# ODD description

## *One theory - many formalisations testing different code implementations of the Theory of Planned Behaviour in energy agent-based models*

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The model description follows the ODD (Overview, Design concepts, Details) protocol by Grimm et al. (2010).

# 1 Purpose

The model aims at estimating household energy consumption and the related greenhouse gas (GHG) emissions reduction based on the behavior of the individual household under different operationalizations of the Theory of Planned Behaviour (TPB). The original model is developed as a tool to explore households decisions regarding solar panel investments and cumulative consequences of these individual choices (i.e. diffusion of PVs, regional emissions savings, monetary savings). We extend the model to explore a methodological question regarding an interpretation of qualitative concepts from social science theories in a formal code of quantitative agent-based models (ABMs). We develop 3 versions of the model: one TPB-based ABM designed by the authors and two alternatives inspired by the TPB-ABM of Schwarz and Ernst (2009) and the TPB-ABM of Rai and Robinson (2015). The model is implemented in NetLogo.

# 2 Entities, state variables, and scales

The main entity is a household agent. The current model is initialized with 5800 households parameterized with attributes from a survey in the Netherlands (CBS; Tariku, 2014). These households are placed on a spatial grid and their spatial location and a geographical distance plays a role when initializing the social network. Each agent is characterized by a set of attributes, which are interconnected (Figure 1). Over time these different variables influence the decision making process of household agents as explained below under the model description.

The state macro variable is the amount of PV installed aggregated over all the households in the simulated region. Based on the diffusion of PVs, the renewable energy production, carbon dioxide emissions and cumulative household money savings are calculated. We run the model for 30 time steps, when a saturation in technology installation is usually reached. A time step corresponds to 6 months.

# 3 Process overview and scheduling

Central to the model is the decision making process of a household who either decides to invest in a technology installation or not. This process is carried our by each household every time step. After each time step the households' attributes are updated and the aggregated results are estimated for the region. Further, the model provides three options for representing the decision making process following different operationalizations of the TPB (Figure 2).

In the *MF* model the decision process regarding a PV installation (Figure 2(a))starts with assessing perceived behavioral control (PBC) as an individual income barrier. Households with a lower income have a lower chance to

