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DOI

[10.1016/j.erss.2020.101782](https://doi.org/10.1016/j.erss.2020.101782)

Publication date

2020

Document Version

Final published version

Published in

Energy Research and Social Science

Citation (APA)

Ghorbani, A., Nascimento, L., & Filatova, T. (2020). Growing community energy initiatives from the bottom up: Simulating the role of behavioural attitudes and leadership in the Netherlands. *Energy Research and Social Science*, 70, Article 101782. <https://doi.org/10.1016/j.erss.2020.101782>

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Growing community energy initiatives from the bottom up: Simulating the role of behavioural attitudes and leadership in the Netherlands

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ARTICLE INFO

Keywords:

Local energy initiatives
Community energy systems
Agent-based modelling
Collective action
Leadership
Solar
Wind energy

ABSTRACT

Local energy initiatives (LEIs) are communities of households who self-organize to meet their energy demand with locally produced green energy. They facilitate citizen participation by developing context-specific solutions, which calls for leadership and complex social dynamics. We present an agent-based simulation model to explore the formation of community energy initiatives from the bottom-up, accounting for social networks and evolution of opinions facilitating or hindering LEIs. Our novel model relies on well-established social theories and uses empirical data on community energy systems in the Netherlands and individual citizens' preferences. Specifically, our computational model captures behavioural drivers and social value orientations, and relates individuals' behavioural traits to aggregated stylized facts about energy initiatives at the community level. The results indicate that when communities lack participants with cooperative orientation, altruistic citizens with prosocial social value orientations become essential for the creation of LEIs, revealing different pathways to achieve public good benefits. Our analysis systematically demonstrates that leaders can be a bottleneck in the LEIs' formation and that an increase in initiators is conducive to the creation of LEIs. Therefore, policies aiming at increasing the number of community initiatives should target small groups and individuals with the leadership potential, who could lead projects, and explore synergies with wider community benefits.

1. Introduction

Enabling energy transitions towards decarbonised energy generation is one of the most pressing challenges of the 21st century. Affordable and clean energy is a prerequisite for countries to achieve their development plans as well as climate change mitigation targets [1]. Exploring the synergies between these goals is fundamental to ensure feasibility and social acceptance of solutions that aim to support the transition from fossil fuel-based technologies to low-carbon renewable energy systems [2]. Countries that are frontrunners in the renewable energy expansion, leverage on decentralised, citizen-driven initiatives to increase renewable installed capacity. These initiatives are laboratories for experimentation and innovation that can generate knowledge for successful policy implementation, transferability, and scalability of solutions [3].

The importance of civil society groups and bottom-up energy initiatives in the energy transition is becoming more evident [4].

Consumers increasingly take active roles in shaping energy systems and seek new forms of engagement to influence their environment [5]. Although there is a vast cohort of literature on community energy initiatives, the current research focuses on their organisational structure, business and financing models, types of technology or the characteristics of members [6–8]. Yet, scientific knowledge on how local energy initiatives (LEIs) are initiated in the first place and how they evolve over time, is limited (e.g., [9–12]).

Furthermore, the mainstream research method in the literature is to extrapolate results from individual cases to derive generalized results (e.g., [13–17]). Simulation models, especially if complemented with data can help generalize principles and support theory development [18]. Simulation approaches are valuable since experimentation with the environment (e.g., by changing technological or institutional settings) is not feasible due to pitfalls regarding the relatively new age of initiatives and the large variety of parameters.

Abbreviations: ABM, agent-based model; LEI, local energy initiative; SVO, social value orientation; TPB, theory of planned behavior; PBT, payback time; SROI, social return on investment.

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<https://doi.org/10.1016/j.erss.2020.101782>

Received 19 March 2020; Received in revised form 3 September 2020; Accepted 14 September 2020

Available online 8 October 2020

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Among different simulation approaches, agent-based modelling is the key approach to study interactions and learning among heterogeneous actors over time in a quantitative manner. With growing applications in energy research, such computational agent-based models (ABMs) rely on solid theoretical and empirical grounds regarding individual decision-making [19], behavioural biases [20] and institutional settings [21,22]. Designed for bottom-up analysis, ABMs help generate better understanding of LEIs dynamics and, consequently, better-targeted policy to stimulate them. However, as a recent review reveals [23], despite ABM proliferation in energy consumption, electricity markets and technological innovations, examples of community-driven energy models are scarce and specially focus on micro-grid and control aspects (e.g. [24–27]).

The goal of this research is to use agent-based modelling to study the behavioural factors that influence the emergence of local energy initiatives. Its innovative contribution to the literature is two-fold. Firstly, by relying on theories of pro-environmental behaviour, leadership and cooperative orientation, we present a novel computational model that simulates the formation of LEIs. Second, we quantitatively explore the bottom-up formation of these initiatives by systematically varying factors that influence their creation. Our theory- and data-grounded ABM with social network dynamics traces feedbacks between actors and local energy initiatives, permitting us to answer research questions that require both a dynamic view and cross-scale interactions among diverse social actors that learn and adapt. Specifically, in this study, we seek to explore what role local leadership and cooperative orientation of community members play in the dynamic formation of LEIs.

The article proceeds as follows. Section 2 presents a theoretical background underpinning the simulation model. We describe the method and data used in the model in Section 3. The ABM concept is presented in Section 4. The article ends with discussing the modelling results in Section 5 and drawing conclusions in Section 6.

2. Theoretical background

2.1. Defining local energy initiatives

Community initiatives are often initiated by several actors who are motivated to pursue a community-wide goal. If these initiators are sufficiently supported by community members, their projects take-off. We define an energy project as an LEI, if it is an organisation initiated, managed or financed directly by actors of the civil-society and if it presents goals associated with the energy sector [13,23,28]. These projects are usually multi-faceted: they combine behavioural measures by, for example, providing information on efficient energy use and by enabling joint procurement of renewable energy technologies [5,8]. They also help in more technical aspects such as development of micro-generation [7,8,29].

