a PID controller, an algorithm based on control theory principles. The objective is to correct the deviation from policy targets (i.e. *e* in equation (A.5)), which is measured as the difference between the actual and the targeted evolution of monthly installed capacity, support costs, or internal return rate for an average adopter, depending on how policy targets are formulated. The deviation is positive if the system falls short of the policy target and negative if the system exceeds it.

The mechanism tries to simultaneously correct the deviation from the monthly policy target during the previous month (i.e. proportional correction), compensate the cumulated deviation since the policy started (i.e. integrative correction), and prevent the growth of the deviation in the following month (i.e. derivative correction). The weighted sum of these corrections determines the adjustment of the incentives see equation (A.5). The proportionality constants were calibrated for each mechanism in order to minimize monthly deviations (see calibration section).

$$\text{Feed-in Tariff}_{\#month} = \text{Feed-in Tariff}_{\#month-1} + k_p \cdot e_{\#month-1} + k_i \cdot \sum_{t=1}^{\#month-1} e_t + k_d \cdot (e_{\#month-2} - e_{\#month-2}) \qquad \text{(A.5)}$$

2) Consumers' adoption decision-making

Once policy incentives are adjusted, agents decide to adopt or not following a two-step procedure to determine (a) if they develop the idea to invest, and (b) whether it is economically attractive. Agents without a solar PV system go through this process every month without learning or remembering previous months, even if they already developed the idea to install.

(a) Getting the idea

Agents first need to develop the idea of installing solar PV in the current month, which depends on the weighted sum of four variables: (i) **peer-effects**, (ii) **available information**, (iii) **environmental awareness**, and (iv) **attractiveness** of investing in solar PV.[22] The weight for each variable is determined during the model calibration.

Peer-effects – the influence of social interactions in the adoption of new products – has proven a driving force for the local diffusion of solar photovoltaics in multiple countries including Germany.[28] Our model represents this variable as the fraction of adopters over the number of neighbors around each agent in a 2 km radius. The radius is estimated during the model calibration.

Available information is a barrier to the diffusion of solar photovoltaics that is attenuated by news articles discussing the technology, among other information sources.[29] Our model represents this influence by how many new and cumulated news articles about solar PV are available to the agents each month. The diffusion of solar PV in Germany and the rest of the world determines the number of articles, following a relation estimated from historical data, see section 12.

Environmental awareness is a behavioral motivation for the adoption of solar photovoltaics even when the technology is not economically viable, inducing highly aware consumers to become early adopters.[27,30] In our model, each agent is assigned a constant awareness level between zero and one following a truncated normal distribution of mean 0.5 and standard deviation 0.2. We use this assumption based on the observation that diffusion of innovations emerge from an attitude towards technological adoption distributed normally across the population.[27]

Attractiveness of investing in solar PV improves the perceived gains from adopting and the satisfaction of adopters, both of which enhance word-of-mouth – a key driver of solar diffusion.[31,32] Attractiveness of investing in solar PV is modeled by the internal rate of return of adoption for an average household in Germany.

Agents develop the idea to install solar photovoltaics when the weighted sum of the four variables exceeds the threshold of 0.5, see equation (A.6). These four variables only take values between zero and one, and are weighted according to the results of the model calibration. The threshold to develop the idea is set to 0.5 and not calibrated with the model. This threshold refrains from any assumption regarding the likelihood of an agent to develop or not the idea to install. If the four ideation variables were to describe the likelihood of an individual agent to develop or not the idea to install solar photovoltaics, a threshold of 0.5 allocates the same likelihood to a positive (idea to install) and to a negative (no idea to install) outcome.

$$k_{\text{peer-effect}} \cdot \left(\frac{\text{neighborsPV}}{\text{neighbors}}\right) + k_{\text{info}} \cdot \text{ArticlesPV} + k_{\text{awareness}} \cdot \text{Awareness} + k_{\text{advantage}} \cdot \text{AverageIRR} > 0.5 \qquad \text{(A.6)}$$

(b) Economic evaluation

Agents enter the economic evaluation only after they develop the idea to install solar PV. Each agent calculates the net present value of the installation and decides to adopt if it is non-negative (i.e. the profitability of adopting matches or exceeds the agent's minimum to install), see equation (A.7). We represent the economic evaluation of the agents through a NPV calculation as it allows to set an agent-based threshold (i.e. non-negative NPV) for adoption, instead of other economic variables, such as payback period, which would force us to rely on self-declared willingness to invest of adopters.[33]

$$\text{NPV}_{\text{PV}}\,[\text{EUR}] = -\,\text{Investment cost [EUR]} + \sum_{\text{year}=0}^{20} \frac{\text{Avoided costs [EUR/yr] - O\&M costs [EUR/yr] + FIT revenues [EUR/yr]}}{(1+\text{discount rate})^{\text{year}}} \geq 0 \qquad \text{(A.7)}$$

Alternatively, highly environmentally aware agents would skip the economic evaluation and directly adopt. These agents represent early adopters and constitute 1.8% of the agents in our model. This fraction results from a 0.92 awareness threshold required to skip the economic evaluation that is estimated during the model calibration.

Agents going through the NPV calculation estimate investment costs from their system size, and the price of solar PV systems, see equation (A.8).

$$\text{Investment cost [EUR]} = \text{System size [kWp]} \cdot \text{PV system price [EUR/kWp]} \cdot \text{Scale effect [-]} \tag{A.8}$$

Scale effects reduce the system price as its size grows larger, see equation (A.9). The impact of scale is derived from historical observations and references to a 10 kWp system (see supplementary information).[14] For systems smaller than 1 kWp, the effect is constant at 1.2.

$$\text{Scale effect [-]} = 1.1246 \cdot \text{System size [kWp]}^{-0.051} \tag{A.9}$$

Avoided costs from self-consumption are considered a positive cash flow for adopters and are a function of the self-consumed share of the solar electricity generation, and electricity prices, see equation (A.10).

$$\text{Avoided costs [EUR/yr]} = \text{Self-consumption [-]} \cdot \text{Solar generation [kWh/yr]} \cdot \text{Electricity price [EUR/kWh]} \cdot \tag{A.10}$$

Revenue from policy incentives is another positive cash flow, which is determined by the feed-in tariff and the solar electricity fed to the grid, see equation (A.11).

$$\text{FIT revenues [EUR/yr]} = (1\text{-Self-consumption [-]}) \cdot \text{Solar generation [kWh/yr]} \cdot \text{Feed-in tariff [EUR/kWh]} \cdot \tag{A.11}$$

Operation and maintenance costs are the only negative cash flows, estimated to be 1.5% of the investment costs.[24]

Solar electricity generation is defined by the irradiation at the agent's location, system size, performance ratio between AC output and DC nominal power (set at 0.85), and production factor, which accounts for heterogeneity across installations (e.g., orientation, tilt, shading), see equation (A.12).[7] Production factors are randomly assigned for each installation from a normal distribution of mean 0.9 and standard deviation 0.2.

$$\text{Solar generation [kWh/yr]} = \text{Irradiation [kWh/kWp]} \cdot \text{System size [kWp]} \cdot \text{PV PR [-]} \cdot \text{Production factor [-]} \tag{A.12}$$

3) Technological learning

Solar PV system prices are comprised of module and non-module prices, which evolve according to one global and one national, one-factor experience curve respectively.[34,35] Solar modules prices depend on the cumulative installed capacity in Germany – determined monthly by the adoption of agents – and the rest of world – based on historical data.[18] Non-module elements prices (e.g., balance of system, installation services) depend only on the cumulative installed capacity in Germany.[36] Based on historical price data, the learning rate for solar modules is estimated 20.3% and for non-module elements 10.2%, see section 9.

Solar PV system prices randomly oscillate 5% around the experience curve prices to represent the noise in price signals. Price reductions are capped at 2% per month, based on historical data, to avoid excessive price volatility during the early months of the simulation.

Model and mechanism calibration

Two calibrations were required: (a) model calibration – to ensure the model reproduces historical patterns, and (b) mechanism calibration – to setup the PID controller.

1) Model calibration

The model is calibrated against the historical evolution of cumulative installed capacity in Germany between 1992 and 2016. The calibration parameters were five: (1,2,3) the weights of three of the variables influencing the development of ideas to adopt (NB: the fourth weighing is linearly dependent so that the four sum up to one), (4) the peer-effect radius, and (5) the awareness threshold to skip the economic evaluation.

These parameters were first approximated by trial and error to identify a value region where the historical pattern was achieved.[37] The definitive combination of parameters was then selected to minimize the sum of absolute monthly deviations from the historical curve (see Table A - 7 and Figure A - 3).

Table A - 7. Calibrated parameters of the model.

Calibration parameter	Unit	Estimated value	Value range
$k_{information}$	[-]	0.20	[0,1]
$k_{awareness}$	[-]	0.49	[0,1]
$k_{profitability}$	[-]	0.10	[0,1]
Peer-effect radius	[km]	2.00	[0,100][a]
High awareness threshold	[-]	0.92	[0,1]

[a]Arbitrarily limited to 100 km to maintain peer-effects as a local influence on adoption.

Our model includes stochastic processes that generate a unique setting for each simulation run. For this reason, the model calibration and results are derived from the statistical analysis of batches of simulations. Samples of 60 simulation runs were deemed representative of the model behaviour – an output variable mean deviates less than ±2.0% from its mean in a sample of 1,000 runs – and could be computed in a reasonable time (about 60 minutes) (see Figure A - 2).

The cumulative installations curve used for the calibration of the model combines yearly data up to 2009 extrapolated into monthly data (see Section 8) and monthly installation data from January 2009 from Germany's federal government. Due to changes in the enforcement of the obligation to register, there is a discrepancy in the installation data between the German transmission system operators and the federal government registry.[38] The difference of around 0.6 GWp in 2009 and in 2015 between the two sources does not affect the calibration of our model. However, it sensibly increases the final cumulative installed capacity at the end of 2016 from above 39 GWp to above 41 GWp.

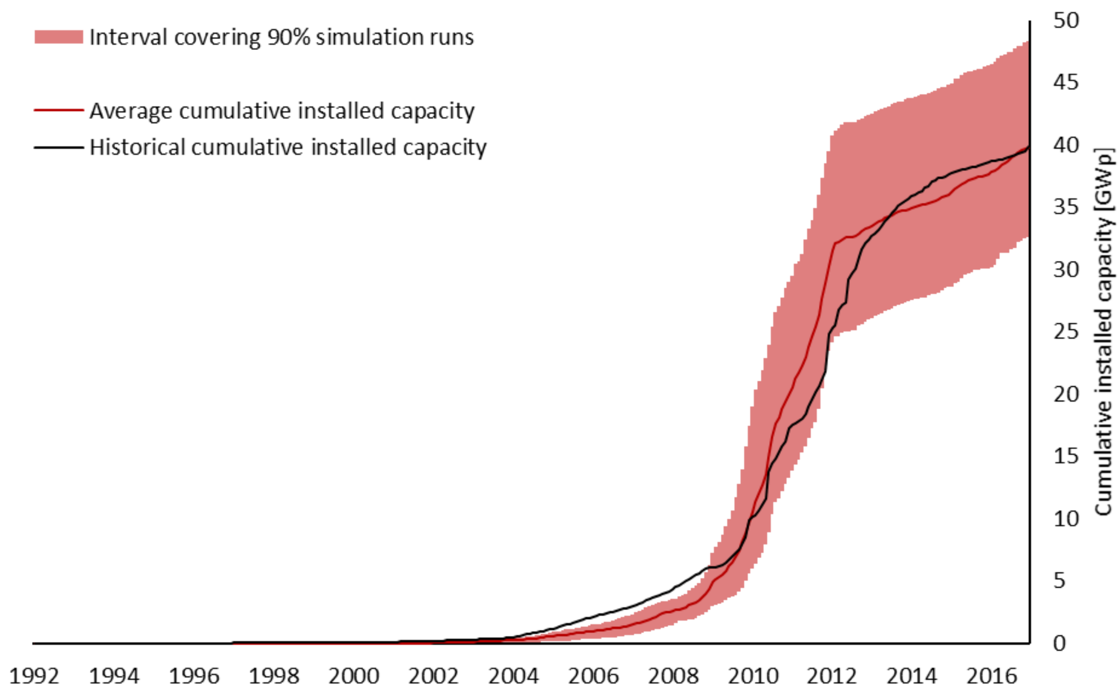

Figure A - 3. Average cumulative installed capacity of 1,000 simulation runs compared to the historical cumulative installed capacity in Germany between 1992 and 2016.

