ODD Description - Energy Model

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1 Purpose

The purpose of the energy model is to investigate the effects of modelling informal institutions in an agent-based model on the uptake of renewable energy methods by consumers. It focuses specifically on changes in estimated greenhouse gas emissions (GHG) related to and cumulative investment in PV panels by households in the Netherlands.

The effects of modelling informal institutions on investment in PV panels are illustrated by comparing three versions of the model: in the first version of the model all agents behave rationally, only taking into account financial considerations. In the second version, the effects of (static) informal institutions on these financial considerations are added by adding an agent-decision making module that follows the Theory of Planned Behavior (TPB). Finally, this second version with behavioral agents is extended with opinion dynamics that allow for the behavioral aspects of agents' decision-making to change over time (evolving informal institutions).

2 Entities, state variables and scales

The main entities of the energy model are the household agents. The model is initialized with 1000 household agents, interacting through a social network which influences the behavioral aspects of the agents' decision-making process. An overview of the household attributes is given in the following table:

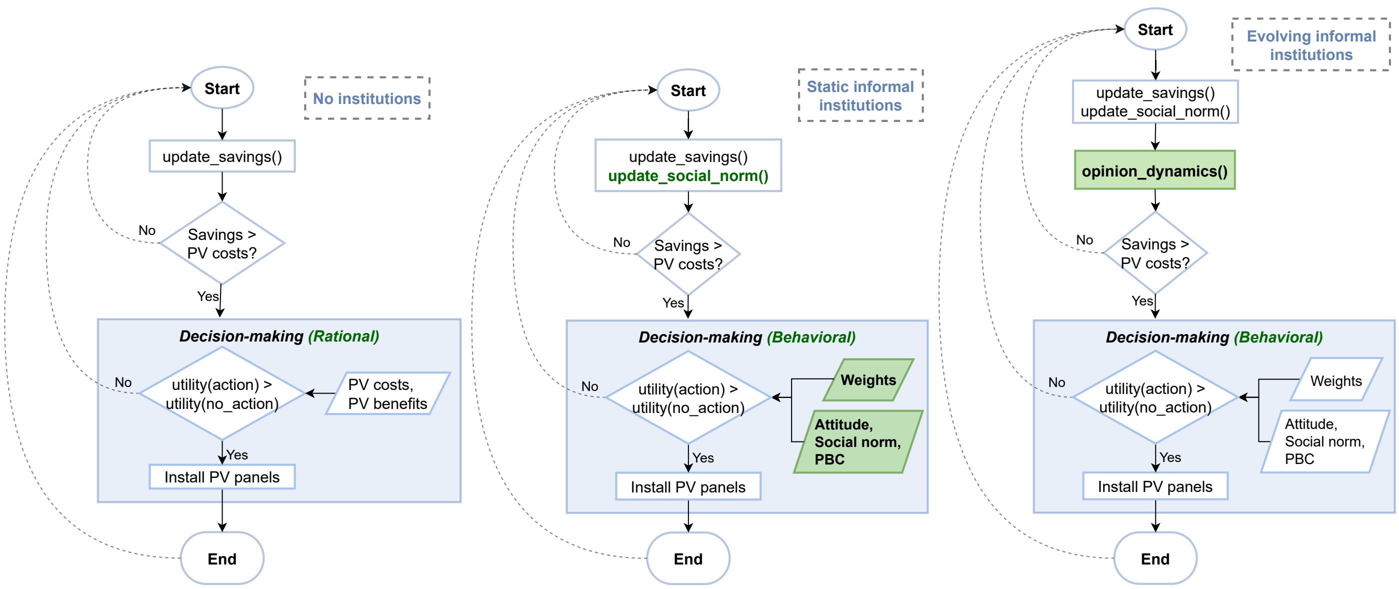
Attribute	Description	Range	Units
Income	Annual household income	[3264, ∞]	Euros
Energy use	Annual energy consumption	[0, ∞]	kWh/year
N_{soc}	Number of social network connections	[0, ∞]	–
Attitude	Attitude towards PV panels	[-1, 1]	–
w_{PBC}	Personal Behavioral Control weight (TPB)	[0,1]	–
w_A	Attitude weight (TPB)	[0,1]	–
w_{SN}	Social norm weight (TPB)	[0,1]	–

Table 1: Household attributes in the energy model.