Local energy initiatives facilitate citizen participation by addressing sustainable energy issues, building on local knowledge and networks, and developing solutions appropriate to local contexts [8,30]. They help the strengthening of local communities and their autonomy while addressing climate change mitigation goals [31]. LEIs provide strong institutional structures for diffusing renewable and local energy production [29].

From an energy transition perspective, the community-based approach can be understood using a multilevel perspective on technological transitions [32]. Technological transition occurs when there are linkages between multiple levels (landscape, regimes, and niches). Radical innovations spur from the niches level when the regime and the landscape levels provide an opportunity.

Through time, technological niches can evolve and become part of the socio-technical regime [32]. The community-based approach shifts the identity of agents of change. The niches, which are *local units*, become responsible for radical innovations [32]. Therefore, until the new technology is part of the established regime, the technological

transition has a local nature. The transition does not happen because of an abrupt regime shift, but through a step by step process of reconfiguration that results in behavioural changes among individual actors affecting the system level. Seyfang et al. [8], are optimistic that with appropriate support, initiatives can become key players in energy transition. They also attempt to understand the process of niche formation by studying the development of LEIs in the UK [8]. Their work builds on theory and case studies to identify factors for the successful establishment of a renewable energy niche, addressing the civil-society nature and focusing on government support. Here, we focus on and expand the former factor.

Once bottom-up initiatives are successful with their energy projects, they take the shape of community energy systems. In this article, we use the term “Local Energy Initiative” to emphasize the fact that we focus on the initiation of community energy systems.

2.2. Behavioural drivers for initiating or joining an LEI

There are many behavioural theories on actor motivation to join collective action (e.g. [33–35]). Since the body of literature on behavioural drivers in community energy is rich, to build our ABM, we use theories and frameworks that are either specifically developed for LEIs or have already shown their usefulness in this area.

In community energy literature, research has revealed no differentiation among front-runners and ordinary members of community energy projects regarding their motivation [7]. Actors’ motivation is defined by a superposition of distinct goal-frames; some being dominant while others are in the background [7,8]. Moreover, Bauwens [14] has found that when a community logic prevails, members are more norm-driven, while in market relationships the goal shifts towards material incentives.

To build our model, we use an existing framework for conceptualizing citizens’ willingness to participate in community energy project proposed by Kalkbrenner and Roosen [29]. This framework outlines three behavioural drivers rather than having a gain-orientation:

- 1- **Environmental Concern** is related to people’s perception about the damage human activities cause to the environment. Pro-environmental behaviour is often a consequence of environmental concern [29].
- 2- **Trust** is the confidence that other parties will not exploit an individual’s vulnerabilities. Individuals are willing to accept their weaknesses since they have positive expectations about the behaviours of the people, they trust [29]. Trust is associated with volunteering behaviour and is shown as fundamental for financial decision-making in LEIs [36,37].
- 3- **Social Norms** are the perception of social pressure to perform, or not, an action. Social norms manifest themselves through respect; if agents believe they would be more respected by others, the subjective norm would trigger them to join in an activity or behaviour [29]. Norms are usually associated with cooperative behaviour when people face social dilemmas [38].

From a holistic view, **Personal Gain** also motivates stakeholders to participate in community energy projects [3,7,8,39]. Personal Gain is a positive personal outcome resulting from engaging in a certain behaviour such as sharing costs and risks, having fun, saving money as well as, of course, profiting. In addition to Kalkbrenner and Roosen’s three proposed drivers, we use personal gain as the fourth driver for initiating or joining an LEI.

2.3. Role of leadership in LEIs

Individuals willing to take a leading position in LEIs will, as any other leading position, pass through a stage of reasoning and motivation before they are ready to act [40]. An expanded way of assessing

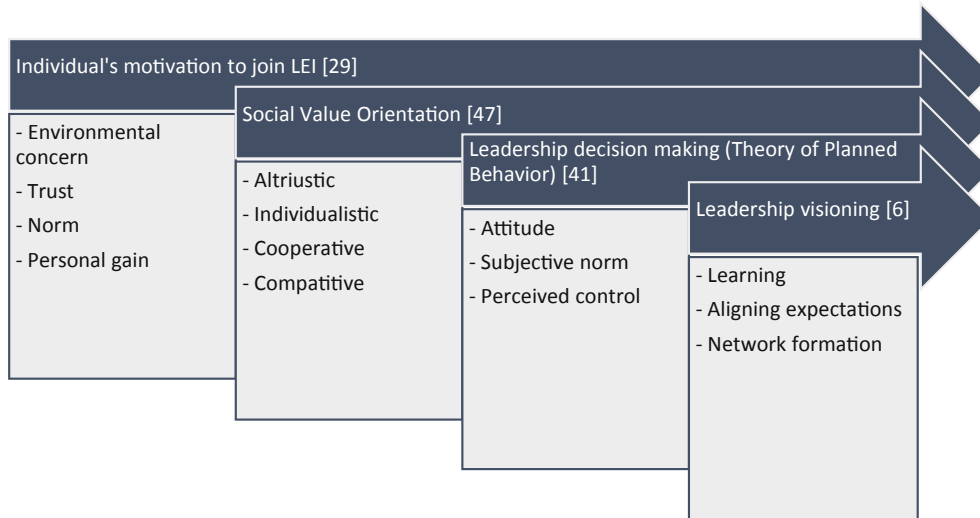


Fig. 1. Theoretical background of the computational model of the formation of LEIs.

leadership decision-making is through the lens of the Theory of Planned Behaviour (TPB) [41,42] which has already been applied in community energy literature [29]. According to this theory, the behaviour of a leader, like any other actor, is preceded by intentions, which are influenced by leaders' global motives [41]. These global motives are: Attitude, Subjective Norm and Perceived Control. Attitude is the way the leader feels towards a behaviour. Subjective Norm is the social pressure felt by the leaders when they need to develop a task. Perceived Control is a subjective measure of how easy it would be to act [41]. This perspective is particularly useful when understanding leaders' decisions in the context of sustainable development since it elaborates the reasons a leader uses as drivers for decision-making [40].