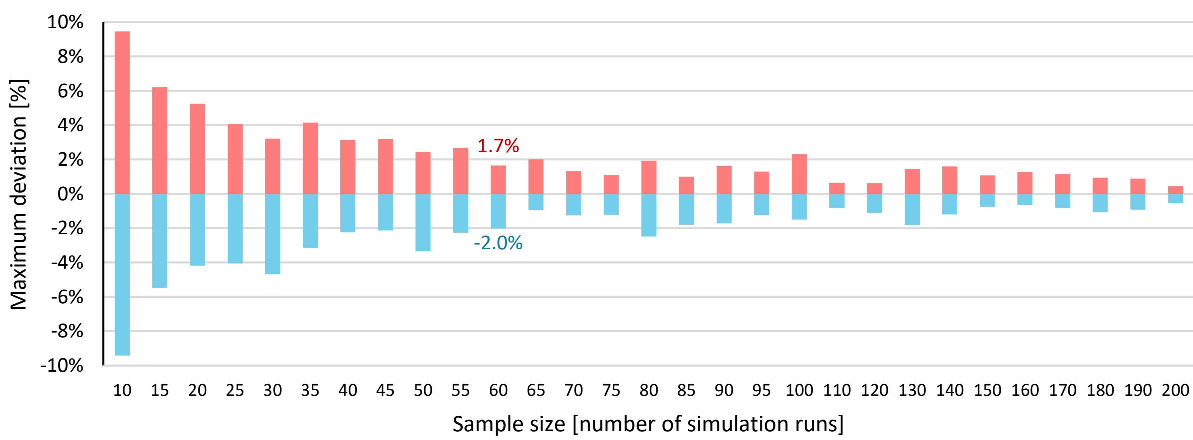

Figure A - 2. Maximum positive and negative deviations for different sample sizes from the average cumulative installed capacity in December 2016 from a sample of 1,000 simulation runs.

2) Mechanism calibration

PID controllers need to be tuned for the system and application they aim to regulate. In short, the user needs to determine the proportionality constants for each corrective element – proportional (k_p), integrative (k_i) and derivative (k_d). In our setting, these constants represent the policy's sensitivity to missing monthly targets, the overall target and deviation growth.

Higher values of k_p, k_i, k_d allow larger corrections, which increases the mechanism's ability to adjust incentives rapidly but also leads to bigger policy (and installations) fluctuations. In order to find a compromise value, the parameters were manually calibrated in sequential fashion (i.e. proportional, then proportional and integrative, and then all three). The calibration goal was to (1) minimize deviations from monthly policy targets while (2) limiting deviation from overall policy targets and (3) avoiding oscillating behaviour or installations stop-and-go. One set of parameters was calibrated for each adjustment mechanism. Manual tuning is often the best option to set PID controllers for complex systems whose behavior cannot be easily characterized such as this study's model.[39]

Table A - 8. PID controller parameters for the proportional, integrative and derivative corrections in the adjustment mechanism.

Policy targets	**Unit**	$\mathbf{k_p}$	$\mathbf{k_i}$	$\mathbf{k_d}$
Deployment	[€/kWh per MWp]	$3.50 \cdot 10^{-5}$	$1.70 \cdot 10^{-6}$	$1.00 \cdot 10^{-5}$
Policy cost	[€/kWh per € million]	$1.20 \cdot 10^{-5}$	$1.00 \cdot 10^{-6}$	$1.00 \cdot 10^{-7}$
Profitability	[€/kWh]	3.20	0.30	0.50

2. Historical adjustment mechanisms and ad hoc adjustments to the feed-in tariff for solar photovoltaics in Germany

The historical design of the feed-in tariff for solar photovoltaics in Germany established in the Electricity Feed-in Act in 1991 and the Renewable Energy Sources Act (EEG) in 2000, as well as the multiple changes to the latter until 2016, is represented in the historical policy scenario.[11,23] The feed-in tariff is adjusted over time using the following mechanisms:

- Annual adjustment according to electricity rates (January, 1992 to March, 2000)[*]
- Annual fixed degression (April, 2000 to December, 2008)
- Annual flexible degression (January, 2009 to March, 2012)
- Monthly flexible degression (April, 2012 to December, 2016)
- Ad hoc adjustments:
    - January, 2004: +25.60%
    - January, 2009: -8.00%
    - July, 2010: -13.00%
    - September, 2010: -3.00%
    - April, 2012: -20.18%

The detailed description of these mechanisms and other prominent characteristic of the historical policy design can be found in Table A - 9. The information contained in Table A - 9 was directly extracted from the legal documents cited in the table, and contrasted with the information in Gründinger (2017) and Grau (2014).[40,41]

Ad hoc adjustments are represented as percentage changes to the feed-in tariff instead of setting their absolute values in order to allow the historical adjustment mechanisms to respond to the evolution of deployment in each simulation run in slightly different ways from the historical pattern. This allows for a fairer comparison of the abilities of the historical adjustment mechanisms and the three novel mechanisms to (a) maintain the deployment policy effective and (b) efficient, but also to (c) contain windfall profits, and to (d) reduce the uncertainty about policy outcomes. The Figure A - 8 shows the resulting evolutions of the feed-in tariff for the individual runs of the historical policy scenario.

We take the historical feed-in tariff values for residential, rooftop solar PV systems are our reference. The feed-in tariffs for medium and large systems are set by reducing the residential feed-in tariff by 10% and 30%. These reductions apply throughout the whole simulation and are based on the average relation of between feed-in tariffs for smaller and larger systems between 2004 and 2016.

[*] No installations occur during this period in the simulations of the historical policy scenario due to the very low economic incentives, the scarce information available, nil peer effects, and the effect of scaling the population.

Table A - 9. Review of historical adjustment mechanisms for feed-in tariff for solar photovoltaics in Germany between 1991 and 2016.

Legislation	Entry in force	Adjustment mechanism	Frequency	Rationale of adjustment	Other characteristics
Electricity Feed-in Act[23]	1 January 1991	-	-	Feed-in tariff at least 90% of average revenue from the delivery of electricity by electricity utilities to all final consumer.	
Renewable Energy Sources Act 2000[11]	1 April 2000	Fixed degression	Annual	Each year the feed-in tariff decreases 5% compared to the previous year, starting in 1 January 2002 (§ 8 1).	• Initial feed-in tariff set at 0.5062 EUR per kWh (§ 8 1) • 350 MWp per year cap for 2000 and 2001 (§ 8 2) • 1,000 MWp per year cap for 2002 and 2003 (23 July 2002 (BGBI. I S. 2778) Art. 7)[42] • Rooftop systems larger than 5,000 kWp are not eligible (§ 2 2.3) • Ground systems larger than 100 kWp are not eligible (§ 2 2.3)
PV Interim Act 2003[43]	1 January 2004	Fixed degression	Annual	Each year the feed-in tariff decreases 5% compared to the previous year, starting in 1 January 2005 (Art. 2).	• Removal of installed capacity caps (Art. 1) • Ground systems larger than 100 kWp become eligible, but only if located in designated areas (Art. 2). • The feed-in tariff is set to 0.457 EUR/kWh (Art. 2) • For rooftop systems, the feed-in tariff is set according to size (Art. 2): ○ Up to 30 kWp, 0.574 EUR/kWh ○ Between 30 kWp and 100 kWp, 0.546 EUR/kWh ○ Larger than 100 kWp, 0.54 EUR/kWh
Renewable Energy Sources Act 2004[44]	1 August 2004	Fixed degression	Annual	• Each year the feed-in tariffs decreases 5% compared to previous year starting in 1 January 2006 (§ 11 5) • For free standing systems, the tariff decreases by 6.5% starting in 1 January 2006 (§ 11 5)	• Sets overall goal of 12.5% of final energy consumption from renewable energy sources by 2010, and at least 20% by 2020 (§ 1 2) • The feed-in tariff is set to 0.457 EUR/kWh (§ 11 1) • For rooftop systems, the feed-in tariff is set according to size (§ 11 2): ○ Up to 30 kWp, 0.574 EUR/kWh ○ Between 30 kWp and 100 kWp, 0.546 EUR/kWh ○ Larger than 100 kWp, 0.54 EUR/kWh

Renewable Energy Sources Act 2009[45]	1 January 2009	Flexible degression	Annual	• For ground systems (§ 20 2.8.a), feed-in tariff decreases by: ○ 10% by 1 January 2010 ○ 9% yearly since 1 January 2011 • For rooftop systems (§ 20 2.8.b): ○ Up to 100 kWp, feed-in tariff decreases ▪ 8% by 1 January 2010 ▪ 9% yearly since 1 January 2011 ○ More than 100 kWp, feed-in tariff decreases ▪ 10% by 1 January 2010 ▪ 9% yearly since 1 January 2011 • For all systems (§ 20 2.a): ○ Degression rate increases by 1% if installed capacity ▪ In 2009 exceeds 1,500 MWp ▪ In 2010 exceeds 1,700 MWp ▪ In 2011 exceeds 1,900 MWp ○ Degression rate decreases by 1% if installed capacity ▪ In 2009 is smaller than 1,000 MWp ▪ In 2010 is smaller than 1,100 MWp ▪ In 2011 is smaller than 1,200 MWp • The installed capacity in the previous year is calculated between 1 October and 30 September, published every year the 31 October (§ 20 2.a).	• Sets overall goal of 30% of electricity consumption from renewable energy sources by 2020 (§ 2) • The feed-in tariff is set to 0.3194 EUR/kWh (§ 32) • For rooftop systems (§ 33), the feed-in tariff is set according to size: ○ Up to 30 kWp, 0.4301 EUR/kWh ○ Between 30 kWp and 100 kWp, 0.4091 EUR/kWh ○ Between 100 kWp and 1,000 kWp, 0.3958 EUR/kWp ○ Larger than 1,000 kWp, 0.33 EUR/kWh
PV Act 2010[46]	1 July 2010	Flexible degression	Annual	• For ground systems (Art. 1 2.a.bb.aaa), feed-in tariff decreases 11% in 1 January 2010 • For rooftop systems (Art. 1 2.a.bb.bbb) feed-in tariff decreases in 1 January 2010 by: ○ Up to 100 kWp, 9% ○ More than 100 kWp, 11% • For all systems (Art. 1 2.d), the degression rate for 2011 is the used for 2010 (see above) adjusted according to the installed capacity between 31 May 2010 and 1 October 2010: ○ Above 6,500 MWp, increase DR by 4% ○ Above 5,500 MWp, increase DR by 3% ○ Above 4,500 MWp, increase DR by 2% ○ Above 3,500 MWp, increase DR by 1% ○ Below 2,500 MWp, reduce DR by 1% ○ Below 2,000 MWp, reduce DR by 2% ○ Below 1,500 MWp, reduce DR by 3% • For all systems (Art. 1 2.d), the degression rate for 2012 and the following years is the used for the previous year adjusted according to the installed capacity in the twelve months prior to 30 September of the previous year: ○ Above 6,500 MWp, increase DR by 12% ○ Above 5,500 MWp, increase DR by 9% ○ Above 4,500 MWp, increase DR by 6% ○ Above 3,500 MWp, increase DR by 3% ○ Below 2,500 MWp, reduce DR by 2.5% ○ Below 2,000 MWp, reduce DR by 5% ○ Below 1,500 MWp, reduce DR by 7.5%	• For ground systems (Art. 1 2.d), the feed-in tariff level is lowered: ○ 12% if the system entered in operation after 30 June 2010 ○ An additional 3% if the system entered in operation after 30 September 2010 • For rooftop systems (Art. 1 2.d), the feed-in tariff is lowered: ○ 13% if the system entered in operation after 30 June 2010 ○ An additional 3% if the system entered in operation after 30 September 2010. ○ Rooftop systems that enter into operation before 1 January 2011, but were developed before 25 March 2010, are excluded.