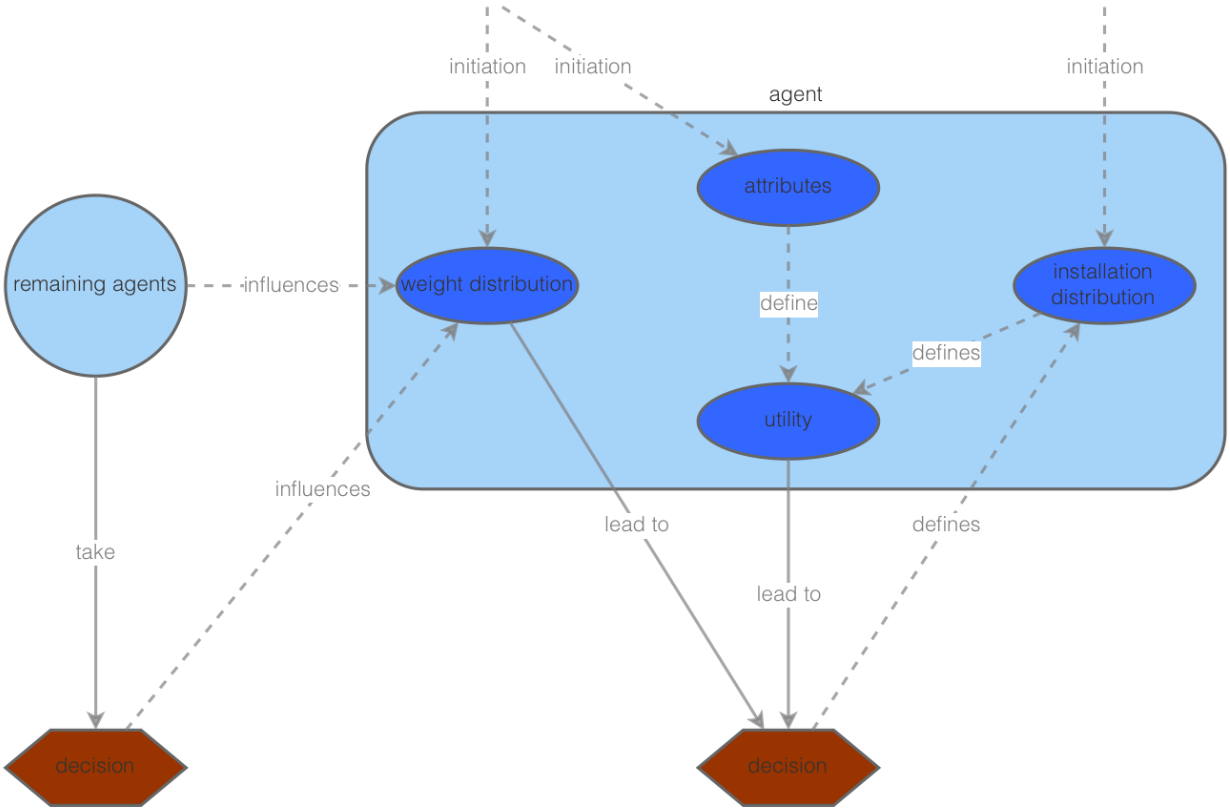


Figure 1: Agents attributes and variables

consider PV and vice versa. If a household passes this probabilistic barrier, it goes on with assessing individual utility with and without solar panel investments. Here households estimate multi-attribute utility function dependent on economic, environmental, social and comfort parameters and individual weights. A household decides to invest in PVs only if utility of this option is higher than the status quo with no investment.

In accordance with Schwarz and Ernst (2009), households in the *SE* ABM decide in one stage (Figure 2(b)): by calculating a utility function based on the income, economic, environmental, social and comfort parameters. As before, utility values with and without PV are calculated and a household chooses the option with the maximum utility. In all 3 operationalizations households make these decision sequentially one by one and are updated at the end of each simulation step.

Following Rai and Robinson (2015), the agents in the *RR* model first have to pass a PBC barrier, which compares the income utility against the economic payback utility. If the income utility is higher than the payback utility the agent continues to a second barrier, which weighs the utility of investing in PVs against a global threshold, see Figure 2(c). The utility is calculated exactly the same as in the *MF* ABM.

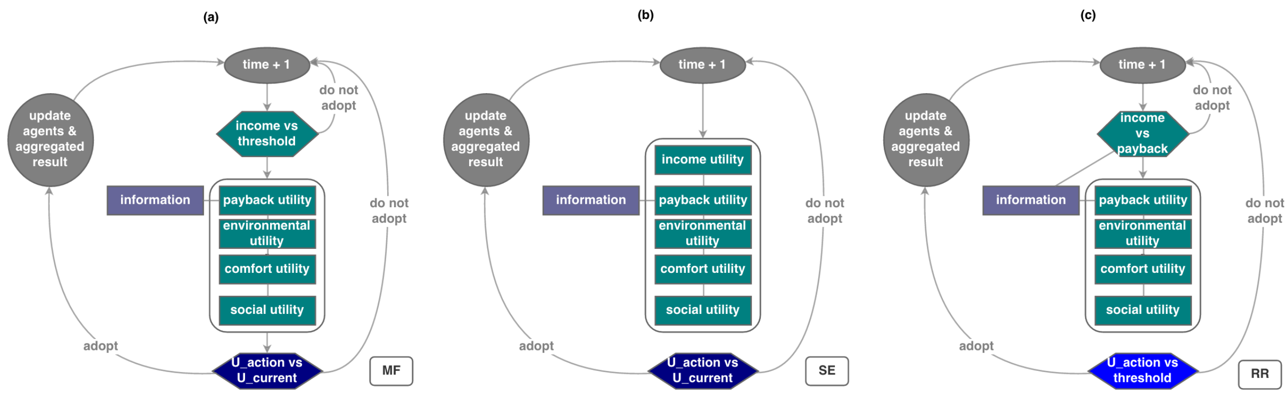


Figure 2: Process of simulation for TPB operationalizations

| Variable | Type | Purpose |
|---|---|---|
| household income | fixed | cumulative income household |
| income class | fixed | create social network |
| area house | fixed | calc. investment costs, benefits |
| $w_{eco}$ $w_{cof}$ | fixed | consumer preferences utility function (U) |
| $w_{soc} = i_{soc}$ | dynamic | consumer preference social norm U |
| $w_{env}$ | fixed | consumer preference environmental attitude U |
| esystems | dynamic | set of installed technologies per household |
| $u_{cof}$ | fixed | aesthetics of PV per household |
| $u_{eco}$ | dynamic | payback utility |
| $u_{env}$ | dynamic | social network dependent environmental utility |
| $u_{soc}$ | dynamic | utility for influence social network |
| $th_{inc}$ | fixed | household income factor (*SE*, *MF*) or threshold (*RR*) |