Strong leadership is fundamental when projects need funding, new skills, or more engagement with stakeholders. There are numerous theories on the emergence of leadership (e.g., [43,44,45]) and leader decision making process (e.g., [40]). Here, we base our model on Martiskainen [6] work who has specifically focused on leadership in LEIs. They have identified processes that are correlated with effective leadership behaviours that can foster the development of community energy projects:

1. **Articulation processes (learning):** Articulating experiences and deriving relations stimulate a process of knowledge sharing. Leaders must, for example, be active in pursuing information about funding and technology options and be able to communicate them to others.
2. **Coupling of expectations:** When a project is still immature and its advantages are not well-defined, differences in expectations can occur. Sharing expectations helps in mitigating implementation issues. Leaders possess this ability and confidence to voice expectations about the project's aim and vision.
3. **Network formation:** When the new idea competes with existing ones, stakeholders may try to slow down the formation of an initiative or even entirely block it. To be able to resist these forces, a new network is needed. Community leaders could become intermediaries and use their position in relation to their communities and intermediaries to trigger change.

These three processes will be used to model leadership formation and decision making process.

2.4. Classifying individuals in social dilemmas

Although individuals might have personal drivers (outlined in Section 2.2), they are bound by interpersonal relationships that alter

behavioural preferences. This impacts their response to social dilemmas: people weigh possible outcomes considering the benefits for themselves and others [46]. Accordingly, the Social Value Orientation (SVO) framework, classifies individuals into four groups [47]:

- **Altruistic:** Altruistic individuals are selfless: the opportunity of helping other is their motivation. They are willing to sacrifice their own outcomes for the benefit of others.
- **Individualistic:** Individuals with this orientation do not get involved with other group members. They may have an impact on others, but that is not part of their goals. They are concerned exclusively with the individual outcomes disregarding others.
- **Competitive:** They aim for own outcome maximisation while striving to minimise others. Individuals with this orientation play to win and are indifferent regarding interpersonal relationships.
- **Cooperative:** They aim to maximise other's outcomes together with their own. People with this orientation prefer that everybody is even at the end of an interplay than to win by themselves.

As a final theoretical basis for our ABM, we use the SVO categorization of people to incorporate more heterogeneity in the population of individuals in the formation of an LEI.

Fig. 1 summarises the theoretical stands we employ in our computational model of LEIs. We rely on personal drivers (trust, environmental concern, norm and personal gain) to model the decision-making behaviour of individuals for joining an LEI. We use the TPB [41] to model leaders decision making and apply Martiskainen's leadership process [6] to model their vision building process. Finally, we use the SVO framework [47] to analyse which attitudes leading to energy community dynamics have positive outcomes at the community level.

3. Method and data

We use agent-based modelling to study the emergence of LEIs, as it has already been proven to provide valuable insights for studying emergence of other types of collective action [48,49,50]. This method is key in analysing choices of individuals represented as software agents with adaptive behaviour and social interactions, who are embedded in an environment [51]. Notably, the changes in the environment itself – spatial and/or institutional – are driven by the cumulative dynamics of individual preferences and choices. From here onwards, we refer to individuals as agents in our explanations, to ensure consistency. We use the statistical software R to build, calibrate, and analyse the model.

Besides reports and data from Statistics Netherlands (CBS) [52], we

Table 1

Technology Distribution in Dutch LEIs in 2011–2016. Source [55].

Technology	% of LEIs database	Target Number of Communities
Solar Utility	5.32%	2
Solar Rooftop	81.38%	24
Wind	13.30%	4
Total	100.00%	30

Table 2

Parameters for calculating agent population in a community.

Parameter, Source	Value used in LEI-ABM
Average Capacity Factor [59]	22%
Average Solar Yield [60]	1158 kWh/kWp
Average Population in a Household [61]	2.17
Average Consumption per Capita [62]	6,713 kWh
'Very Interested' People Ratio [53]	8%

use two other disaggregated data sources:

- 1- Survey among 599 citizens in the Netherlands [53]: the survey data is relevant for designing the decision-making processes of agents in the ABM. In addition to demographic information, the survey includes data about individual preferences regarding collective action and renewable energy sources.
- 2- Local Energy Monitor Report: this monitor reports surveys conducted among over 300 community energy projects in the Netherlands as part of HIER *Opgewerkt*. HIER *Opgewerkt* is the official Dutch platform for information about LEIs [54].

Below we provide a brief explanation of some of the data that is used for agent population, drivers, value-orientation, and subsidies. Complete information about other data sources that have been included in the model can be found in [Appendix A](#).

3.1. Data for determining agent population

Each simulation experiment consists of a number of neighbourhoods which are independent of each other. Each neighbourhood is considered as a community where an LEI may emerge. Therefore, the size of the neighbourhood is the *same* size of a community and is predetermined according to the size of existing communities in the Netherlands. The size of an LEI, however, is emergent from the model and determined by the number of agents joining an initiative.

To calculate the number of agents in the model, we use data on the number of communities and the size (i.e., population) of communities where LEIs can potentially emerge. In the Netherlands, the smallest community has 39 agents and the biggest almost 40,000 [55]. Therefore, considering the order of magnitude, the range is assumed to be from 100 to 10,000 agents in each community. The average number of LEIs created every year in the Netherlands is 32.5 [55]. Therefore, the number of communities for the simulation is set at 30, implying that a maximum number of 30 LEIs can be initiated in each simulation experiment. The total number of agents is then calculated by multiplying the number of communities by the number of agents in each community.

By assessing the distribution of technologies among the LEIs founded during 2011 and 2016 ([Table 1](#)), we define target values for the number of LEIs per technology in our ABM.