PV Interim Act 2011[47]	1 July 2011	Flexible degression	Annual* (biannual if installed capacity exceeds target)	• For all systems, the degression rate is 9% (Art. 1 17) • The degression rate is adjusted according to the installed capacity in the twelve months prior to 30 September of the previous year (Art. 1 §20a): ○ Above 7,500 MWp, increase DR by 15% ○ Above 6,500 MWp, increase DR by 12% ○ Above 5,500 MWp, increase DR by 9% ○ Above 4,500 MWp, increase DR by 6% ○ Above 3,500 MWp, increase DR by 3% ○ Between 2,500 MWp and 3,500 MWp, do not adjust the degression rate ○ Below 2,500 MWp, reduce DR by 2.5% ○ Below 2,000 MWp, reduce DR by 5% ○ Below 1,000 MWp, reduce DR by 7.5% • The feed-in tariff of the systems who enter in operation between 30 June and 1 January of the running year is adjusted by 1 July (1 September for ground-mounted systems Art. 13 2) if the installed capacity between 30 September of the previous year and 1 May of the running year (multiplied by 12/7) exceeds (Art. 1 §20a): ○ 7,500 MWp, decrease feed-in tariff by 15% ○ 6,500 MWp, decrease feed-in tariff by 12% ○ 5,500 MWp, decrease feed-in tariff by 9% ○ 4,500 MWp, decrease feed-in tariff by 6% ○ 3,500 MWp, decrease feed-in tariff by 3%	• Establishes the policy goals in terms of fraction of final electricity consumption from renewable energy sources as (Art. 1 2): ○ 35% by 2020 ○ 50% by 2030 ○ 65% by 2040 ○ 80% by 2050 • As the result of the flexible degression mechanism established in the PV Act 2010, the resulting discount rate was 13% and the remuneration levels:[48] ○ For ground-mounted systems 0.2111 EUR/kWh (Art. 1 32) ○ For rooftop systems (Art. 1 33), the feed-in tariff is set according to size: ▪ Up to 30 kWp, 0.2874 EUR/kWh ▪ Between 30 kWp and 100 kWp, 0.2733 EUR/kWh ▪ Between 100 kWp and 1,000 kWp, 0.2586 EUR/kWp ▪ Larger than 1 MWp, 0.2156 EUR/kWh • In 1 July 2011, no adjustment took place because the installed capacity between 28 February 2011 and 1 June 2011 (multiplied by 4) [EEG 2009 v. 1 May 2011 §20 (4)] was below 3.5 GWp.[49,50]
Renewable Energy Sources Act 2012[51]	1 January 2012	Flexible degression	Annual* (biannual if installed capacity exceeds target)	• For all systems, the degression rate is 9% (§ 20 a.2) • The degression rate is adjusted according to the installed capacity in the twelve months prior to 30 September of the previous year (§ 20 a.3 and 4): ○ Above 7,500 MWp, increase DR by 15% ○ Above 6,500 MWp, increase DR by 12% ○ Above 5,500 MWp, increase DR by 9% ○ Above 4,500 MWp, increase DR by 6% ○ Above 3,500 MWp, increase DR by 3% ○ Between 2,500 MWp and 3,500 MWp, do not adjust DR ○ Below 2,500 MWp, reduce DR by 2.5% ○ Below 2,000 MWp, reduce DR by 5% ○ Below 1,000 MWp, reduce DR by 7.5% • The feed-in tariff of the systems who enter in operation between 30 June and 1 January of the running year is adjusted by 1 July if the installed capacity in the twelve months prior to 1 May of the running year (multiplied by 12/7) exceeds (§ 20 a.5): ○ 7,500 MWp, decrease feed-in tariff by 15% ○ 6,500 MWp, decrease feed-in tariff by 12% ○ 5,500 MWp, decrease feed-in tariff by 9% ○ 4,500 MWp, decrease feed-in tariff by 6% ○ 3,500 MWp, decrease feed-in tariff by 3%	• As the result of the flexible degression mechanism established in the PV Interim Act 2011, the resulting discount rate was 15% and the remuneration levels:[52] • For ground-mounted systems 0.1794 EUR/kWh (§ 32 1) • For rooftop systems (§ 33), the feed-in tariff is set according to size: ○ Up to 30 kWp, 0.2443 EUR/kWh ○ Between 30 kWp and 100 kWp, 0.2323 EUR/kWh ○ Between 100 kWp and 1,000 kWp, 0.2198 EUR/kWp ○ Larger than 1,000 kWp, 0.1833 EUR/kWh

PV Act 2012[53]	1 April 2012 (retroactively)	Flexible degression	Monthly	• For all systems, the degression rate is 1% (Art. 7) • The degression rate is adjusted at the beginning of each quarter (1 January, 1 April, 1 July, 1 October) according to the installed capacity during the previous qualifying period (Art. 7): ○ Above 7,500 MWp, increase DR by 1.8% ○ Above 6,500 MWp, increase DR by 1.5% ○ Above 5,500 MWp, increase DR by 1.2% ○ Above 4,500 MWp, increase DR by 0.8% ○ Above 3,500 MWp, increase DR by 0.4% ○ Between 2,500 MWp and 3,500 MWp, do not adjust the degression rate ○ Below 2,500 MWp, reduce DR by 0.25% ○ Below 2,000 MWp, reduce DR by 0.5% ○ Below 1,000 MWp, reduce DR to zero ○ Below 500 MWp, reduce DR to zero and increase the feed-in tariff 1.5% the first month of the quarterly • The qualifying periods to calculate the installed capacity for the adjustment of the degression rate are as follow: ○ Between 30 June 2012 and 1 October 2012, for the degression rate applied starting in 1 November 2012 – multiplied by 4. ○ Between 30 June 2012 and 1 January 2013, for the degression rate applied starting in 1 February 2013 – multiplied by 2. ○ Between 30 June 2012 and 1 April 2013, for the degression rate applied starting in 1 May 2013 – multiplied by 4/3. ○ Between 30 June 2012 and 1 July 2013, for the degression rate applied starting in 1 August 2013 ○ Between the last day of the fourteenth previous month to the month of application of the degression rate and the first day of the month immediately previous to it.	• Explicit goal of installing between 2,500 and 3,500 MWp of solar photovoltaics per year (Art. 7). • Limit on total eligible capacity of 52,000 MWp (Art. 7). • The feed-in tariff is set to 0.1350 EUR/kWh (Art. 11). • For rooftop systems (Art. 11), the feed-in tariff is set according to size: ○ Up to 10 kWp, 0.1950 EUR/kWh ○ Between 10 kWp and 40 kWp, 0.1850 EUR/kWh ○ Between 40 kWp and 1,000 kWp, 0.1650 EUR/kWp ○ Larger than 1,000 kWp, 0.1350 EUR/kWh • Systems larger than 10,000 kWp become non-eligible (Art. 11). • Entered in force retroactively in 1 April 2012 (Art. 11) (the amendment was published in 17 August 2012). • Possibility to switch to a market premium incentive.

Renewable Energy Sources Act 2014[12]	1 August 2014	Flexible degression	Monthly	• For all systems, the degression rate is 0.5% (§ 31 2) • The degression rate is adjusted at the beginning of each quarter (1 January, 1 April, 1 July, 1 October) according to the installed capacity during the previous qualifying period (§ 31 2-4): ○ Above 7,500 MWp, use a DR of 2.8% ○ Above 6,500 MWp, use a DR of 2.5% ○ Above 5,500 MWp, use a DR of 2.2% ○ Above 4,500 MWp, use a DR of 1.8% ○ Above 3,500 MWp, use a DR of 1.4% ○ Above 2,600 MWp, use a DR of 1.0% ○ Between 2,400 MWp and 2,600 MWp, do not adjust the degression rate ○ Below 2,400 MWp, use a DR of 0.25% ○ Below 1,500 MWp, use a DR of zero ○ Below 1,000 MWp, use a DR of zero and increase the feed-in tariff 1.5% once, on the first month of the corresponding quarterly • The qualifying periods to calculate the installed capacity for the adjustment is between the last day of the fourteenth previous month to the month of application of the degression rate and the first day of the month immediately previous to it (§ 31 2-4).	• Establishes the policy goals in terms of fraction of final electricity consumption from renewable energy sources as (§ 1 2): ○ 35% by 2020 ○ 50% by 2030 ○ 65% by 2040 ○ 80% by 2050 • Explicit goal of installing 2,500 MWp per year of solar photovoltaic systems (§ 3). • The feed-in tariff is set to 0.0923 EUR/kWh (§ 51 1). • For rooftop systems (Art. 11), the feed-in tariff is set according to size: ○ Up to 10 kWp, 0.1315 EUR/kWh ○ Between 10 kWp and 40 kWp, 0.1280 EUR/kWh ○ Between 40 kWp and 1,000 kWp, 0.1149 EUR/kWp ○ Larger than 1,000 kWp, 0.0923 EUR/kWh • Possibility to switch to a market premium incentive.

3. Additional information on the main results

In this section, the Table A - 10 gathers the median outcomes for the key policy variables in all scenarios and the interval around those values that cover 90% of the simulation runs.

The Figure A - 4 displays the relation between the amount of windfall profits and the policy cost-efficiency for the 60 individual simulation runs for each scenario. This figure shows that (1) adjusting incentives according to profitability targets limit windfall profits to a narrow range around a value that grows with the target (e.g., around €9 bn for the IRR-5% scenario and €40 bn for the IRR-9% scenario). (2) A relation between windfall profits and the policy's cost-efficiency is apparent in the DEP and COST scenarios, which is stronger when the adjustment mechanisms responds to the evolution of policy costs.

For the same decrease in windfall profits, the policy's cost-efficiency increases more if incentives are adjusted in response to policy costs that to deployment. This result is a consequence of the design of the adjustment mechanisms. Less windfall profits do not influence installations because agents would install as long as the incentives ensure a non-negative present value of the investment. However, less windfall profits directly translates into less policy costs. Faced with a reduction in windfall profits, an adjustment mechanism responding to policy costs would either (a) reduce less the incentives – if policy costs are above policy targets – or (b) increase the incentives – if policy costs are below policy targets. Either case, the result is higher incentives if windfall profits reduce, which encourages adoption and improve the policy's cost-efficiency.

Finally, the figures Figure A - 5, Figure A - 6, Figure A - 7 and Figure A - 8 show the evolutions of the feed-in tariffs and cumulative installed capacities of the 60 individual simulation runs for each scenario. These figures show how the fluctuations of feed-in tariffs in the individual simulation runs is larger than suggested by the median outcomes, particularly for the later months in the DEP and COST scenarios, see figures Figure A - 5 and Figure A - 6. For future research or practical implementations, we anticipate several paths to reduce fluctuations without endangering the benefits of the novel adjustment mechanisms. (1) Calibrating the PID algorithm to each mechanism – currently, the mechanisms responding to the same policy variable (e.g., DEP-L and DEP-B) share the same PID parameters to facilitate the comparison between them. (2) Adjusting the feed-in tariff for small, medium and large solar PV systems independently. Since medium and large installations have a disproportionately large impact on the evolution of deployment, policy costs or technology prices, adjusting feed-in tariffs separately would allow for smoother evolutions. (3) Estimating the deviation from policy targets in relative rather than absolute terms might be a third option. In the current design, a deviation of e.g., 100 MWp from the policy targets results in the same correction of the feed-in tariff whether the policy target is e.g., 1 MWp or 100 MWp.

Table A - 10. Summary of key policy outcomes for all scenarios.

The median value from 60 simulations is reported together with the distance to the upper and lower boundaries of the interval around the median covering 90% of the simulations. The statistical significance of the difference between the average outcome to the average outcome of the historical scenario is reported.

	Total Installed Capacity (median) [GWp]	Total Policy Cost (median) [bn EUR]	Windfall Profits (median) [% of policy cost]	Policy Cost Efficiency (median) [Wp / EUR]
HIST	41.0	114.1	18.7%	0.36
	(-2.6,+11)	(-10.5,+28.7)	(-1.4,+3.7)	(-0.02,+0.03)
DEP-L	*41.1*	154.5	33.1%	0.27
	(-0.6,+1.4)	(-19.9,+10.6)	(-6.3,+3.1)	(-0.02,+0.04)
DEP-S	<u>42.2</u>	108.8	17.7%	0.39
	(-0.4,+0.9)	(-21.9,+4.4)	(-8,+1.6)	(-0.01,+0.09)
COST-L	48.6	<u>114.5</u>	18.1%	0.42
	(-1.9,+5)	(-1.1,+1.8)	(-2.7,+2)	(-0.02,+0.05)
COST-S	50.9	<u>117.0</u>	15.5%	0.44
	(-2.3,+7.5)	(-0.7,+1.4)	(-1.9,+1.3)	(-0.02,+0.06)
IRR-5%	29.6	72.2	12.8%	0.41
	(-2.6,+8)	(-4.3,+9.5)	(-1.3,+1)	(-0.02,+0.06)
IRR-7%	<u>41.8</u>	<u>116.9</u>	<u>18.7%</u>	<u>0.36</u>
	(-2.2,+6.5)	(-4.1,+10.5)	(-1.2,+1.6)	(-0.01,+0.03)
IRR-9%	51.0	162.7	25.2%	0.31
	(-3.3,+7.9)	(-7.3,+16.6)	(-1.7,+1.8)	(-0.01,+0.03)

The average of each policy outcome for each mechanism is statistically different from the outcomes of the historical scenario (HIST) with a confidence level exceeding 99.999% according to a two-tailed t-test robust to heteroskedaticity. The confidence level for values in *italics* is 95% or higher and for <u>underlined</u> values between 65% and 95%.