Table 1: Agent-dependent variables

| Variable | Type | Purpose | Value |
|---|---|---|---|
| weight distribution | fixed | heterogenous or homogenous for all agents | het. |
| close links | fixed | amount of neighbours same income class per agent | 3 |
| random links | fixed | chance for agent link close geographic distance | 0 |
| initial PV share | fixed | share of households owning a PV at time 0 | 0.1 |
| interest rate | fixed | interest rate on investment | 0 |
| PV SDE premium | fixed | governmental subsidy | 0 |

Table 2: Characteristics agent population

# 4 Design concepts

## 4.1 Basic principles

As any ABM, this model starts with micro-behaviour and individual interactions and aggregates them towards a macro-economic and environmental output. The micro-behaviour of agents is grounded in one of the most widely used psychological theories - TPB. TPB assumes that one's intention to behave in a specific way is contingent on three factors: one's attitude, social norms and PBC. The latter depends largely on one's actual control in a specific situation and is therefore equal to actual behavioural control in this model (please see the original JASSS paper for the discussion on the gap between the two). The PBC component does in turn also influence the behaviour directly (**?**), as visualised in Figure 3.

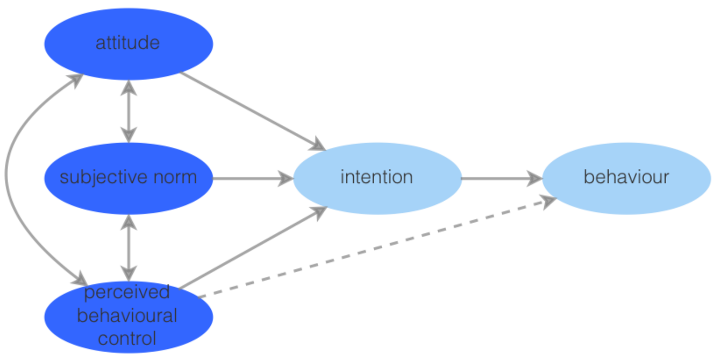


Figure 3: Theory of Planned Behaviour, adapted from Ajzen (1991)

The PBC addresses financial, time and knowledge constraints. The current version of the model uses the financial constraint for all operationalizations. It comes in the form of an income factor. Additionally it is possible to include a technology awareness barrier following Faber et al. (2010) for the *MF ABM*, depending on market share and marketing.

The attitude and social norm are collectively computed using a multi-attribute utility function, which is a weighted sum of an economical factor (measured as an economic payback of an investment), an environmental one (measured based on CO2 emission savings), an aesthetics parameter for PV installations (which is randomly assigned) and social network parameter (measured as percentage of PV installations in the neighbourhood).

| Variable | Type | Purpose | Value |
|---|---|---|---|
| probability financial information | fixed | percentage households with information initially | off |
| Uncertainty | switch | inaccuracy computation $u_{eco}$ | off |
| Info Costs | switch | costs information search in $u_{eco}$ | off |
| Info-Costs-Revenue | switch | include revenue in computation info costs | off |
| Info-Costs-Income | switch | include hh income in computation info costs | off |
| influence costs time | fixed | ration of revenue and income used for costs information | 0.3 |
| information distribution | fixed | uniform normal poisson empirical | none |
| Information-Threshold | switch | implement threshold for minimum information | off |
| information threshold | fixed | value of minimum information threshold | 0 |
| $MF$-Income | switch | include income in PBC ($MF$) | on |
| $MF$-Income-Barrier | switch | income threshold versus probabilistic barrier ($MF$) | prob. |
| $MF$ income barrier | fixed | income threshold ($MF$) | 0 |
| Visibility | switch | include a technology visibility barrier ($MF$) | off |
| $i_{att}$ | fixed | technology dependent importance of attitude ($SE$) | 0.2 |
| $i_{pbc}$ | fixed | technology dependent importance of PBC ($SE$) | 0.2 |
| $th_{rr}$ | fixed | external threshold for utility ($RR$) | 0.05 |
| $RR$ sensitivity barrier | fixed | PBC threshold instead of $th_{inc}$ ($RR$) | 0 |