Besides the size of the population, the shape of distribution is also determined using empirical data. The empirical distribution shows that 80% of the communities have less than 200 people, and that the communities' size drops fast, indicating an exponential distribution for the community population [55]. Furthermore, our model assumes that only a part of the population of a community (i.e., neighbourhood) has their

Table 3

Solar financial parameters.

	Rooftop	Utility	Unit
Subsidy Period	15 [64]	15 [64]	Years
Subsidy	9.0 [65]	5.7 [59]	cents/kWh
Investment Period	25 [67]	25 [67]	Years
Investment Share	100 [55]	30 [55]	%
Electricity Price	3.7 [68]	3.7 [68]	cents/kWh
Investment Costs	1,072 – 1,381 [59]	919 – 1,072 [59]	EUR/kWp

Table 4

Wind financial parameters.

Parameter	Wind Energy	Unit
SDE + Period	15 [63]	Years
SDE+	5.7 [63]	cents/kWh
Investment Period	20 [55]	Years
Investment Share	30 [55]	%
Electricity Price	3.7 [68]	cents/kWh
Investment Costs	900 – 1,900 [59]	EUR/kW
Fixed O&M	30.58 [69]	EUR/kW
Variable O&M	0.0118 – 0.0148 [69]	EUR/kWh

energy supplied by LEIs. To take that into consideration, we use the survey data regarding the level of interest to join an LEI. As a conservative measure, only people that are very interested in joining an initiative (according to the survey) are considered in the calculation of the community population (Eq. (1)).

$$CommunityPopulation = \frac{C * CF}{Con * HS * IPS} \quad (1)$$

Here C is capacity [kW/kWp], CF is conversion factor, Con is consumption, HS is household size and IPS is interested people ratio. We assume that the conversion factor is the capacity factor times the number of hours in a year for wind projects, or the solar yield for solar projects.

[Table 2](#) summarizes the parameters for calculating the population using Eq. (1).

3.2. Data used for agent drivers

Based on the theoretical basis outlined in [Section 2.2](#), there are four drivers for initiating or joining LEIs. Using survey data, we populate agents based on these four drivers. In the survey, there is a direct reference to **Environmental Concern** where actors are asked if they agree with certain statements using a 5-point Likert scale [53]. To instantiate the **Trust** distribution in a community in the model, we combine two survey variables: Community Involvement and Community Trust (5-point Likert scale both). [Appendix A.1](#) provides a more detailed overview of the data used for these drivers.

The **Personal Gain** driver is based on the survey data and is modelled using the social return on investment theory (SROI) [56]. SROI accounts for resource allocation and value creation by attributing monetary values to distinct forms of investment [56]. It captures the idea that stakeholders (i.e., agents) employ money as well as time, when committing to LEIs. Using survey data, we calculate an SROI indicator per agent. Reversing the SROI calculation is equivalent to calculating a payback time (PBT) which will be used in the agent decision-making process (Eq. (2)).