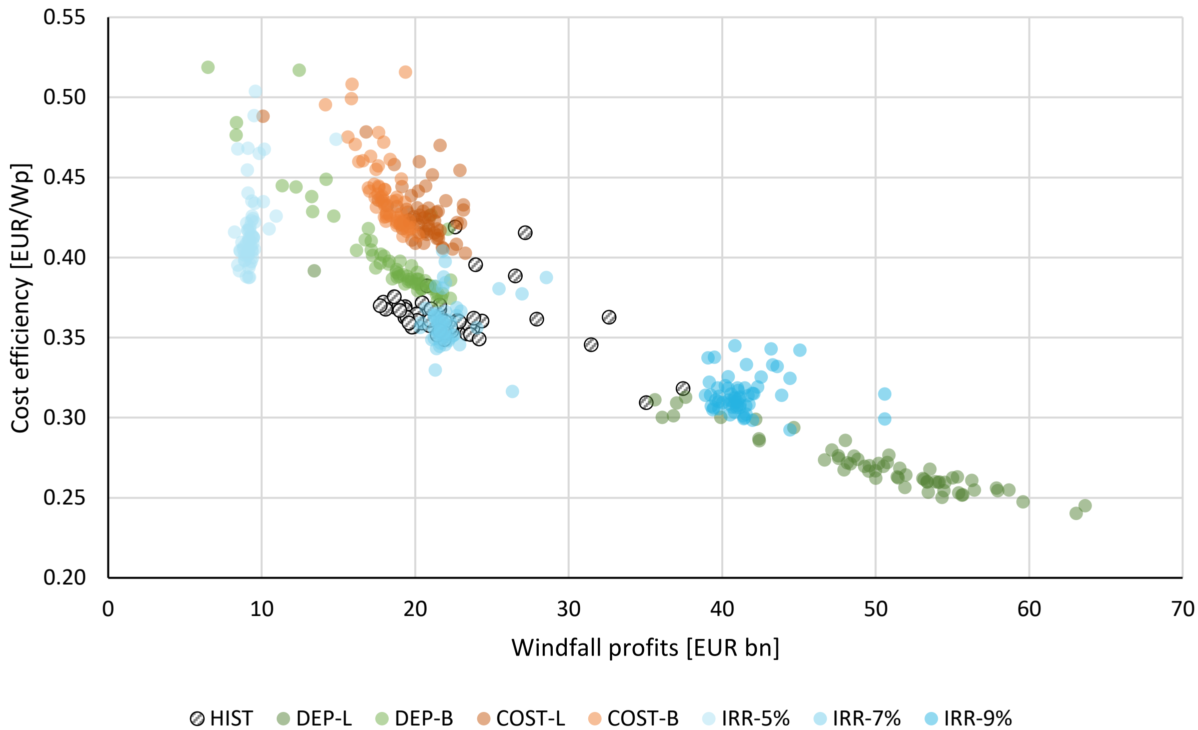

Figure A - 4. Policy cost-efficiency and windfall profits for the individual simulation runs of the eight scenarios.

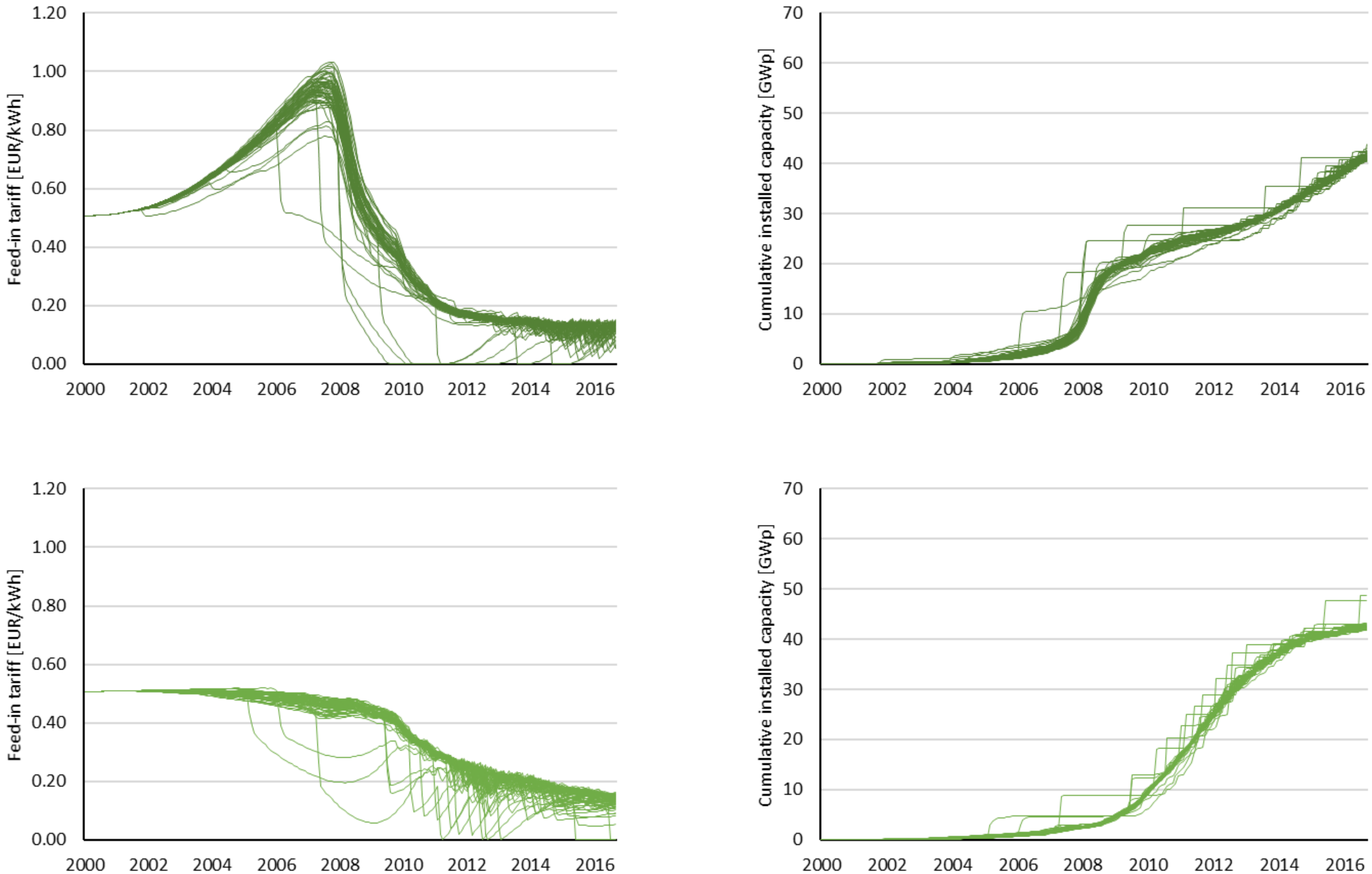

Figure A - 5 Feed-in tariff and cumulative installed capacity evolutions in individual runs of the scenarios using deployment goals. Top: DEP-L. Bottom: DEP-B.

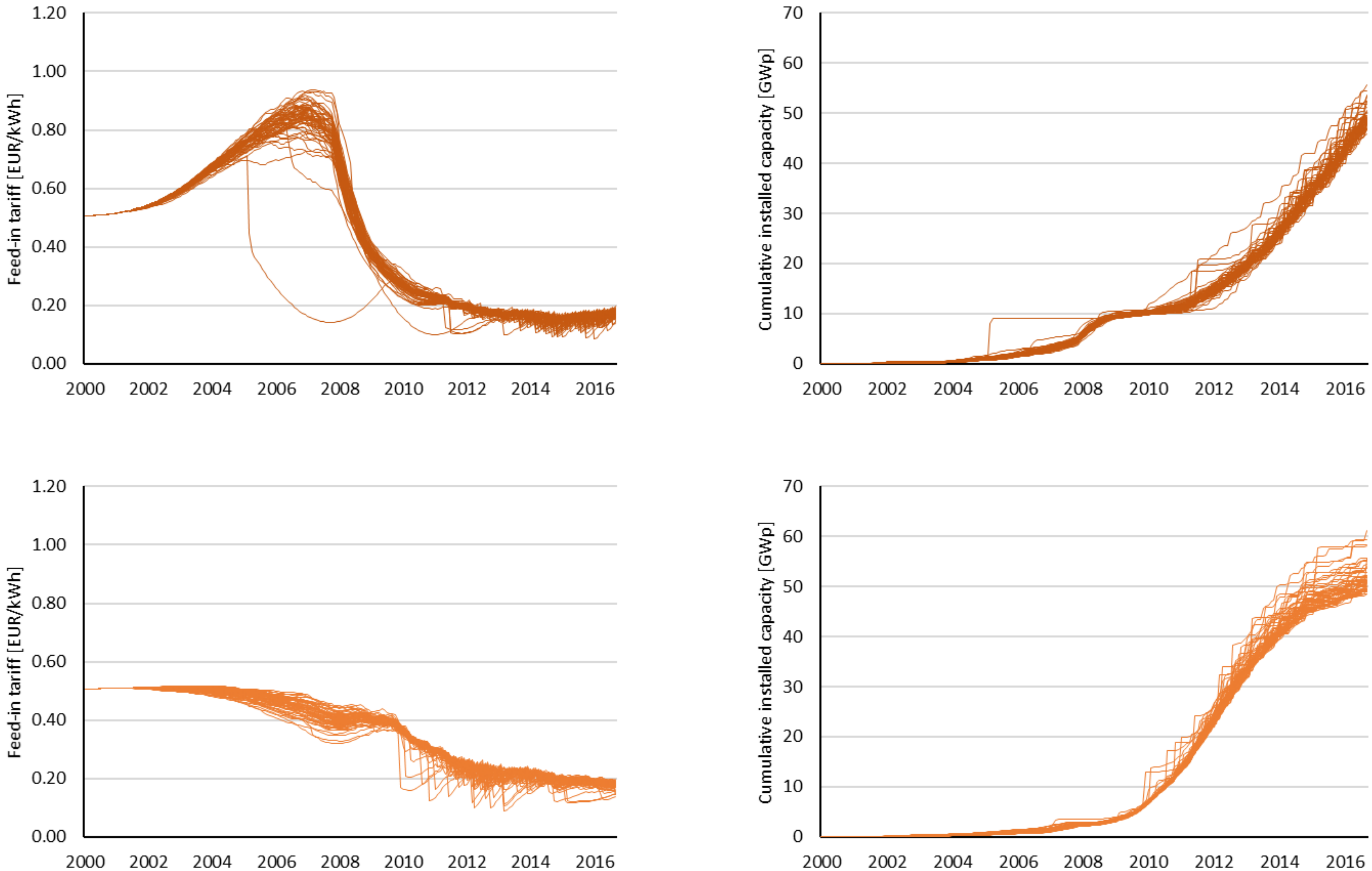

Figure A - 6 Feed-in tariff and cumulative installed capacity evolutions in individual runs of the scenarios using policy cost goals. Top: COST-L. Bottom: COST-B.

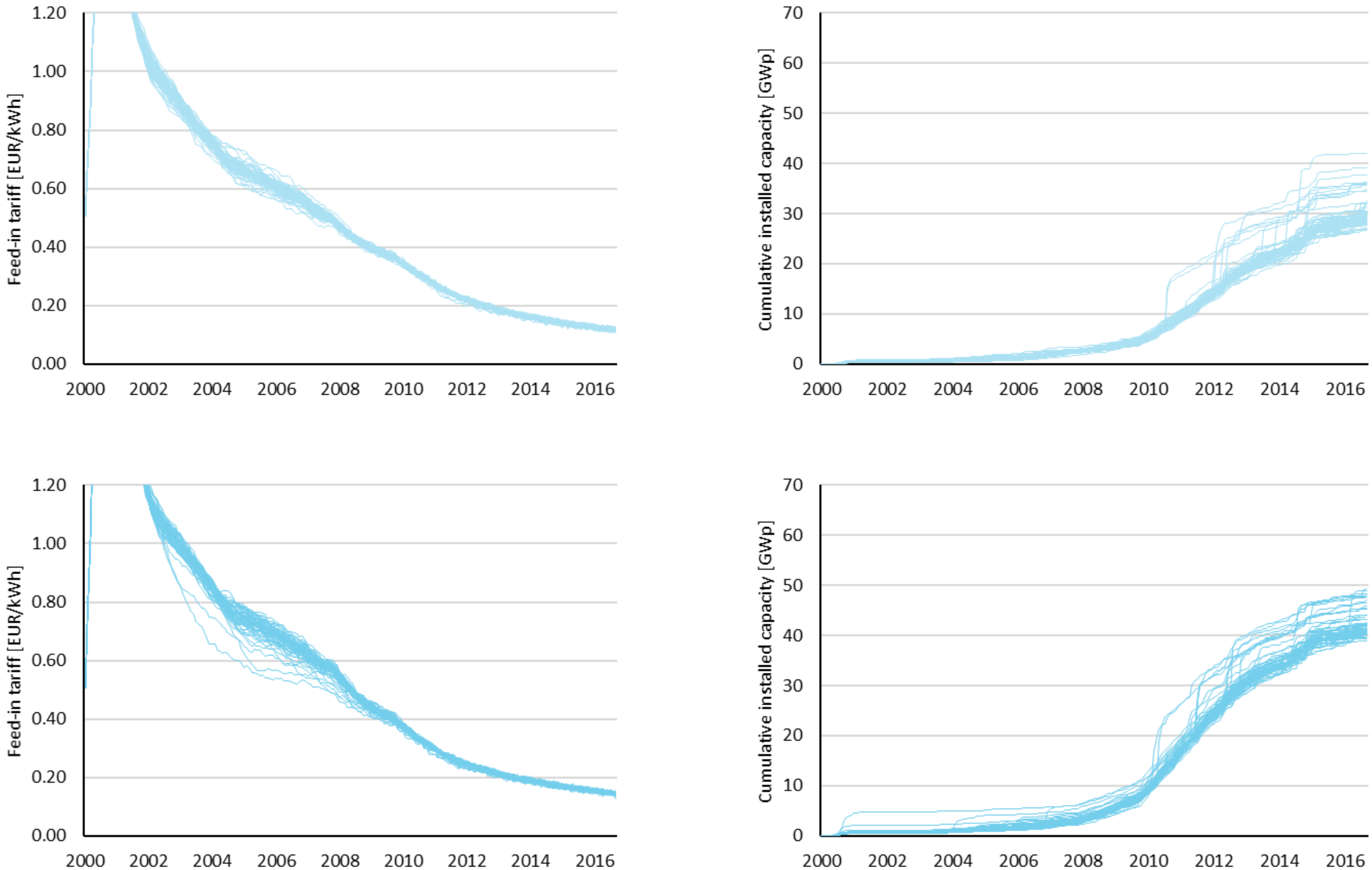

Figure A - 7. Feed-in tariff and cumulative installed capacity evolutions in individual runs of the scenarios using profitability goals. Top: IRR-5%. Bottom: IRR-7%.