Table 3: Process Variables

| Variable | Type | Purpose | Value |
|---|---|---|---|
| $\overline{s_{c02}}$ | fixed | average CO2 savings per ktonne/KWh | 0.6759 |
| $e_{max}$ | fixed | PV peak power | 1 |
| $t_{sun}$ | fixed | total sunshine hours NL | 1000 |
| $p$ | fixed | overall performance efficiency PV | 0.75 |
| $t_{pv}$ | fixed | PV life time in years | 20 |
| $c_{pv}$ | fixed | PV price in EUR/$m^2$ | 2000 |
| $c_e$ | fixed | Average costs of energy on grid EUR/kwh | 0.19 |

Table 4: Technology related Variables (CBS; MilieuCentraal, 2017)

The weights in this multi-attribute utility function represent individual preferences of households towards each of the 4 factors, as explained further in the sub model section.

Agents' attributes include: income, preferences and social network, compare with Table 1. Together these individual decisions driven by a desire to improve personal utility, contribute to the aggregated benefits for the entire population. These benefits are measured in terms of renewable energy production, CO2 emission saving as well as financial benefits for households.

## 4.2 Emergence

The emergent patterns to be considered using this model are the diffusion of PVs installation within the scope of a region. A growth in technology investments correlates with an aggregated monetary and CO2 emission saving as well as solar energy production.

## 4.3 Adaptation

As household agents take decisions to install PVs, the social norm changes within a particular social network every time step.

## 4.4 Objectives

The objective of agents in this model is to increase their personal utility. This utility is based on economic, environmental, social and comfort parameters.

## 4.5 Learning

Agents learn when searching for information about financial aspects of a PV system. This learning is simplified in the current version of the model. In addition, agents learn about updating social norms as they see their neighbours installing PVs in the previous time steps.

| Variable | Type | Purpose | Value |
|---|---|---|---|
| $A_j$ | fixed | level of technology advertisement for technology awareness (TA) | 0.02 |
| $ms_j$ | fixed | market share for TA | |
| $\sigma_j$ | fixed | bandwagon effect confidence in market for TA | |
| $A_j^{adv}$ | fixed | level of technology advertisement for TA | 0.02 |
| $A_j^{soc}$ | dynamic | level of advertisement through social network for TA | 0.02 |

Table 5: Variables visibility barrier ($MF$) following Faber et al. (2010)