$$PBT = \frac{1}{SROI} = \frac{MI + TI * 5}{YS} \quad (2)$$

Here MI is money investment, TI is time investment and YS is yearly

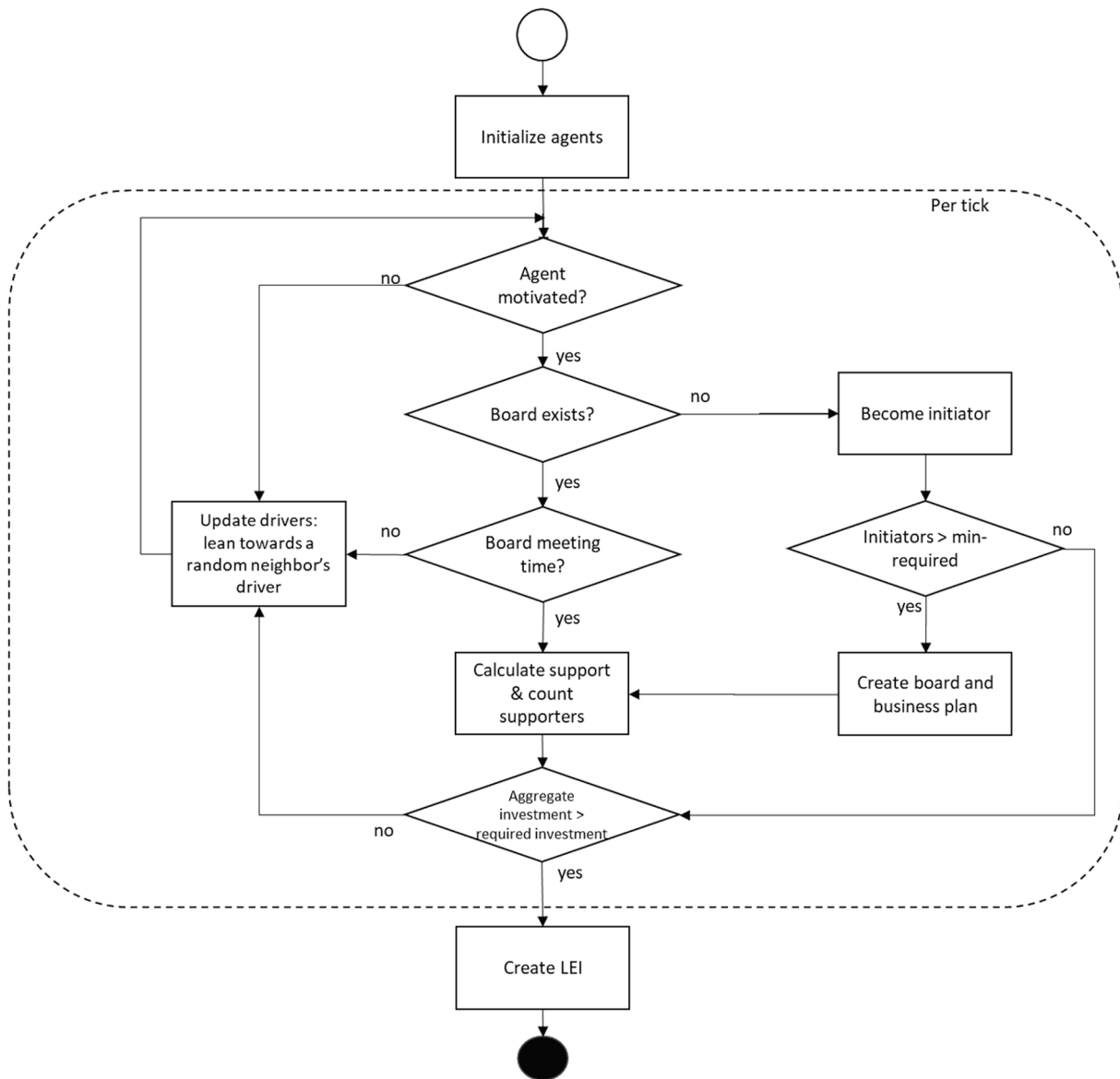


Fig. 2. Overview of the sequences of steps towards a local energy initiative formation simulated in the agent-based model.

savings with bonus¹.

The time investment is arbitrarily limited to five years to capture the idea that people lose motivation to work on community projects as years pass. Each participant in the survey, specified their PBT threshold. By comparing the calculated payback time with the threshold, it is possible to parametrize an indicator ranging also from 0 to 10. More information regarding the personal gain driver can be found in [Appendix A.1](#).

For the final driver – **Social Norm** – we do not have direct survey data for parameterization. Therefore, we rely on the standard opinion dynamics model to estimate the evolution of social norms driven by peer interactions as described in [Section 4.3](#) and [Appendix A.2](#).

3.3. Data on Agents' social valuation orientation

The SVO of the agent is used post-factum to analyse the results of our

simulation. We use the survey data to create social value orientation for the agents in the model. We first identify altruistic and individualistic orientations based on the scores each person gave to the reasons (R) to join an LEI (Eq. (3)).

$$\Delta R = (R_{\text{environmental}} + R_{\text{community}}) - (R_{\text{financial}} + R_{\text{independence}}) \quad (3)$$

If the agent has a higher score for environmental and community reasons than for financial and independency reasons it is altruistic ($\Delta R > +1$), otherwise it is individualistic ($\Delta R < -1$).

If the value of ΔR is between these values, the agent is evaluated on whether it is cooperative or competitive. For that, the information in our survey about the willingness to work with the community is used as an indication of cooperative behaviour. [Appendix A.3](#) provides a more detailed account for SVO parametrization.

The values for various agent attributes (Invest, PBT limit, Wind discomfort, Solar discomfort, Responsibility) that are derived from the survey data are distributed among agents based on their SVO values ([Appendix A.3](#))

¹ A random bonus is added to the savings and may range from 0 to 50% of their energy bill. This is an attempt to include other social benefits like enhancing citizen well-being or the feeling of belonging to the community since these cannot be quantified in this work.