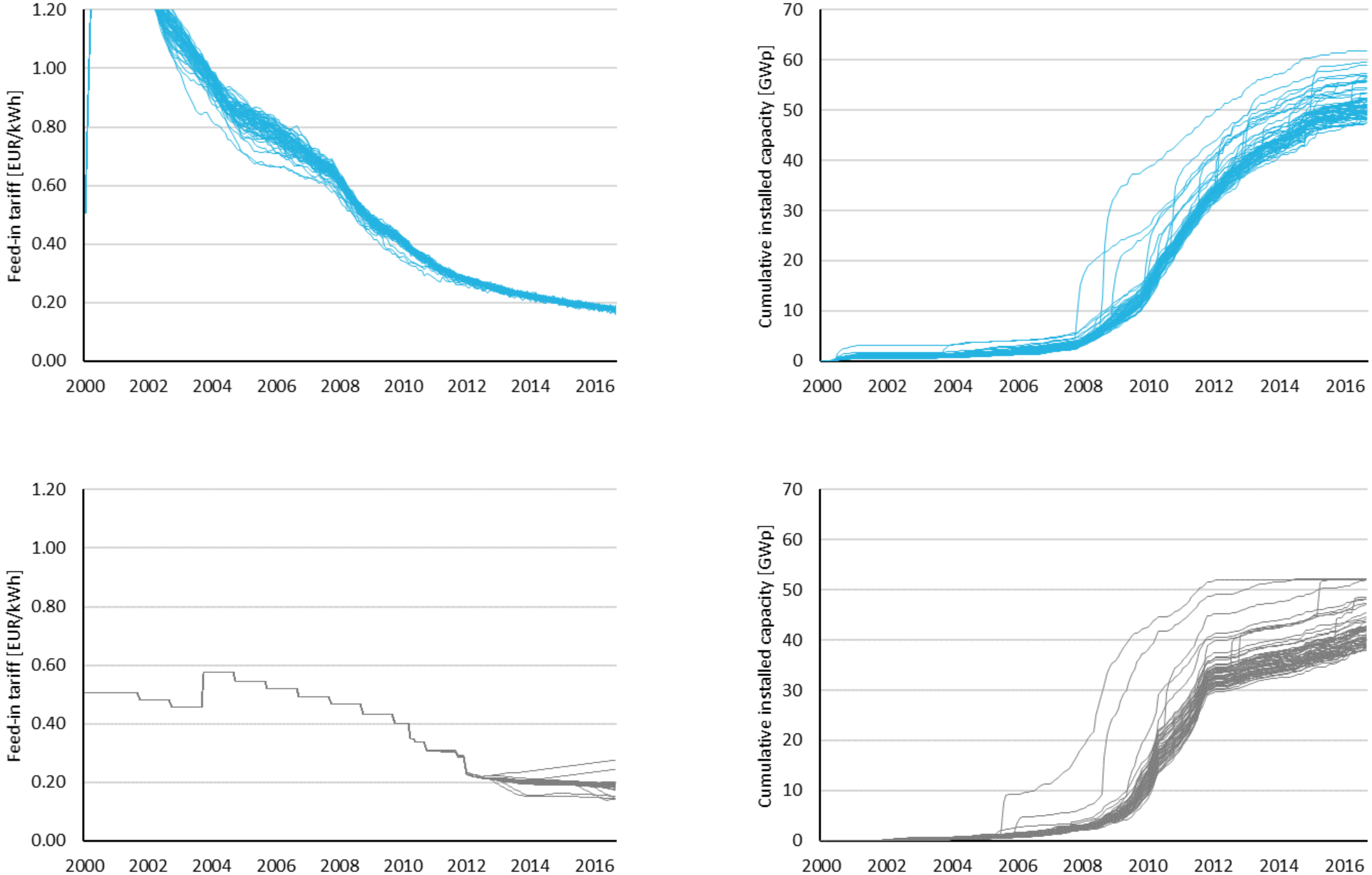

Figure A - 8 Feed-in tariff and cumulative installed capacity evolutions in individual runs of the scenario using profitability goals (top: IRR-5%) and the historical policy scenario (bottom: HIST)

4. Sensitivity analysis of calibrated parameters

In order to evaluate the sensitivity of the model to variations of the five calibrated parameters, their values were increased or reduced by 5, 10 and 20 per cent, see Table A - 11. In Figure A – 6, the disproportionate effect of the *k_awareness* parameter becomes evident as well as that of the *k_information* parameter. The rest of the calibrated parameters have a smaller impact on the key outcomes of the model.

Two reasons justify the model's sensitivity to changes in the *k_awareness* and *k_information* parameters. First, (1) the environmental awareness of the agents and the available information about solar photovoltaics influence when early adopters develop install. Potential early adopters are characterized by very high environmental awareness, which means they skip the economic evaluation step in the decision-making process and install after developing the idea. Due to the small installed capacity within Germany and around the world during the early months of the policy, early adopters have a disproportionate impact on the evolution of technology prices and availability of information. Besides, early adopters kick-start the influence of local peer-effects. For these reasons, small changes in the weight given to the agent's environmental awareness in the ideation step has major implications for the cumulative installed capacity, policy costs and windfall profits (see Figure A – 6). The critical role of early adopters is stressed in the literature and has been studied empirically.[27,30,54]

Second, (2) the values of environmental awareness and available information are, in general, larger than the values of peer-effects or attractiveness of solar PV. While half of the agents have an environmental awareness above 0.50 and the available information typically peaks at 1.00 in the late 2000s, the attractive of solar PV (i.e. the internal rate of return for an average household) and local peer-effects (i.e. the fraction of an agent's neighbors with solar PV systems) generally remain below 0.50 for most agents during most simulations. This is a consequence of how the ideation variables are operationalized. The empirical observations that support this modelling decision point to the adopters' attitude towards the environment, the technology and the effects of adoption (e.g., increase of self-sufficiency), as well as to the availability of information, as the main elements influencing the decision to install solar PV.[29,55]

Table A - 11. Variations of the calibrated parameters evaluated in the sensitivity analysis.

	-20%	-10%	-5%	+5%	+10%	+20%	Calibrated value
k_awareness	0.39	0.44	0.47	0.51	0.54	0.59	0.49
k_information	0.16	0.18	0.19	0.21	0.22	0.24	0.20
k_profitability	0.08	0.09	0.10	0.11	0.11	0.12	0.10
High awareness	0.74	0.83	0.87	0.97	1.01	1.10	0.92
Peer-effect radius	1.60	1.80	1.90	2.10	2.20	2.40	2.00

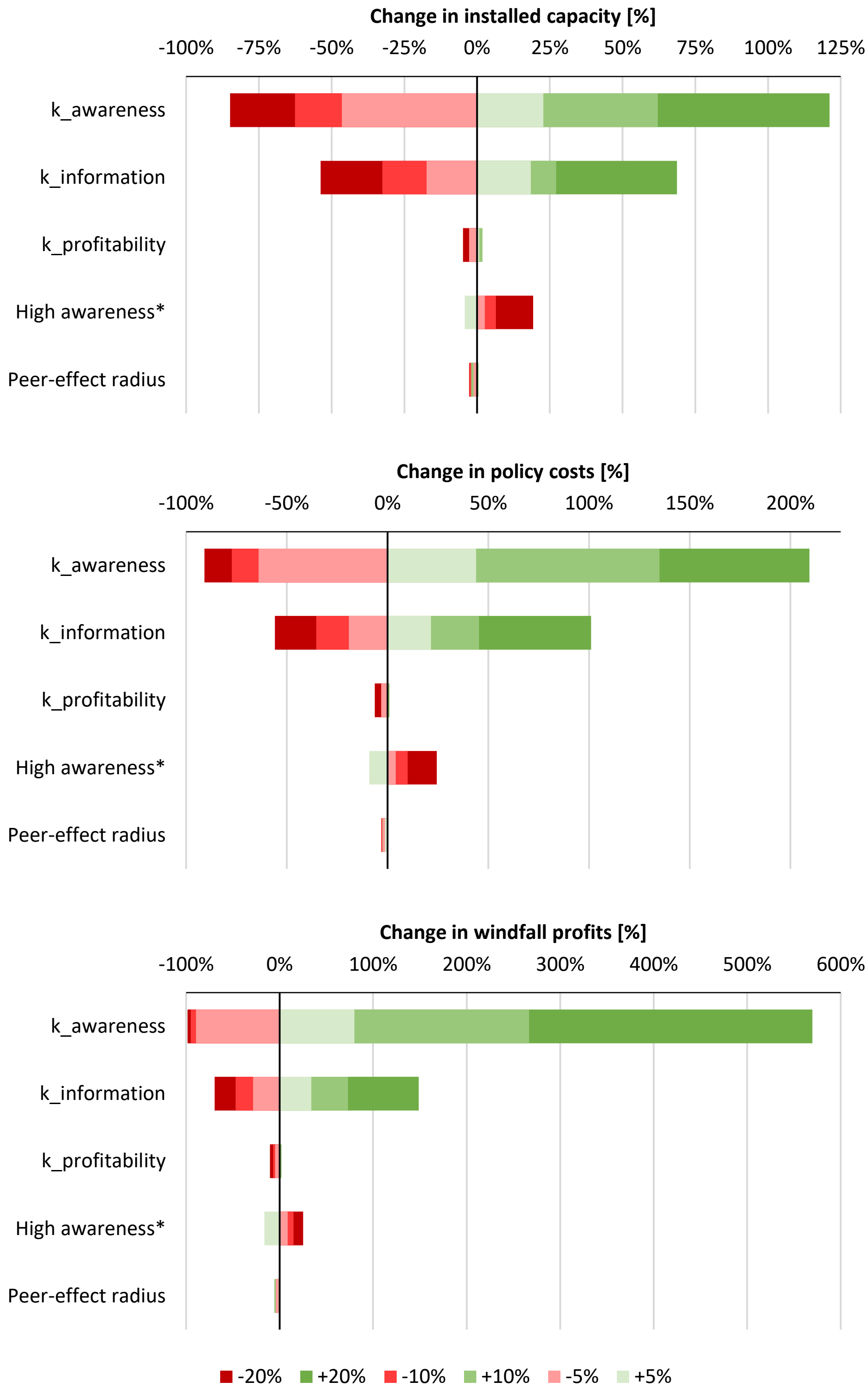

Figure A - 9. Sensitivity analysis to 5%, 10% and 20% variations of the model calibration parameters.

*High awareness represents the environmental awareness threshold above which an agent skips the economic evaluation step when deciding to invest in solar PV. Values above one (e.g., +10% or +20%) result in no installations, policy costs or windfall profits.

5. Sensitivity analysis of PID parameters

In order to analyze the sensitivity of the adjustment mechanisms to the calibrated parameters of the PID algorithm (i.e. K_proportional, K_integrative, K_derivative), we increased and decreased these parameters by 20%. The results shown in Table A - 12 show very small sensitivity to changes in these parameters that support the robustness of our main results.

Table A - 12. Sensitivity analysis to the PID algorithm parameters.

		K_proportional		K_integrative		K_derivative	
		+20%	-20%	+20%	-20%	+20%	-20%
DEP-L	Installed capacity	1.2%	-0.4%	0.1%	1.4%	0.6%	1.1%
	Policy cost	-1.8%	0.4%	0.0%	-2.6%	-0.3%	-0.4%
	Windfall profits	-3.1%	2.6%	2.9%	-7.5%	-1.6%	-0.3%
DEP-B	Installed capacity	0.2%	-0.1%	-0.3%	1.0%	0.1%	0.0%
	Policy cost	-0.8%	-0.7%	-1.5%	0.5%	-0.3%	-0.8%
	Windfall profits	-4.9%	-0.9%	-5.7%	1.2%	-0.3%	-2.5%
COST-L	Installed capacity	0.8%	0.0%	0.5%	-0.9%	0.9%	-0.9%
	Policy cost	0.2%	-0.3%	-0.3%	0.2%	0.0%	-0.4%
	Windfall profits	-2.8%	-0.5%	-2.0%	0.3%	-0.9%	-2.8%
COST-B	Installed capacity	-0.7%	-1.1%	-1.0%	-0.5%	-1.0%	-0.7%
	Policy cost	-0.1%	0.0%	0.1%	0.2%	0.0%	0.0%
	Windfall profits	0.2%	3.1%	1.7%	2.3%	3.4%	2.8%
IRR-5%	Installed capacity	1.5%	-1.7%	0.0%	-0.9%	0.1%	0.8%
	Policy cost	0.8%	-0.6%	0.5%	-0.3%	-0.5%	0.4%
	Windfall profits	-1.5%	0.2%	-0.5%	-1.2%	0.0%	-0.6%
IRR-7%	Installed capacity	0.8%	-1.4%	0.7%	-0.7%	-0.7%	-0.9%
	Policy cost	0.9%	0.1%	0.9%	-0.3%	-0.7%	-0.5%
	Windfall profits	-1.3%	0.6%	0.4%	-1.6%	-0.7%	-0.7%
IRR-9%	Installed capacity	-0.9%	-2.6%	-2.1%	-2.2%	-1.4%	-1.2%
	Policy cost	-0.3%	0.0%	-0.7%	-0.7%	0.2%	-0.2%
	Windfall profits	-0.7%	1.4%	-0.1%	-0.5%	0.2%	0.1%

6. Sensitivity analysis to policy goals

In order to estimate the robustness of our results to changes in the overall policy targets used, these were modified by 10 and 20 per cent, see Table A - 13. The median policy outcomes for different targets confirmed our results, supporting the same qualitative implications see Figure A - 10.