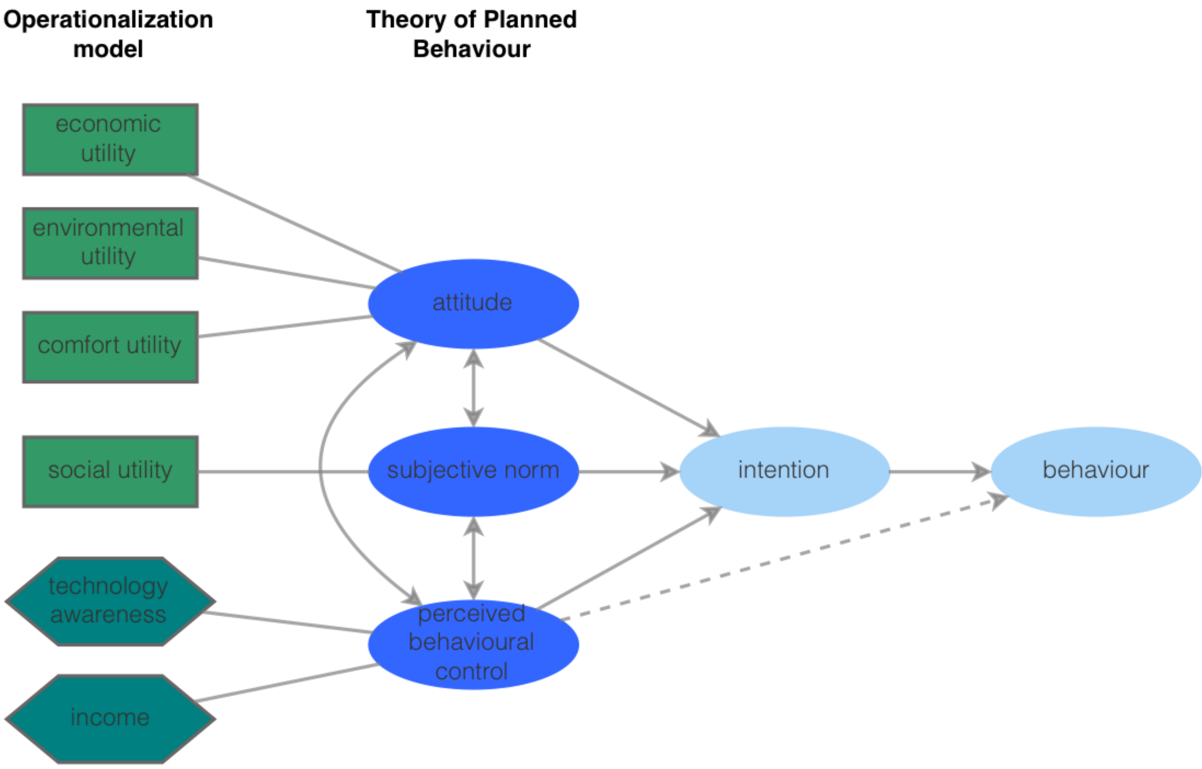


Figure 4: Integration factors and theoretical framework model

### 4.6 Prediction

This model is not meant for prediction; it explores a methodological issue. Agents are not predicting anything either.

### 4.7 Sensing

Sensing occurs in this model at the individual and collective levels. Unless defined explicitly otherwise, individual agents have full information on costs and benefits of the technology installation. Collectively, technology investments within the social networks are sensed by others and influence households' decision making process.

### 4.8 Interactions

Agents' choices are indirectly influenced by the decisions of their neighbours. The interactions are realized through the small world network. Agents are connected to other agents within the same income group within a defined spatial radius. They are also randomly connected to other agents of the same income class outside of the defined spatial radius. Whether or not neighbours have installed the technology at question can influence both: the social parameter of the technology awareness submodel as well as the social utility within the overall utility function. The two submodels are explained more in depth below.

### 4.9 Stochasticity

A small proportion of agents establish random links with other agents. Initial adaptation of technology is selected randomly as well as the initial distribution of weights, i.e. agents' preferences, and incomes. Further random numbers and floats are used to implement probability barriers for the technology awareness and income barrier as well as for the inclusion of information as a parameter in the economic component of the utility function.

### 4.10 Collectives

Agents are connected into social networks. Social norm variable, which impacts individual utilities, is estimated at the level of this collective.

## 5 Observation

The following data are collected each time step:

- share of agents purchasing solar PVs
- the total amount of electricity generated summed over all installed PVs, with $e_{max}$ - PV peak power, $t_{sun}$ - sunshine hours and $p$ - performance ratio of the PV and $a$ - roof size:

$$E_{tot}(t_{pv}) = e_{max} * t_{sun} * p * a \tag{1}$$

- the total households' money savings from installing solar panels, based on the total revenue of the PV $r_{tot}$, which is calculated as sum of the power generated by the PV system $E_{tot}$ and the electricity costs $c_e$ over the lifetime of the PV $t_{pv}$, and the total cost per $m^2$, $c_{pv}$, and again roofsize $a$:

$$\begin{aligned} S_{mon} &= r_{tot}(t_{pv}) - (c_{pv} * a) \\ r_{tot}(t) &= \sum_{t=1}^{t_{pv}} E_{tot}(t) * c_e \end{aligned} \tag{2}$$

- the total quantity of CO2 emission saved thanks to installing PVs, where $\overline{s_{c02}}$ are the average CO2 savings per KWh:

$$S_{co2} = E_{tot}(t_{pv}) * \overline{s_{c02}} \tag{3}$$

- the number of PV installations per income class
- the mean environmental weight of households with PV installation per income class
- the mean environmental weight of households without PV installation of the low income class

## 6 Initialization

During the initialization the spatial grid of the Dutch municipality of Dalfsen is loaded. In addition, the area and year of construction of houses is loaded. Further, the population of 5800 households is created and parameterized with empirical incomes, preferences from the survey data and randomly assigned ownership of PVs. Finally, a social network is created based on the income-class and the geographical distance.

## 7 Input data

The input data includes a dataset of 5800 households from Dalfsen, including their address, income, area and year of construction of their houses. The initial weights are collected from a small survey among 11 participants, and thus not representing the average distribution of these weights over a town like Dalfsen. The rest of the data used to operationalize decision making processes are drawn from the literature and mostly based on empirical research.

## 8 Submodels

The submodels are all related to the decision making process, (1) the technology awareness barrier, (only for *MF*) (2) the PBC and (3) the attitude and social norm component according to all operationalizations and (4) the social network.