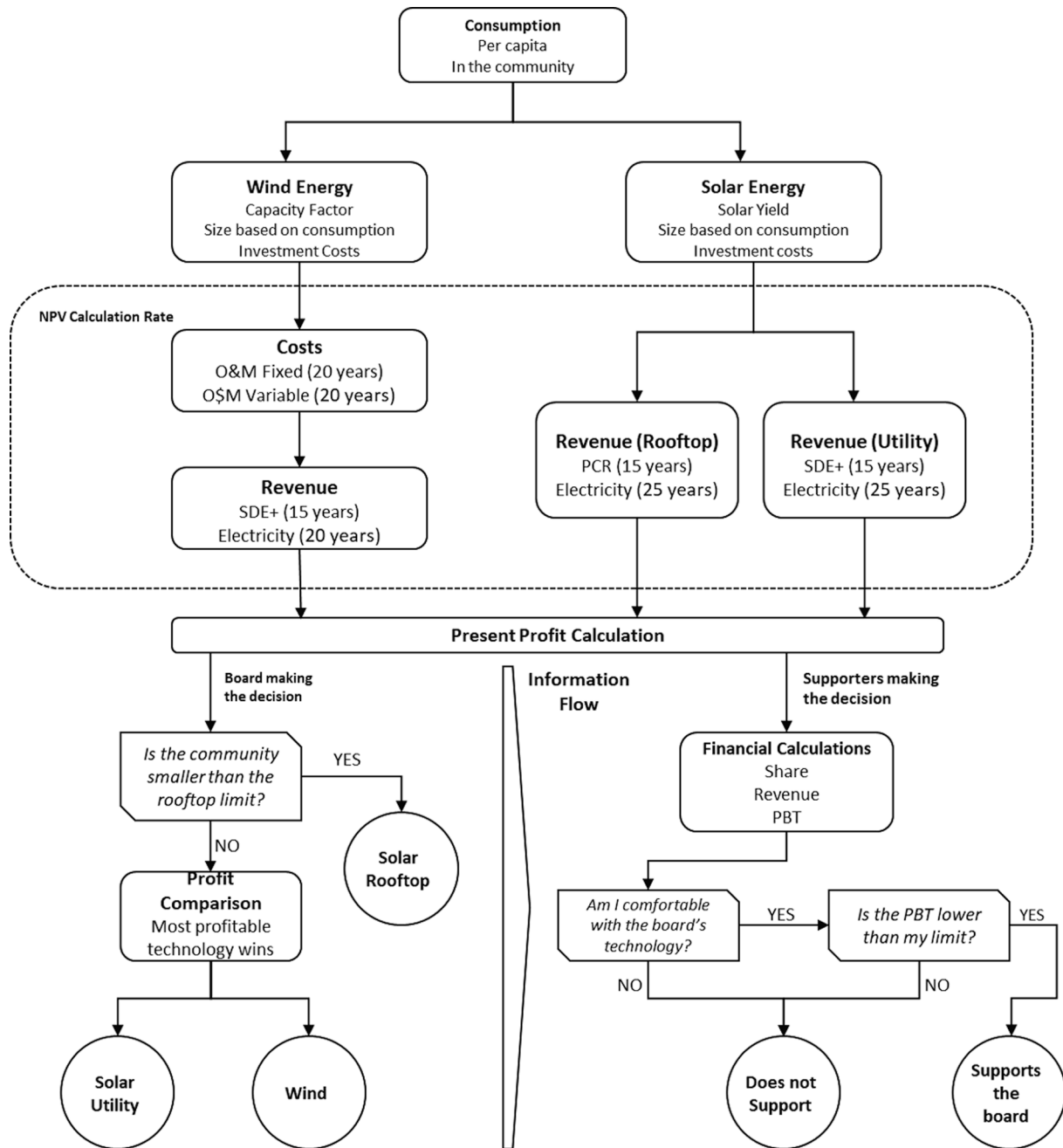


Fig. 3. Sequences of steps in the decision-making of the Leadership board and the Supporters in the agent-based model.

3.4. Data on subsidies and technologies

Subsidies are considered fundamental tools for small scale projects like LEIs [29,31,57,58]. Based on the Dutch regulations supporting LEIs, we model two subsidies: postal code regulation (appropriate for smaller projects) and SDE+ (solar panels with a capacity >15 kWp and wind technology of all size). These subsidies enable the creation of more viable business plans [63,64,65], although they are not necessary. For this model, we assume that all projects use subsidies for the maximum possible period of 15 years [66].

The technology parameters in the model follow the distribution observed in Dutch LEIs. We use the HIER *Opgewerkt* platform to collect all projects' data – names, year when operation started, financing structure and size, for wind in kW and solar in kWp – in one database. For wind projects we consider those that started their operation before 2012 because that is when the SDE + programme started influencing

projects [55].

Dutch LEIs invest in solar energy via photovoltaic (PV) panels in both residential scale, on rooftops, and, utility scale [55]. The main distinction between decisions regarding residential and utility PV panel in this model is the subsidy option. For rooftop projects, the choice is the Postal code regulation that gives 9.0 cents/kWh produced as a tax reduction [64] and is valid up to 15 years [63]. For utility scale, the option is SDE+, with a contribution of 5.7 cents/kWh. The financial parameters related to solar technology are summarized in Table 3.

Similar to solar energy, the data used for wind projects are summarized in Table 4. For wind energy only the SDE + subsidy is considered given the size.

4. An agent-based model of LEI formation

In this section, we explain the conceptualization and implementation

details of our ABM. The assumptions that guide the development of this model are either theory-driven or data-driven as explained in Sections 2 and 3. All assumptions are listed in Table B.1 with reference to their origin. We will refer to Table B.1 in the following text while addressing the assumptions. For a limited number of parameters that we will explain later, the values were not supported by data. Therefore, we conducted a sensitivity analysis to explore the full range of values and their potential influence on model outcomes.

4.1. General model overview

To explore the process of LEI formation, we develop an ABM that simulates the initialization phase of an LEI. The model consists of a number of communities (i.e., neighbourhoods) (Table B.1). Each agent in the model belong to one community where an initiative may emerge.

Each agent can decide to take the role of an initiator or a supporter of an LEI based on its attributes (Appendix A.3, e.g., invest) and drivers (Appendix A.1, e.g., personal gain). The initial values of the drivers are data-driven but these drivers change throughout the simulation as they are influenced by other agents in the community.

Every week (one timestep, Table B.1) agents (re)consider if they would like to become an initiator or a supporter of a project. To determine their motivation, the driver values are checked sequentially per agent; if agents have a high enough environmental concern, their trust in the community is assessed, and finally an ex-ante assessment of their personal gain is calculated. The fourth driver, i.e., the norm, is not directly considered in the decision making of the agent but indirectly incorporated through the social network and the influence the agents have on each other (Section 4.3).

If the agents are sufficiently motivated based on the criteria above, and if there is no leadership board in the community and the agent is willing to take management responsibility (agent attribute, Table B.1), the agent becomes an initiator. After four weeks (1:4 timesteps, Table B.1), if there are sufficient initiators (Table B.1), the leadership group is established. If not, the agents continue to make the same decision regarding joining the initiative in the next time steps until 1) the simulation period is over, 2) the investment of the initiators is sufficient for an initiative and there is no more need for supporters, or 3) the board is established. The board then makes a proposal for the technology and the other agents in the community assess if they support the board or not.

To make an LEI proposal, the leadership board, as a single entity, assesses the community size and the profit of each technology to make the technology decision. Each community member compares the payback time and the technology chosen by the board with their expectations; if both match their preferences, they join the initiative and become supporters of the plan (Section 4.2.3).

The LEI is established if the sum of the agents' investment contributions exceeds the required initial investment. Alternatively, an LEI is formed whenever a solar on rooftop project is small enough so that the investment of initiators is sufficient. In this case, the LEI forms even before the establishment of the leadership board. This case is rare but represents the only possibility for an LEI to be created without the existence of a leadership board. Fig. 2 presents the overall model dynamics, which is discussed in detail below.

Table 5
Summary of driver distributions (normalized).

Driver	Average	SD	Variance	Mode	Median
Environmental Concern	8.34	1.77	3.15	10	9
General Trust	6.31	1.79	3.22	7	6
Personal Gain	5.97	1.83	3.36	6	6

4.2. Leadership vision and member support

By considering the needs and history of the community, the leadership board creates a vision for the LEI [6]. The members then decide whether they are supporters of this vision or not. Fig. 3 provides an overview of both board vision building, as well as members' decision to support.