Relations between the scenarios remained constant as policy targets grew larger or became smaller. For any desired installed capacity or policy cost expenditure, the COST-B scenario is the most cost-efficient one followed by the COST-L and DEP-B scenario.

Table A - 13. Overall deployment and policy cost targets used for the sensitivity analysis to policy goals.

	-20%	-10%	Reference policy targets	+10%	+20%
DEP-L [MWp]	32,800	36,900	41,000	45,100	49,200
DEP-B [MWp]	32,800	36,900	41,000	45,100	49,200
COST-L [bn EUR]	92.0	103.5	115.0	126.5	138.0
COST-B [bn EUR]	92.0	103.5	115.0	126.5	138.0

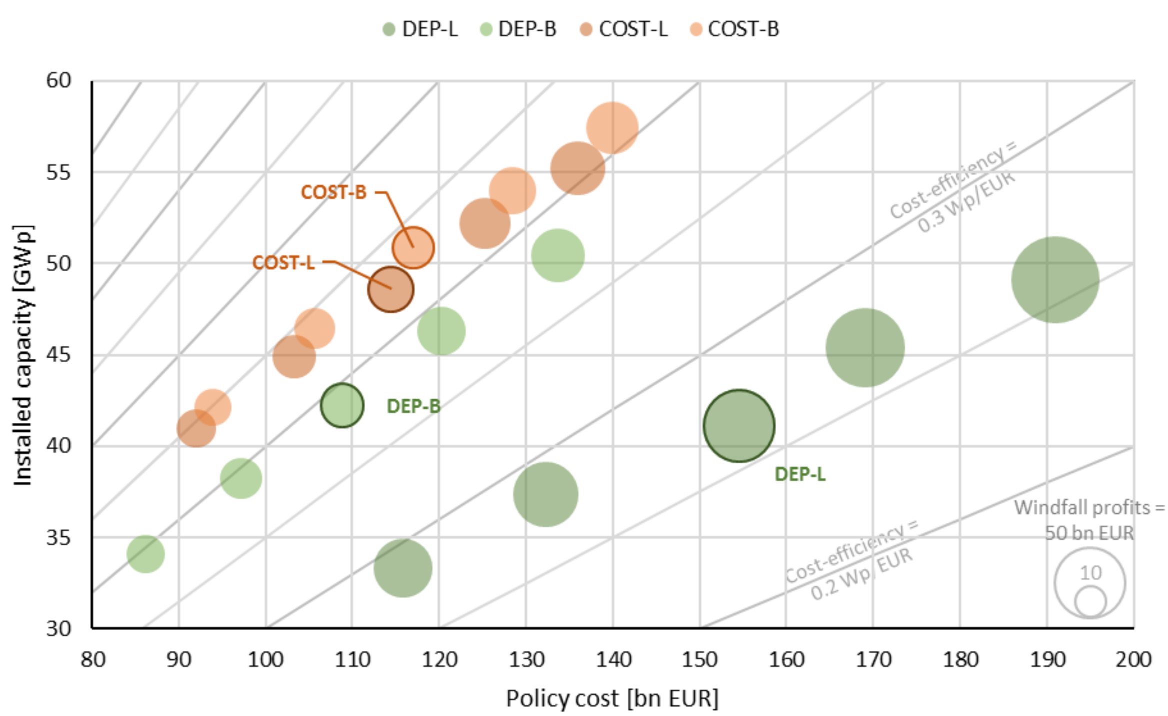

Figure A - 10. Sensitivity analysis to different policy targets for policy cost and deployment scenarios.

The figure shows the median outcome in installed capacity, policy cost, windfall profits and cost-efficiency of 60 simulation runs for the different deployment (DEP-L, DEP-B) and policy-cost (COST-L, COST-B) scenarios.

7. Sensitivity analysis to the timing of bell-shaped distributed policy targets

In order to assess the influence of how the distribution of policy targets according to a bell-shaped curve influenced the results, we considered changes in the two key parameters of the distribution: its steepness and its peak month.

Figure A - 11 shows the median outcome for 60 simulation runs of the DEP-B and COST-B scenarios for policy targets distributed following a bell-shaped distribution with a *faster* ramp-up (i.e. steepness set at 0.09), the reference case used in the main results (i.e. steepness 0.07) and a *slower* ramp-up (i.e. steepness 0.05). Notably, the mechanism is able to steer adoption towards the deployment or policy cost goals under the different distributions. Slower ramp-ups place larger policy targets in earlier months of the policy, which explains the lower cost-efficiencies of such distributions.

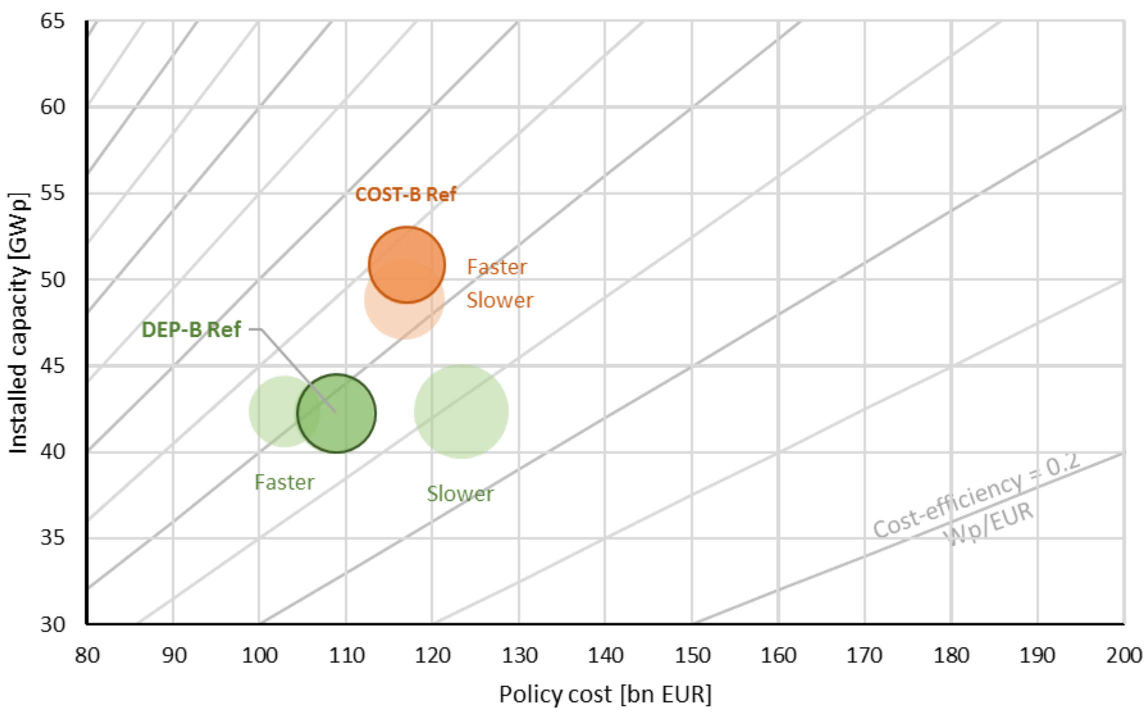

Figure A - 11. Sensitivity analysis to changes in the steepness of the policy target distribution following a bell-shaped curve.

The figure shows the median outcome in installed capacity, policy cost, windfall profits and cost-efficiency of 60 simulation runs for the deployment (DEP-B) and policy-cost (COST-B) scenarios with targets distributed following a bell-shaped curve. The results from the faster COST-B scenario overlap almost perfectly with those of the COST-B Ref scenario.

Figure A - 12 shows the median outcome for 60 simulation runs of the DEP-B and COST-B scenarios for policy targets distributed following a bell-shaped distribution with targets peaking 12 or 24 months earlier or later than the reference scenarios.

The impact of using different peak months – which determines when half of the cumulative policy targets is reached – on the key policy outcomes is substantial. This supports our decision for choosing the peak month in the reference case so that the scenarios using a linear distribution of policy targets and those using a bell-shaped curve distributions achieve half their cumulative targets simultaneously.

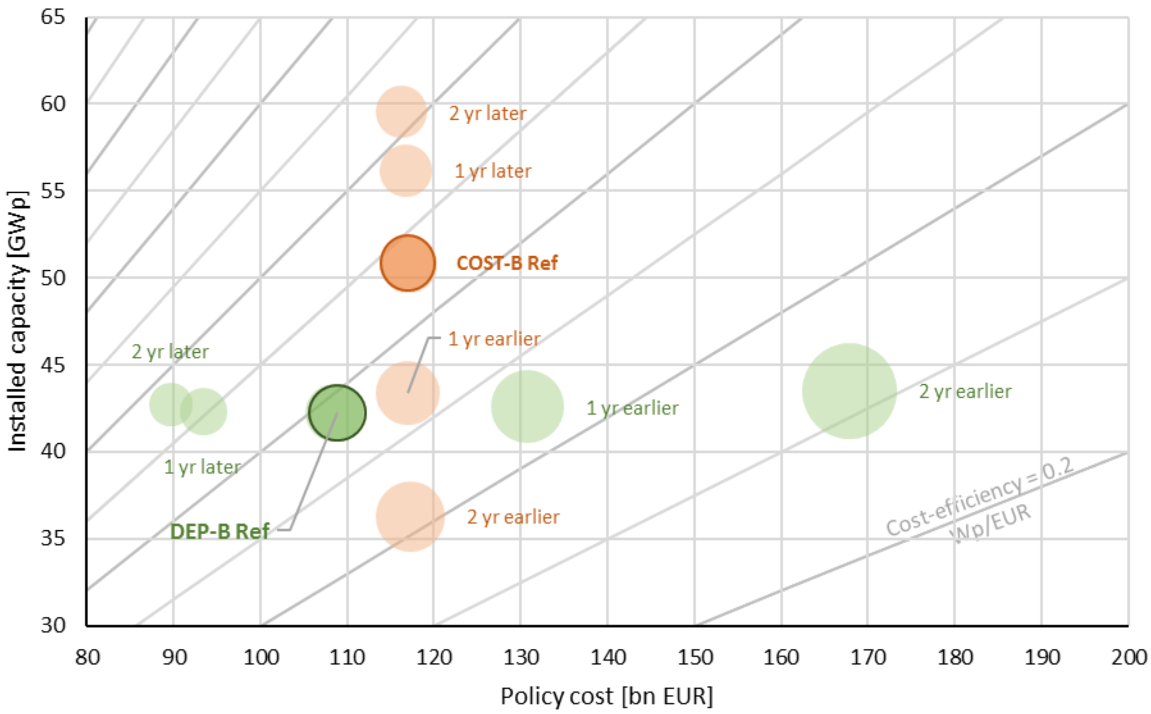

Figure A - 12. Sensitivity analysis to changes in the peak month of policy targets distributed following a bell-shaped curve.

The figure shows the median outcome in installed capacity, policy cost, windfall profits and cost-efficiency of 60 simulation runs for the deployment (DEP-B) and policy-cost (COST-B) scenarios with targets distributed following a bell-shaped curve.

8. Historical solar photovoltaic installations data and system size distributions

The model uses historical solar photovoltaic installations data for Germany during the calibration and the creation of the agents, and from the rest of the world to represent deployment out of Germany.[3,18,36]

Historical installations in Germany are available at a yearly resolution until 2009, when they become available monthly from the registry of solar PV installations, which also contains information about the size of the individual system installed each month.[3,36] We use this data to build three distributions of sizes that we employ to assign different sizes to each category of agents in the model (i.e. households with systems between 0.5-10 kWp, commercial and industrial systems between 10kWp and 40 kWp, and utility-scale systems between 40-5,000 kWp), see Figure A - 13. The system size ranges are aligned with the Renewable Energy Sources Act since 2012.[53]

We limit the size of utility-scale projects allowed to be installed to 5,000 kWp because there were only 489 installations larger than that size in Germany.[3] Due to the population scaling factor of 1:1000, having one agent with a system size larger than 5,000 kWp would mean over-representing that segment by a factor of 2:1.