## 8.1 Technology awareness barrier

The technology awareness function ($V$) is only available for the base operationalization of the *MF* ABM and can be activated in the model in two different way, both adapted from Faber et al. (2010). The first one depends on advertisement of the technology ($A$) as well as on the influence of its market share ($MS$). The influence of the market share in turn depends on the market share ($ms_j$) as well as a parameter illustrating the confidence in the market($\sigma_j$):

$$V(t) = MAX[V(t-1); min(1; A + MS)] \tag{4}$$

$$MS = ms(t-1)^{\sigma} \tag{5}$$

The second possibility combines Faber et al. (2010) with Rai et al. (2016). The idea is that direct advertisement only acts as sparking events for taking the decision for or against a PV cell for approximately 33.2% of people. In addition, seeing a neighbour installing PVs drives 16% of the people to consider buying PV cells. The equation for the advertisement parameter ($A_j$) then looks as follows:

$$A = p_{adv} * A_{adv} + p_{soc} * A_{soc} \tag{6}$$

Currently both $A_j^{adv}$ as well as $A_j^{soc}$ are estimated to have a value of 0.02 (Faber et al., 2010). The technology awareness parameter can be turned off using the "Visibility?" switch and fine tuned in terms of $A_j$ for the PV purchase decision by the user and per run.

## 8.2 Perceived Behavioural Control

For the *MF* ABM, PBC depends solely on income. The income component is operationalized as a probability function. This function has a sigmoid form starting at 0 and saturating at 1, with $x$ being the income of a household in 10.000 EUR and and $n$ being a factor that normalizes $x$ with regard to the average household income.

$$th_{inc} = 1 + \frac{1}{e^{-n*x} + 6} \tag{7}$$

This decreases the chances for low income households to decide for or against PV but does not eliminate those chances. The threshold value is then compared to a random float between 0 and 1 drawn from the uniform distribution. If the threshold is smaller than the float the household proceeds with the decision making process. Alternatively, the next household is going to be activated and go through the next stage of utility assessment.

The income barrier can be turned on or off.

In the implementation for the *RR* ABM the income threshold is compared against another economic factor, the payback utility. Here thus cut a set of agents with specific attributes from the agent population continuing with the decision making process.

The payback utility is calculated as follows, with the lifespan of the technology equal to 20 years, and $t_{pp}$ the payback period for the installation. The payback period is a measure of the time it takes for the cumulative revenue ($r_{pv}$) to be larger than the initial PV costs ($c_{pv}$).

$$f_{eco} = \frac{(20 - t_{pp})}{20} t_{pp} = t(c_{pv} < r_{pv}) \tag{8}$$

For the *SE* ABM, the PBC, attitude and social norm component are calculated in one utility function that is optimized. It will be presented in the next section.

## 8.3 Utility function for attitude and social norm component

The utility function for *MF*, as well as for *RR*, consists of an economical, environmental, comfort and social component, each including a utility value and a weight. The weights are provided by empirical data. For *MF*, the utility is calculated for both the decision for and against PV, the choice with maximal utility is chosen. For *RR*, the utility is compared to a threshold, which in the baseline model is set to 0.05, as determined by a sensitivity analysis.

$$U_{RR} = U_{MF} = w_{eco} * u_{eco} + w_{env} * u_{env} + w_{cof} * u_{cof} + w_{soc} * u_{soc} \tag{9}$$

For the *SE* ABM, the arrangement looks slightly different, with $i_{soc}$ set equal to $w_{soc}$, thus an agent-dependent parameter. $i$ stands for importance, *att* for attitude and *pbc* for perceived behavioural control. $i_{att}$ and $i_{pbc}$ are technology dependent parameters, which for this simulation have been set to 0.2, based on a sensitivity analysis.

$$U_{SE} = i_{att} * u_{att} + i_{pbc} * u_{pbc}) * (1 - i_{soc}) + i_{soc} * u_{soc}$$
$$u_{att} = w_{eco} * u_{eco} + w_{env} * u_{env} + w_{cof} * u_{cof} \quad (10)$$
$$u_{pbc} = w_{eco} * u_{inc}$$

The utility sub-functions are computed as follows, in all ABMs assuming full information. The economic utility function is computed using a technology lifespan ($t_{pv}$) of 20 years, and $t_{pp}$ the payback period for the installation. The payback period is a measure of the time it takes for the cumulative revenue ($r_{pv}$) to be larger than the initial PV costs ($C_{pv}$).