By collecting information about financing options, technological options, costs, and revenue, the leadership group fulfils part of its learning task [70]. Additionally, by incorporating different discount rates and assessing the population size of the community, the leader can fulfil and align expectations of various community members [70]. Discount rates not only reflect diversity of individual and social preferences but could also cause a pre-disposition to technologies (Appendix B.2).

4.2.1. Financial decision

In practice leaders assess financing options and projects' viability (Fig. 3). In the model, each LEI board calculates the Net Present Value (NPV) of a project (Eq. (4)). The discount rate is used as a calibration variable and discussed in Section 4.4.

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \quad (4)$$

where C_t is the net inflow during period t , C_0 is the total investment costs, r is the discount rate, and T is the number of time periods. The investment costs, as well as the net inflow, depend on the system's capacity, i.e., number of supporters. The discount rate varies among technologies and is calibrated based on technological availability in the Netherlands (Appendix B.2).

4.2.2. Technology choice

The leadership board decides what technology is more suitable for the community based on community size [50]. By assessing the distribution of electricity consumption per capita in the Dutch municipalities [77], it is possible to determine the electricity consumption for the initiative as shown in Eq. (5).

$$Con = N * ph * ipr * con \quad (5)$$

Here Con is Consumption, N is the number of households, ph is the population per household, ipr is the interested people ratio and con is consumption per capita.

The leaders generally do not attempt to fulfil the full electricity demand of the community. However, if the project gets more supporters than initially assumed, it could be scaled up. The LEI board checks if the community is big enough (since 95% of the solar rooftop projects are smaller than 400 kWp [55], this value is used as the threshold for the technology choice) for wind or utility solar project. If not, it opts for the rooftop solar following the financial specifications (Fig. 3). The leadership board considers the financial part using the net-present-value calculation [71] as illustrated in Eq. (4).

4.2.3. Decision to support the board

Potential supporters make the decision based on their own preferences using a multi-criteria decision-making strategy (Fig. 3). First, they will assess if the technology chosen by the board matches their preference. Agents accepts or rejects a technology based on their own attributes that signals to what extent a specific technology is disturbing or not (according to the survey, Table B.1). Then, they will consider if the project adopted by the board is financially attractive for them, by calculating the PBT.

Based on the agent's investment (parameterized using the surveys' distribution) and the vision of the leaders, it is possible to calculate the actual PBT (see Table B.1 and Eq. (2)). The investment share of each agent is calculated dividing the amount he/she is willing to invest in the LEI by the capital costs of the technology chosen by the board. The profit

Table 6
Number of LEIs Created in the model in Distinct Threshold scenarios.

Situation	Threshold	Average number of LEIs created
Standard Threshold	90%	14.00
Conservative Threshold	100%	1.92
Progressive Threshold	60%	22.80

Table 7
Simulation results for neighbour influence percentage.

Dynamics Percentage	Number of LEIs
10%	14.00
20%	17.60
25%	18.07
33%	20.80
50%	21.87
100%	22.73

of each agent is then calculated annually considering this share. Every year, the total amount earned up to that point is compared with the initial investment to calculate the payback time. If this estimated payback time is smaller than the limit (parameterized using survey data), the agent becomes a supporter.

4.3. Networks, trust and norms

In the model, agents interact with other agents only within their community. For each community, all agents are put in a network which is created using the Watts-Strogatz method for small-networks, common in the literature, also in the context of renewable energy [72–74].

Trust is closely related to the social network of agents. Therefore, we incorporated the trust values coming from the survey data to build the social network of the agents. The trust of a community is the average value of the trust driver of its agents. The networks in the model are generated based on trust percentiles using three parameters: network size (number of agents in the community), neighbourhood, and rewiring probability (to simulate changing community trust) (see Table B.1). In the ABM, the higher the level of trust, the more agents are connected in a community. In other words, the denser a network and the shorter the average diameter is, the higher the level of community trust. For each community, the trust percentile is used to assign distinct values of rewiring probabilities. The higher the community ranks in the trust percentile, the higher the rewiring probability in the Watts-Strogatz method. Therefore, the number of weak ties is higher and, consequently, the average diameter of the network is shorter. More details

about the network can be found in Appendix A.2.

To implement the “norm” driver of agents, the agents are influenced by other agents in the network. We do not have survey data to parameterize social norms directly. Hence, we rely on the standard opinion dynamics models: each time step, a random agent interacts with one of the neighbours in its social network and is influenced by it (leans 10% (see Section 4.4.3) towards the neighbours’ values of the other 3 behavioural drivers) [75]. In other words, if the agent’s drivers (Environmental Concern, Trust and Personal Gain) are not above the threshold for joining an initiative, they will be updated leaning towards the selected neighbour’s opinion, this being for better or for worse. This form of opinion dynamic is used at the beginning of each simulation step to update the values of Environmental Concern, Personal Gain and Trust in the community for each agent (Fig. 2).

4.4. Parameter setup and sensitivity analysis

In Table B.1 we have specified all parameters of the model and their value ranges. While many of these values were driven by real-world data, for some, parameter ranges had to be assigned due to unavailability of real-world data. In this section, we explain our parameter calibration and sensitivity analysis for the latter case.

4.4.1. Driver threshold sensitivity

The formation of LEIs is most sensitive to driver thresholds, or the minimum value of a driver an agent needs to have for that driver to be considered fulfilled (Table 5). We define three distinct model scenarios to capture driver thresholds levels: Business-As-Usual (*Standard*) and two extremes (*Progressive* and *Conservative* scenarios). We parametrize these scenarios based on averages values per driver in our survey dataset (Appendix A.1).

To evaluate how the driver *threshold* impacts the final number of LEIs created, we run simulations varying the thresholds in each simulation. The threshold for each driver was set as the average value for the driver multiplied by a factor (25%, 50%, 60%, 75%, 90% and 100%).