To transform yearly data into monthly, the installed capacity per year is distributed linearly within each year's months from 1991 to 2016 for world data and from 1991 to 2008 for Germany's data. The linear distribution determines the installed capacity each month so that the sum of all the months of one year equals the capacity installed that year and the slope of the linear distribution approximates the slope of the exponential curve described by the yearly data. For example, in 2015 around 50 GWp were installed in countries other than Germany. Instead of distributing them uniformly among the twelve months of the year (50 ÷ 12 = 4.17 GWp), the linear distribution allocates installations mimicking the growth in installations observed in the yearly data, resulting in around 3.5 GWp in January and around 4.7 GWp in December. This approach helps avoiding large jumps from one year to another and a linear growth of the cumulative installed capacity in the rest of the world within each year.

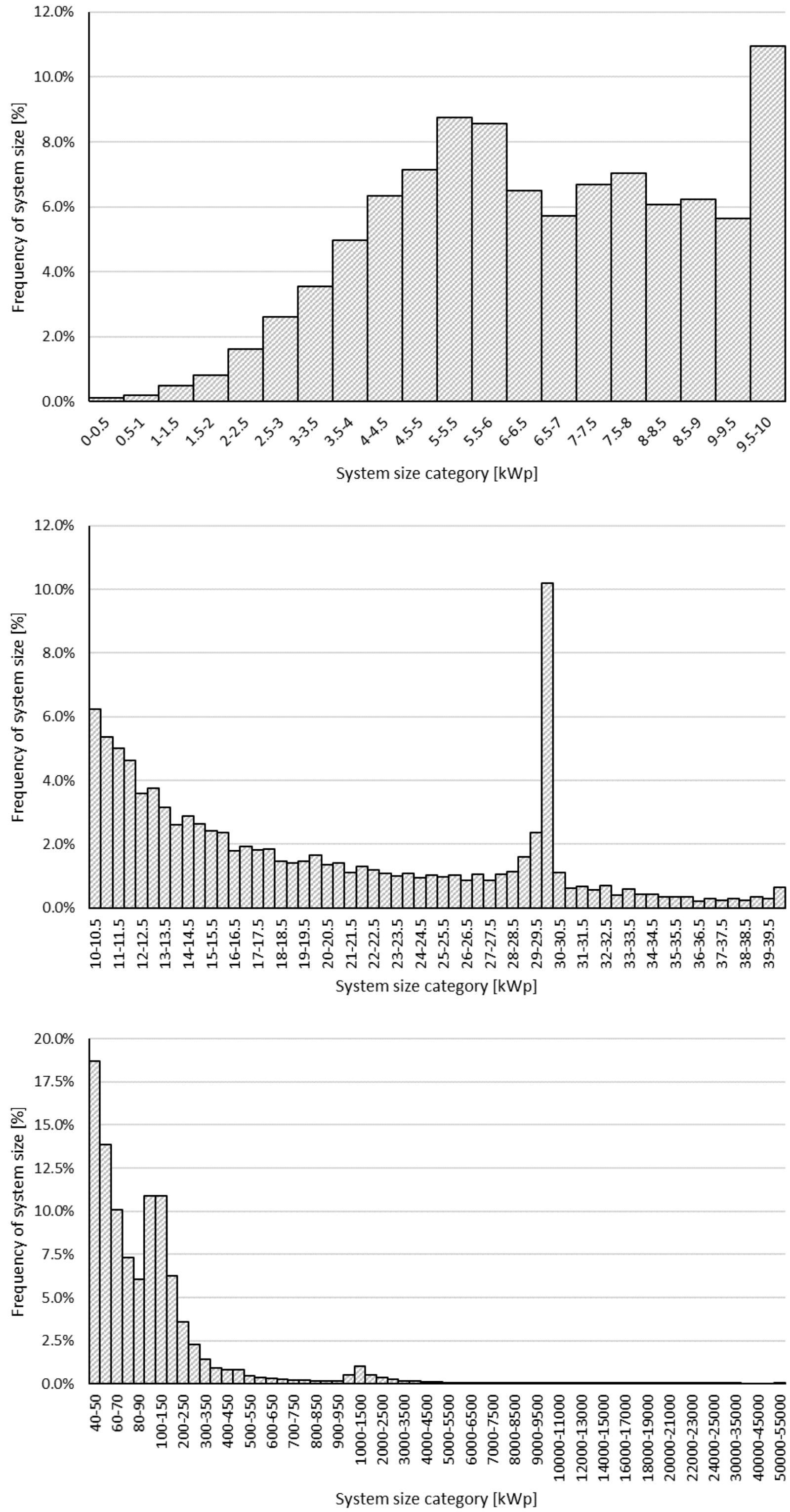

Figure A - 13. Empirical distribution of solar photovoltaics system sizes installed in Germany between 2009-2016 for systems between 0-10 kWp, 10-40 kWp, and 40-55,000 kWp.

The peaks around 30 kWp, 40 kWp, 100 kWp and 1,000 kWp result from the categories employed to differentiate the solar PV installations by size throughout the versions of Germany’s feed-in tariff (see Table A - 9).

9. Solar photovoltaic experience curves

The learning rates used in the model to represent the experience curves of solar PV modules and non-module elements of a solar system are estimated from historical data in Germany.[3,36] We use errors weighted by the installed capacity each month to improve the fitting of the experience curve for the months where large amounts of solar PV where installed. The results provide a learning rate for modules of 20.3% and for non-module elements of 10.2%, in good alignment with previously reported values.[35,56]

The historical solar PV system prices for Germany are disaggregated as composed of module and all other elements. The distribution of costs between module and other elements changed over time, from modules representing 70% of the price, in 1991, to just 50%, in 2016.[57] The original historical data is composed of annual, bi-annual, quarterly and monthly data on solar prices between 1991 and 2016.[36] To transform this data into monthly data, the missing data points are linear extrapolations from the closest available data points. To allow some monthly variability in prices, each monthly price is allowed to fluctuate randomly by ±5% from the value of the linear extrapolation.

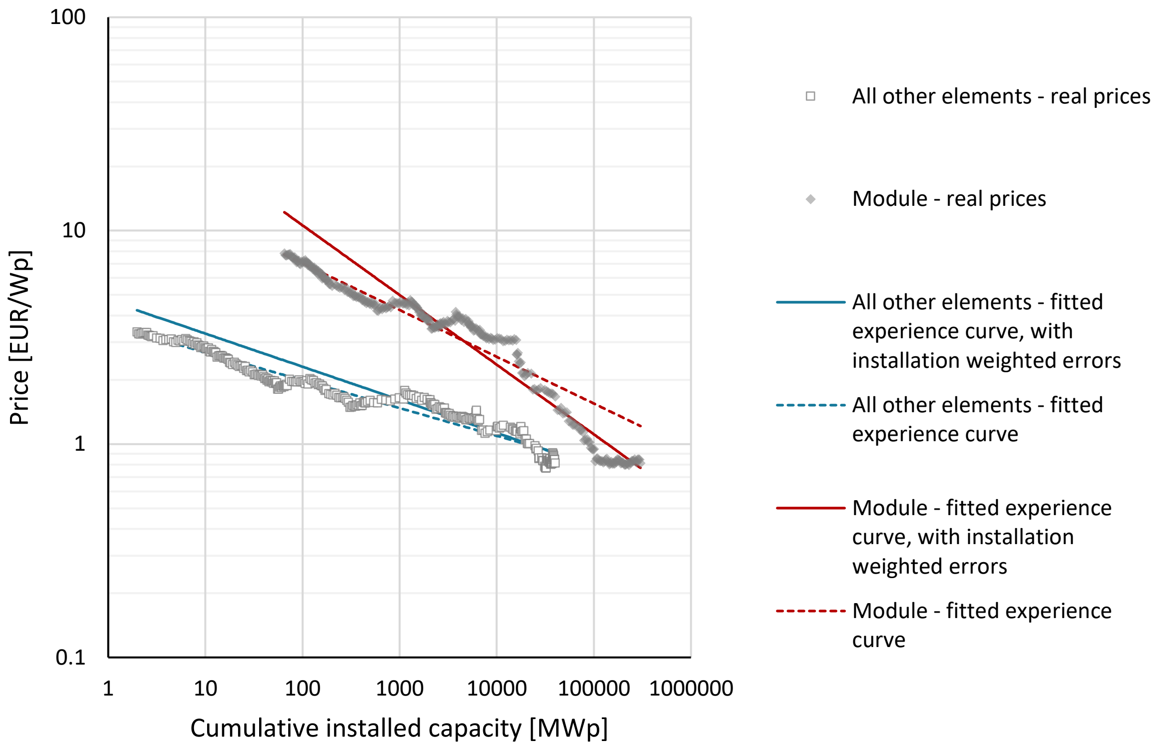

Figure A - 14. Estimated solar PV module and non-module elements experience curves compared to historical prices in Germany and non-weighted estimations.

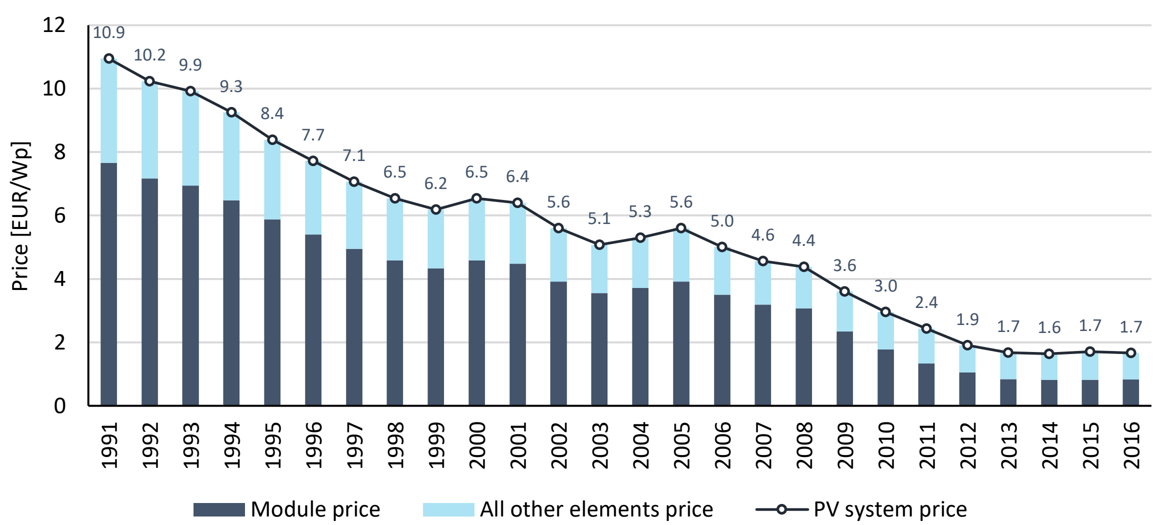

Figure A - 15. Historical evolution of the distribution between module and non-module costs in the price of solar PV systems in Germany between 1991-2016.

10. Electricity rates and wholesale electricity market price

Monthly electricity prices including all taxes and levies between January 1991 and December 2016 for agents with residential and utility-scale system sizes (i.e. residential consumers between 2.5-5.0 MWh/yr and industrial consumers between 2-20 GWh/yr)) are extrapolated from bi-annual historical series using polynomial functions, see equation (A.13).[8,9] The overall fitness of both curves to the historical data is above 0.97 R^2. The electricity price for commercial and industry agents is represented as the middle point between residential and industrial consumers.

$$\text{Electricity price}_{\text{residential}} = -1.98\cdot10^{-7}\cdot\text{month}^4+2.05\cdot10^{-5}\cdot\text{month}^3-5.89\cdot10^{-4}\cdot\text{month}^2+6.39\cdot10^{-3}\cdot\text{month}+0.13$$

$$\text{Electricity price}_{\text{commercial\&industrial}} = 0.5\cdot(\text{Electricity price}_{\text{residential}} + \text{Electricity price}_{\text{residential}}) \qquad \text{(A.13)}$$

$$\text{Electricity price}_{\text{utility-scale}}=-1.81\cdot10^{-10}\cdot\text{month}^6+3.26\cdot10^{-8}\cdot\text{month}^5-2.46\cdot10^{-6}\cdot\text{month}^4+ \\ +9.44\cdot10^{-5}\cdot\text{month}^3-1.73\cdot10^{-3}\cdot\text{month}^2+1.19\cdot10^{-2}\cdot\text{month}+8.85\cdot10^{-2}$$

Between 1992 and 2000, the wholesale electricity price is estimated from the electricity price for industrial consumers before taxes and other levies.[9] Between 2000 and 2016, we use the market value of solar electricity as the best estimation of the electricity price paid to solar generators.[15] Finally, between 2017 to 2036, the wholesale electricity prices are assumed to increase annually by 1.5%.[13]