The household attributes *income*, *energy use*, *attitude* and the weights used in TPB decision-making are parameterized using survey data on adoption of PV panels by households in the Netherlands [Niamir et al., 2018]. *TODO: refer to section where this is explained in more detail.*
The energy model is non-spatial, but agents are connected through a social network, which represents the households' social connections. The model is run with 1000 agents, roughly representing a small neighborhood in a Dutch city, and for 20 timesteps, where each timestep represents one year.

3 Process overview and scheduling

The core of the model is formed by the household decision-making process. This decision-making process is implemented in three different ways, as described in Section 1. In the first version of the model, the agents behave rationally (no institutions), in the second version, the agents make decisions based on the Theory of Planned Behavior (static informal institutions) and finally, in the third version, agents update their attitude towards installing PV panels over time. These attitude updates are determined by certain opinion dynamics, which will be explained in more detail later *TODO: refer to correct section on opinion dynamics.* A schematic overview of each of these three implementations is given below:



(a) No institutions (b) Static informal institutions (c) Evolving informal institutions

Figure 1: Process overview for all three model implementations.

Next to the differences in the design of the decision-making process, the different model implementations have a lot of overlap. In all models, at the beginning of every timestep, all households save a fraction of their income. If they have saved enough so that they can afford to install PV panels, they will start considering investment. In all implementations, it is assumed that households always install the number of PV panels that they need to fulfill their annual energy needs entirely, leaving out possible restrictions on roof size, etc.
Next, households that have saved enough to be able to consider investing in PV panels enter the decision-making module in which they decide whether they will install PV panels or not. If they do, their status is updated from not having PV panels to having PV panels installed, and the model keeps track of how much CO_2 is saved by the households with PV panels installed.

4 Design concepts

4.1 Basic principles

Theory of Planned Behavior (TPB)

The main component of the model is the decision-making process, in which the agents behave rational, or their behavior follows the Theory of Planned Behavior (TPB). In TPB, it is assumed that there are three factors that play a role in human decision-making, namely *attitude*, *subjective norms* and *perceived*

behavioral control (PBC) [Ajzen, 1985]. Together, these factors contribute to one's *intention* to display certain behavior or take a certain action.
The attitude component concerns one's own judgement of whether a certain action (in this case: investing in PV panels) is positive and to what degree it is favorable. The subjective norm describes the influence of (the opinions) of others one's decision to take action. Usually, this is represented by *social norms*, which represents a person's belief on whether others expect them to take action. Finally, PBC indicates a subjective judgement of one's ability to actually take the action that is considered. This usually refers to ease of implementation, previous experience and perceived barriers s.a. financial, time and knowledge constraints.

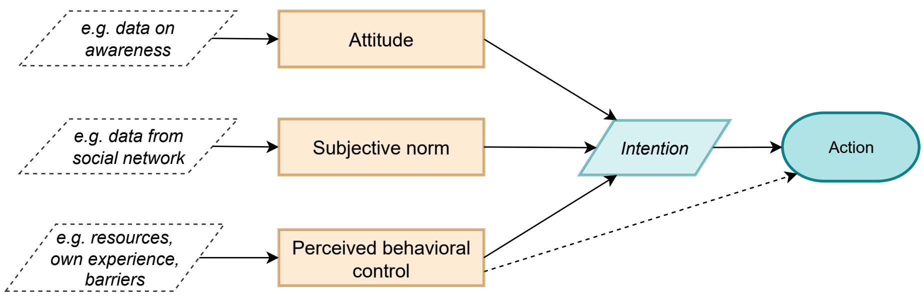


Figure 2: Theory of Planned Behavior, schematic overview.

The attitude component of the TPB decision-making process is quantified using survey data on household decision-making regarding renewable energy options [Niamir et al., 2018]. The social norm is represented by the fraction of social connections that have already taken action by installing PV panels. The PBC component represents financial considerations, and is equal to the financial considerations of rational agents in the model implementation without institutions. It is computed as the Net Present Value (NPV), which weighs the (monetary) costs and benefits to compute the utility of installing PV panels.
In the version of the model with informal institutions (either static or evolving), the utility of installing PV panels is computed as a weighted function of the three TPB components. Weights are parameterized using the survey data mentioned above [Niamir et al., 2018]. This process is explained further in Section *TODO: refer to section*.