$$u_{eco} = \frac{(t_{pv} - t_{pp})}{t_{pv}}$$
$$t_{pp} = t(C_{pv} < r_{pv}) \quad (11)$$

The income factor, needed for the *SE*, *RR* is calculated in the exact same way as the income probability in the *MF* model:

$$f_{inc} = 1 + \frac{1}{e^{-n*x} + b} \quad (12)$$

Environmental utility is displayed next, dependent on the specific CO2 emission saving for household and technology at question ($s_{co2}$) and the average emission saving for that technology ($\overline{s_{co2}}$).

$$u_{env} = \frac{e^{(s_{co2} - \overline{s_{co2}})}}{(1 + e^{(s_{co2} - \overline{s_{co2}})})} \quad (13)$$

The comfort utility for PV installations ($u_{cof}^{pv}$) is randomly chosen from [1,-1] for PV installed and 0 if PV is not installed.

To finish up the social utility function with $n_{tec}$ being the number of neighbours in the network who have the technology at question installed and $n_{tot}$ the total number of neighbours:

$$u_{soc} = \frac{n_{tec}}{n_{tot}} \quad (14)$$

The weights of the utility function can either be set to be homogeneous, thus equal for every single agent, or heterogeneous. If they are heterogeneous, a weight set is drawn randomly from a collection of eleven weight sets. Besides they can be fixed, thus not change over time, or dynamic, meaning that over time they are adapted based on the environmental weight of the social network.

## 8.4 Information on Finances

The model offers the possibility to implement an additional factor, namely information on economic aspects of PV, by means of influencing the economic utility in monetary or non-monetary forms for all TPB operationalizations. The percentage of households to be informed on the financial aspects can be specified. Here the equation for economic utility once again, with $t_{pp}$ as payback period, $C_{pv}$ as initial costs of PV, and $r_{pv}$ the revenue from the PV.

$$u_{eco} = (20 - t_{pp})/20$$
$$t_{pp} = t(C_{pv} < r_{pv}) \quad (15)$$

For both implementations and all TPB operationalizations, $r_{inf}$, a value between 0 and 1 is randomly drawn and provides a measure of the quantity/quality of information. It's distribution can be varied between Poisson, normal, uniform and a discrete distribution based on empirical research about household's time to take decisions on PV installation by Rai et al. (2016).

### 8.4.1 Information as monetary Costs

The monetary option assumes that each household pays for the time they spent on searching for the information on the financial aspects of PV installation. A share of households is assumed to be informed by their installer Rai et al. (2016) and, therefore, do not need to "buy" information. The costs for this information search are integrated using the following formula for the calculation of the costs of PV ($C_{pv}$) which in depends on the price of PV per $m^2$, $c_{pv}$ and the roof size $a$. The information costs, $c_{inf}$, Equation 16, are computed using an approximation of the costs of time ($c_{time}$) from the transport literature Move (2014). $r_{inf}$ is a value between 0 and 1, representing the amount of time spent on searching for information.

$$C_{pv} = c_{pv} * a + c_{inf}$$
$$c_{inf} = (R_{mth} + I_{mth}) * c_{time} * r_{inf} \tag{16}$$

Differently from Move (2014) original formula on waiting time, see Equation 17, the costs do not only depend on the household income ($I_{mth}$) but also on the potential revenue $R_{mth}$ we miss out by not having installed the PV system.

$$c = I_{mth} * c_{time} * r_{inf} \tag{17}$$

Using this updated version of the costs of the PV, the economic utility is calculated as in Equation 9.

### 8.4.2 Information as non-monetary Uncertainty

In the non-monetary option we assume that information is related to the (in)accuracy of the economic utility assessment, where both over- and underestimation are possible. It is equal to $r_inf$ - a randomly drawn value with the economic utility - being the mean of its distribution $P$.

$$r_{inf}\ P(u_{eco})$$
$$u_{eco} = r_{inf} \tag{18}$$

## 8.5 Social network

Agents form a social network, which resembles the small-world network in the Watts-Strogatz model Janssen and Jager (2002). Links are created based on the geographical proximity and the association with a specific income class. On top of that, there is a probability that random links are initiated outside geographic and income-group boundaries. The number of neighbours in the network who have PVs installed, can, if desired, influence the technology awareness component as well as the social parameter in the utility function.

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