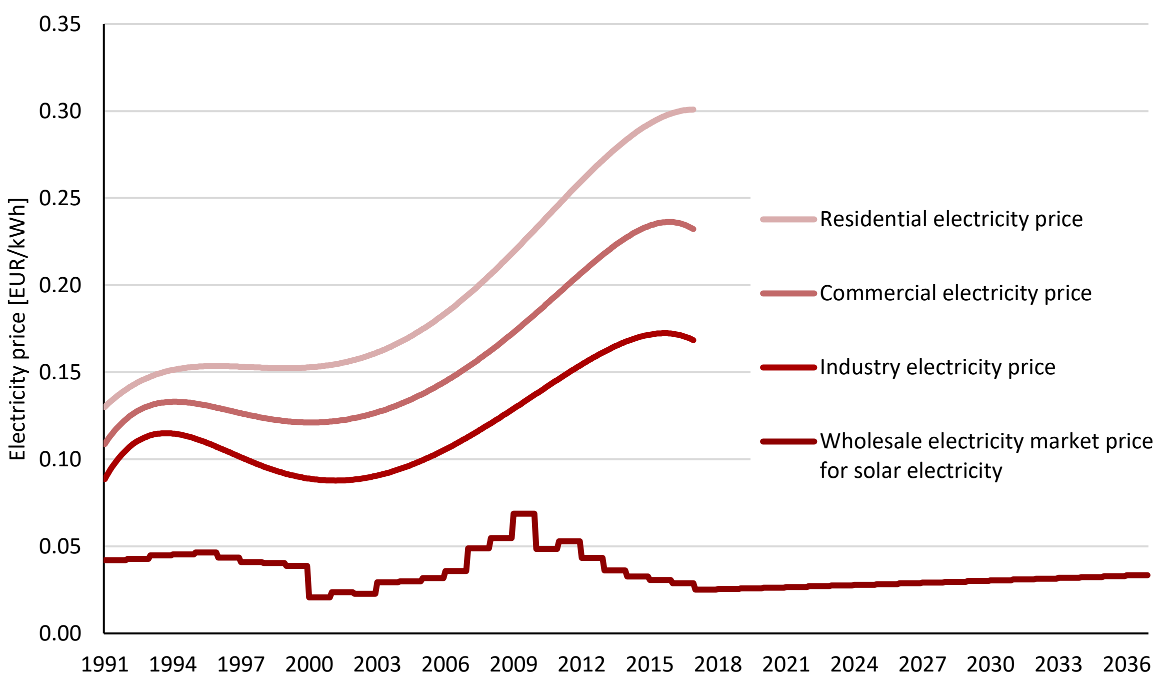

Figure A - 16. Electricity prices for potential adopters and electricity market prices paid for solar electricity.

11. Discount rates and German bonds

The discount rate for each agent type is represented by the historical cost of capital for different individuals and corporations in Germany.[10] The discount rate of residential agents is represented by the average of historical lending rates of banks for mortgage loans secured by residential real estate with interest rates fixed for 10 years (BBK01.SU0046 for 1991-2003 and BBK01.SUD119 for 2003-2016). For commercial and industry agents, the discount rate is represented by the historical effective interest rates of German banks new business for loans to non-financial corporations up to EUR 1 million with an initial rate fixation of over 5 years (BBK01.SUD126 for 2000-2016). Before 2000, the interest rate is estimated based on the expected real interest rates of German government bonds with 10 years maturity (BBK01.WZ8587) and the average spread between bond rates and this type of loans between 2000 and 2016, which is on average 2.95%. Finally, for utility-scale agents, the discount rate is represented by the historical effective interest rates of German banks new business for loans to non-financial corporations over EUR 1 million with an initial rate fixation of over 5 years (BBK01.SUD129 for 2000-2016). Before 2000, the interest rate is estimated using the same approach as for commercial and industrial agents, but with an average spread of 2.75%.

The discount rate employed to bring future costs of the policy supports to the month of adoption is represented by the interest rate of German government long-term interest rates.[16]

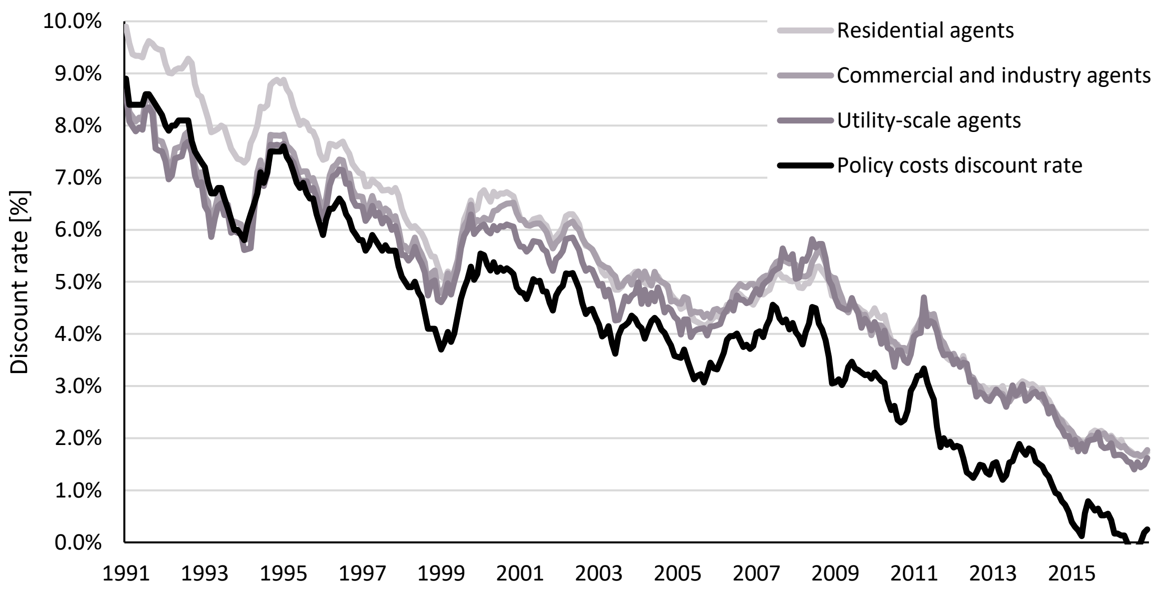

Figure A - 17. Evolution of discount rates for each type of agent and the discount rate for policy costs calculations.

12. Information on solar photovoltaics

We use the number of news articles on solar photovoltaics as a proxy for the available information and media attention to solar photovoltaics. To estimate the historical evolution of news articles on solar PV, we collect data on the number of news articles matching the keywords in equation (A.14) from the LexisNexis database for international and German media outlets (see Table A - 14).[17]

solar photovoltaics OR "solar PV" OR "photovoltaic" OR "sonnenenergie" OR "sonnenkraft" OR "solarenergie" (A.14)

The evolution of news articles published on solar PV in Germany is normalized using the maximum number of articles published (5215 articles, in 2012). Although the number of news articles published each month in the following years decreased, the variable is kept constant at one as it represents the abundance of available information on solar PV. Thus, we argue that the availability of articles on solar PV can become saturated but not decrease. The cumulative articles on solar PV are normalized by the maximum value of the series (40,590 articles, in 2016). The normalized curves are then estimated to a logistic function using least square errors, see equation (A.15). The information variable used in the model is a combination of the two curves with equal weights.

$$\text{New articles } [0,1] = -52.76 + \frac{53.75}{1 + \exp(-6.69 \cdot 10^{-5} \cdot \text{Cumulative installed capacity in the world} - 4.00)}$$
$$\text{Cumulative articles } [0,1] = -121.38 + \frac{122.31}{1 + \exp(-1.72 \cdot 10^{-5} \cdot \text{Cumulative installed capacity in the world} - 4.91)} \quad \text{(A.15)}$$

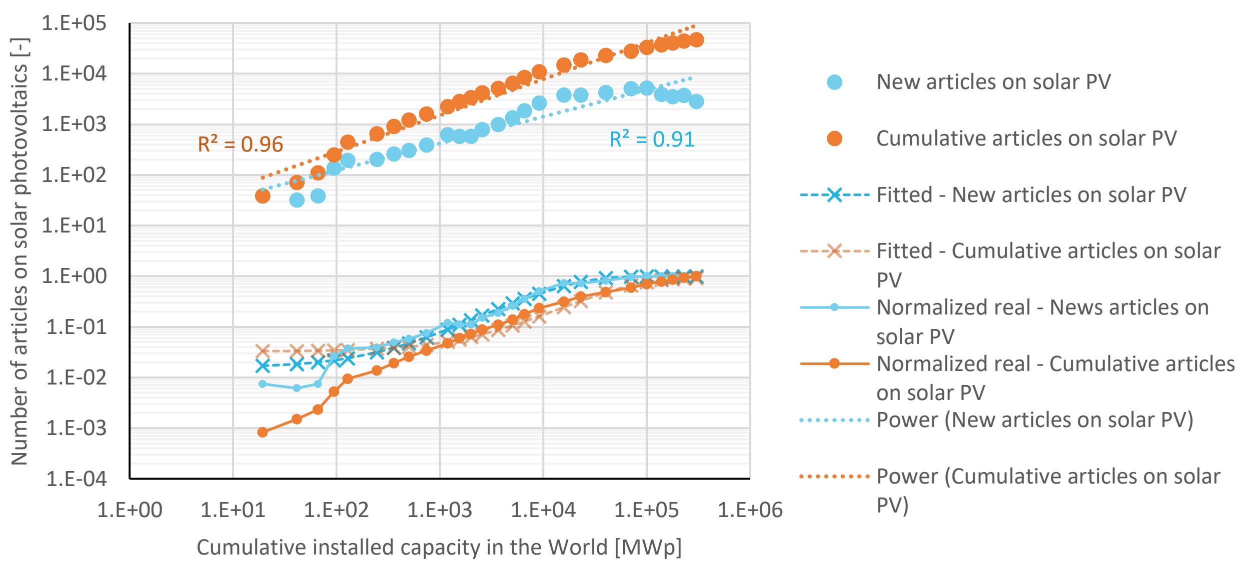

Figure A - 18. Evolution of the number of new and cumulative news articles on solar PV and cumulative installed capacity in the world.

Table A - 14. Evolution of the number of news articles published annually about solar photovoltaics in Germany and the world.

	Annual number of news articles World	Cumulative news articles World	Annual number of news articles Germany	Cumulative news articles Germany
1990	234	1766	0	0
1991	247	2013	39	39
1992	278	2291	32	71
1993	266	2557	39	110
1994	494	3051	138	248
1995	560	3611	196	444
1996	619	4230	203	647
1997	787	5017	259	906
1998	884	5901	304	1210
1999	1087	6988	394	1604
2000	1429	8417	625	2229
2001	1648	10065	583	2812
2002	1771	11836	583	3395
2003	1944	13780	788	4183
2004	2626	16406	990	5173
2005	4582	20988	1349	6522
2006	8425	29413	1853	8375
2007	12915	42328	2644	11019
2008	20105	62433	3808	14827
2009	27366	89799	3814	18641
2010	39229	129028	4244	22885
2011	45181	174209	5037	27922
2012	42853	217062	5215	33137
2013	42192	259254	3918	37055
2014	52891	312145	3535	40590
2015	54946	367091	3754	44344
2016	59315	426406	2824	47168

13. Scale effect on solar photovoltaic prices

Larger solar systems benefit from substantial economies of scale, mainly associated with the costs of inverters, installation, and balance of system elements. This effect has been widely studied.[14,58,59] We apply the results from Haelg et. al. (2018) who used a log linear regression of the relation between the system size and the system price for Germany.[14] After comparing the relation with other references, we adopted it after shifting it to make the scale effect one for systems of 10 kWp, used as a reference for the price of solar systems, see equation (A.16). Due to the power form of the scale effects, it grew excessively large for values closer to zero. Thus, a fixed scale effect of 1.2 is used to approximate the scale effect on system sizes below 1 kWp.

$$\text{Scale effect} = 1.1246 \cdot \text{System size [kWp]}^{-0.051} \tag{A.16}$$

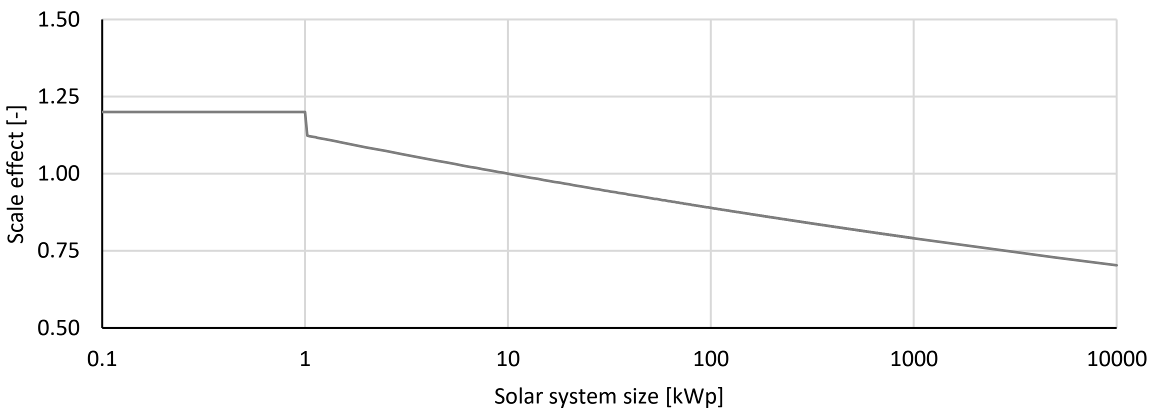

Figure A - 19. Effect of economies of scale for solar photovoltaic systems.

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