Opinion dynamics

In the third version of the model, opinion dynamics are added to the model to allow for households to influence each other's attitude towards PV panels. [Flache et al., 2017] distinguish several ways to implement this social influence: 1) as assimilative social influence, where connected agents always influence each other towards reducing opinion differences; 2) as similarity biased influence, where only similar agents influence each other towards reducing differences; or 3) as repulsive influence, where agents that are dissimilar can also increase opinion differences. For simplicity, social influence is implemented as assimilative social influence, where connected agents influence each other so that their attitudes towards PV panels become more similar over time. However, if we were to model the influence of all agents equally, this would eventually always lead to convergence, which does not seem to apply for attitudes towards renewable energy options. Therefore, the social connections of each household all have a different influence weight, so that some household's opinions matter more than others. More details are given in Section *TODO: refer to right section*

4.2 Emergence

The key outputs of the model are the uptake of PV panels, the associated total cost of investment in PV panels over time, as well as the annual reduction in CO_2 emissions. These results are highly correlated, since higher uptake of the technology asks higher investment and directly leads to lower CO_2 emissions, but, since investment varies in number of PV panels that are installed, the uptake measured as number of households with PV panels installed does not directly predict how much CO_2 is saved. Therefore, both outputs are reported.

4.3 Adaptation

In the model implementation without institutions, households do not exhibit adaptive behavior. Their decision on whether to install PV panels is based on financial considerations that weigh the costs and benefits, which do (in the current version of the model) not change over time. Apart from this decision-making process, they have to meet the requirement that they can afford to install PV panels, which is only met after they have saved enough, but this does not alter their behavior or decision-making.

For the model implementation with informal institutions that utilizes TPB as a decision-making module, household behavior does change over time, based on differences in the social norm component of TPB. This social norm is represented as the fraction of connections in the social network having PV panels installed, meaning that the social norm of other households increases as more households install PV panels.

Finally, adding opinion dynamics to the model implies another form of adaptation, namely changes in households' attitude values. These attitude values are influenced by the attitudes of others in a household's social network. Therefore, depending on the attitudes of their social connections, a household's attitude value might in- or decrease over time.

4.4 Objectives

The objective of every household is to maximize their utility. In the model with rational agents, this means maximizing their NPV, which only takes into account the monetary costs and benefits of installing PV panels. In the other two implementations, with informal institutions in the form of a TPB decision-making module, this means maximizing a weighted utility function, based on all three components of TPB: attitude, social norm, and PBC.

4.5 Learning

Similar to the adaptive behavior described in Section 4.3, household learn about their surroundings in terms of the adaptive behavior that their social connections display. They learn about the number of PV panels installed in their direct proximity through the social network. Second, the social influence in the model implementation with opinion dynamics can be considered as learning as well, since the changes in attitude represent exchange of information as well as opinions between households.

4.6 Prediction

The model investigates different methods of implementing decision-making in ABMs, and is thus not meant for prediction. Agents do implicitly predict their future benefits of installing PV panels in estimating utility, both in rational as well as in behavioral decision-making. Apart from this, the model does not use any form of (explicit or implicit) prediction.

4.7 Sensing

The household agents are aware of the decisions made by other households in their social network: they see the outcome if any other household decides to invest in PV panels. In the model implementation with evolving informal institutions (opinion dynamics), the households are also implicitly aware of the attitude values of households in their social network, in the sense that they are directly infleunced by these attitudes.
Every household also has full information on the (current) costs and benefits of installing PV panels. It is assumed, however, that households have no information on possible changes in costs and benefits in the future. Therefore, they estimate utility based on current values.

4.8 Interactions

In the models with informal information (static or evolving), household interact with each other through a social network. The fraction of households having PV panels installed forms the social norm component of the TPB decision-making process. In addition, in the model with evolving informal information, households also interact through social influence on their attitude values. Attitudes are influenced through social network connections so that connected households are influenced towards decrease differences in attitude towards installing PV panels.

4.9 Stochasticity

Stochasticity plays an important role in the initialization of the model. The initial values of income, energy use and attitude towards installing PV panels are drawn from normal distributions, parameterized by survey data [Niamir et al., 2018]. The number of social connections in households' social networks is drawn from a normal distribution as well, and the influence weights for each of the household's social connections are initialized randomly by being drawn from a uniform distribution between 0 and 1.
Between the intention resulting from the decision-making module and the actual investment to install PV panels, there is also a probabilistic barrier, formed by a draw from a binomial distribution ($B(1, 0.6)$) to determine whether the action is taken or not.

4.10 Collectives

Households form social groups through their social network connections. These connections influence social norms, and, for the model with evolving informal institutions, attitude values. All social groups are connected, so that no disconnected groups exists within the social network. The social groups have no separate functions in the model, all interactions are modeled on the individual household level.

4.11 Observation

Every timestep, the following output variables are collected at the model level:

- The number of households with PV panels installed.
- The cumulative cost of the installation of these panels up to the current timestep. The total cumulative cost of all PV panel installations is then given by

  $$C_i = \sum_{i=1}^{N} (1484 + 428 \cdot PV_i), \tag{1}$$

  where PV_i is the number of PV panels installed by household i, based on their energy use, and N the total number of households in the model.
- The annual reduction of CO_2 emissions, as well as the annual remaining CO_2 being produced by households that did not install PV panels.
  The annual CO_2 produced is given by

  $$\mathrm{CO2}_{\mathrm{produced}}(t) = 0.425 \sum_{i=1}^{N} E_i[PV_i(t) = 0], \tag{2}$$

where $[PV_i(t) = 0]$ indicates that a household does not have PV panels installed at timestep t and E_i is the annual energy consumption for household i.
Annual CO_2 reduction is then given by:

$$\mathrm{CO2}_{\mathrm{saved}}(t) = 0.425 \sum_{i=1}^{N} E_i[PV_i(t) \neq 0], \tag{3}$$

5 Initialization

The model is initialized with 1000 household agents, whose values for the income, energy use and attribute values are drawn from normal distributions, parameterized by the empirical survey data [Niamir et al., 2018]. The survey data is used to directly parameterize the distribution of income and energy use. The attitude values are quantified using survey questions on energy decision knowledge and awareness. The parameters of all distributions can be found in Table 2.
Second, the survey data is also used to parameterize the weights of the components in TPB decision-making. These weights are based on a survey question on motivation for adopting renewable energy methods. From this question, the fraction of the population that is motivated by financial reasons, themselves, or others, or any combination of these three is determined and the agent population is initialized in the same ratios.
Finally, the social influence weights of the social connections of each household are initialized in a range between 0 and 1, so that all weights of the connections of a single household sum to 1.

Variable	**Description**	**Distribution**	**Range**
I	Annual household income in Euros	$N(47052, 25232)$	$[3264, \infty]$
E	Annual household energy use in kWh	$N(2770, 1553)$	$[0, \infty]$
A	TPB attitude component	$N(0.2004, 0.4580)$	$[-1, 1]$
w_{inf}	Influence weights	$U(0, 1)$	$[0, 1]$

Table 2: Distribution of household attributes

Apart from the variables parameterized by the survey data, there are some constants used in the model that describe, for example, energy price or the lifetime of PV panels. These constants are important for households to be able to estimate their revenue, and, on a model level, to estimate total PV investment and CO_2 reduction. All values refer to the year 2021, before consumer energy prices were sharply increasing. All constants are described in Table 3.

Constant name	Value	Units	Source
Savings ratio	0.235	–	[CBS, 2022b]
Interest rate	-0.54877	–	[DNB, 2022]
Average PV lifetime	25	Years	[Consumentenbond, 2022]
PV peak power	370	Watt-peak (Wp)	[Milieu Centraal, 2022]
PV panel efficiency loss	0.1	–	[Consumentenbond, 2022]
Electricity price (fixed part)	-228.70	Euros	[CBS, 2022a]
Electricity price (variable part)	0.25618	Euros	[CBS, 2022a]
CO_2 emission of electricity	0.425	kg/kWh	[CBS, 2022c]

Table 3: Overview of constants used in the model

6 Input data

In addition to the constants used in the model, and the household attributes parameterized by the survey data, there are several input parameters that influence the model. First, in initialization of the social network, the number of connections per household is drawn from a normal distribution. Following [Taberna et al., 2022], the mean of this distribution is initialized at 7. Another input parameter is the influence rate of the opinion dynamics. In addition to the influence weights of each of a household's social connections, this influence rate determines to what extent a household's opinion is influenced at all by his connections. Following [Flache et al., 2017], the default value for this parameter is 0.1. Finally, all implementations of the decision-making module include a probabilistic barrier between the intention to take action and the actual installation of PV panels. This barrier represents for example a time lag in the implementation of the action. The probability of passing this barrier is initialized at 0.6.
The following table gives an overview of the input parameters of the model:

Parameter	Description	Default value
N_{soc}	Average number of social connections	7
μ	Influence rate	0.1
p_{barrier}	Probability to pass decision-making barrier	0.6

Table 4: Overview of input parameters of the energy model

7 Submodels

The energy model consists of several submodels that are all related to the decision-making process(es), namely: 1) rational decision-making (no institutions), 2) behavioral decision-making, based on TPB (static informal institutions) and 3) behavioral decision-making with opinion dynamics (evolving informal institutions). The following sections describe the different decision-making processes in more detail.

7.1 Rational decision-making

As stated before, the model without institutions is based on agents with rational decision-making.
First, it is checked whether the household has enough savings to afford PV panels. If so, it continues to estimate the utility of PV panel investment.
The rational decision-making process only takes into account financial considerations. These financial considerations are implemented as a utility function based on the costs and benefits of either installing or not installing PV panels, computed as the Net Present Value of this action:

$$\mathrm{NPV}_{\mathrm{PV}} = \sum_{t=0}^{t} \frac{B_t - C_t}{(1+r)^t}, \tag{4}$$

where B_t are the benefits at time t, C_t the costs at time t and r the average annual bank interest rate, which represents the extra profit a household would get if it does not invest its money in PV panels. The costs and benefits of installing PV panels for household i are given by:

$$C_{\mathrm{PV},i} = 1484 + 428 \cdot \lceil \frac{E_i}{0.9 \cdot 370} \rceil \tag{5}$$

$$B_{\mathrm{PV},i} = -228.70 + 0.25618 \cdot E_i \tag{6}$$

where E_i is the annual energy consumption of household i.
The NPV forms the utility of installing and not installing PV panels, where the costs of installation are the benefits of no installation and vice versa. These utilities are compared and if the utility of installing PV panels is higher than the utility of not installing PV panels, the household has the intention to install.
Finally, the probabilistic barrier between intention and action is applied. Each household with the intention to install PV panels has a 60% chance to pass the barrier, otherwise the decision-making process is repeated from the start in the next timestep.

7.2 Behavioral decision-making (TPB)

In the behavioral decision-making process, the NPV of installing PV panels or not is computed in the same way as for rational-decision making described above. Again, it is first check whether households can afford to install PV panels, then the utility of installing or not installing PV panels is compared, only now these utilities are based on attitudes and social norms as well as the NPV value that represents the PBC component of TPB.
The utilities of installing or not installing PV panels are computed as a weighted function of attitude, social norms and PBC, given by:

$$U_{\mathrm{PV},i} = w_{\mathrm{A}} \cdot A_i + w_{\mathrm{SN}} \cdot \frac{\mathrm{SN}_{\mathrm{PV}}}{\mathrm{SN}_{\mathrm{total}}} + w_{\mathrm{PBC}} \cdot \mathrm{NPV}_{\mathrm{PV}} \tag{7}$$

$$U_{\mathrm{no\_PV},i} = w_{\mathrm{A}} \cdot -A_i + w_{\mathrm{SN}} \cdot \frac{\mathrm{SN}_{\mathrm{no\_PV}}}{\mathrm{SN}_{\mathrm{total}}} + w_{\mathrm{PBC}} \cdot \mathrm{NPV}_{\mathrm{no\_PV}} \tag{8}$$

where A_i is the attitude of household i towards installing PV panels and SN_{PV} is the number of household connections in the social network with PV panels installed.
Again, the utility of installing PV panels is compared to the utility of not installing PV panels and if this utility is higher, the household has the intention to invest in PV panels. It then again has to pass the probabilistic barrier, and if it does, the PV panels are installed.

7.2.1 Opinion dynamics

In addition, opinion dynamics are added to the behavioral decision-making by applying social influence on the attitude values of the households, so that these attitudes can change over time.
The effect of the social influence if given by:

$$A_{i,t+1} = A_{i,t} + \mu \sum_j w_{ij}(A_{j,t} - A_{i,t}) \tag{9}$$

with

$$\forall i : \sum_j w_{ij} = 1 \tag{10}$$

where $A_{i,t}$ is the attitude of household i at timestep t, and w_{ij} is the influence weight of household j on household i, and $0 < \mu \leq 1$ is the influence rate that determines how fast opinions converge. This μ is equal for all agents. The influence weights w_{ij} are drawn from a uniform distribution $U(0, 1)$ and are nonsymmetric ($w_{ij} \neq w_{ji}$). All opinions are updated simultaneously at the beginning of each timestep.

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