On the one hand, the closer to the average the threshold is, the harder it is for an agent to fulfil that driver. In the simulation experiments, the number of LEIs created drops significantly as the threshold for each driver gets close to the reference value, or 100% of the average. We define 100% of the average as the *Conservative* scenario. On the other hand, at a certain point, any further decrease in the threshold value does not lead to the creation of more LEIs; this point is at 60% of the average. We define 60% of the average as the *Progressive* scenario. Finally, the *Standard* scenario is the middle point: the threshold value where the average number of LEIs created is between the *Conservative* and the *Progressive* scenarios. This central point is at 92%, rounded to 90%

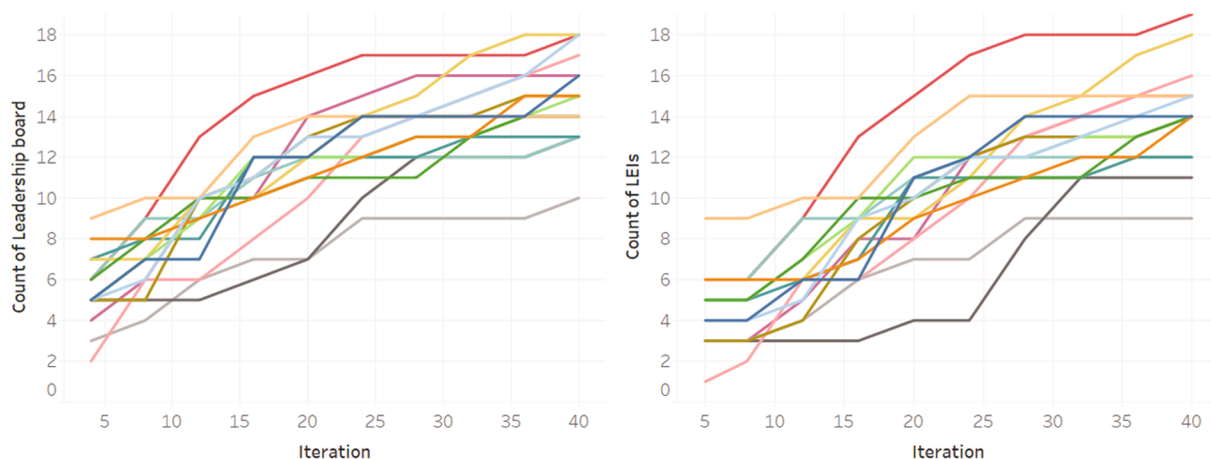


Fig. 4. Count of leadership boards formed (left) and LEI projects initiated (right) over time, for each simulation run (out of 15 repetitions) under the baseline scenario. Each coloured curve represents one simulation run.

Table 8
Summary of driver threshold results.

Threshold	% of LEIs	% of Initiators	% of Supporters
60% – Progressive	78.9%	2.7%	50.8%
90% – Standard	47.3%	1.9%	26.4%
100% – Conservative	6.9%	0.4%	1.0%

Table 9
Average values for characteristics of communities, with and without established LEIs based on technology type of established LEIs.

Technology	Variable (averaged)	Possible Range	Without LEI	With LEI
Utility Solar	Population size	100 – 10,000	917	875
	Consumption	2.30–3.90	2,970	3,077
	Income	1–5	3.73	4.11
	Environmental Concern	1–10	7.02	8.28
	Trust	1–10	5.31	5.78
	Gain	1–10	5.31	5.02
	Capacity Factor	%	20.3%	20.5%
	Solar Yield	kWh/kWp	918	935
	Population size	100 – 10,000	301	429
	Consumption	2.30–3.90	3,065	3,062
Rooftop Solar	Income	1–5	3.94	3.79
	Environmental Concern	1–10	7.12	8.11
	Trust	1–10	5.31	5.73
	Gain	1–10	5.24	5.03
	Capacity Factor	%	20.9%	21.1%
	Solar Yield	kWh/kWp	819	861
	Population size	100 – 10,000	740	926
	Consumption	2.30–3.90	3,197	3,060
	Income	1–5	4.14	4.20
	Environmental Concern	1–10	6.53	7.88
Wind	Trust	1–10	5.13	5.63
	Gain	1–10	5.44	5.07
	Capacity Factor	%	21.3%	21.4%
	Solar Yield	kWh/kWp	661	674

(Table 6).

4.4.2. Network sensitivity

As explained in Section 4.3, the social network is created using the Watts-Strogatz method for small-networks. This method has been long utilised for the study of social network, even in the context of the renewable energy [72–74]. Nonetheless, it does not take into consideration the fact that agents are more likely to connect with other agents that already have multiple connections, meaning that this method neglects the effect of preferential attachment. Therefore, we performed sensitivity analysis to test whether using other types of network structures has any impact on our experiments. The results indicate no significant statistical difference between the average number of LEIs created using other networks structures. Therefore, the fact that the Watts-Strogatz method does not contemplate the preferential attachment does not impact the creation of LEIs. The details of our network sensitivity analysis can be found in Appendix B.3.

4.4.3. Opinion dynamics sensitivity

In our model, the agents lean towards their neighbours' opinions regarding their motivation to join an initiative (through driver values) following the voter's model. In this part of the sensitivity analysis, the influence percentage (i.e., intensity of neighbours' opinion influence) is modified to assess the impact of this parameter in the model. The driver threshold is kept constant and equal to 90% (i.e., standard scenario) throughout this analysis. The results of this sensitivity experiment are presented in Table 7 which indicate that increasing the percentage of the opinion influence increases the number of LEIs created.

This analysis shows that the variation in the number of LEIs created under different opinion dynamic scenarios is equivalent to the variation under the distinct driver threshold scenarios. For a fixed driver threshold, it is possible to define values for the dynamics percentage to obtain the same results as in the three threshold scenarios defined in Section 4.4.1. Therefore, as the impact of these two parameters is equivalent, we assume that the scenarios defined for the driver thresholds are sufficient to capture the uncertainty range and decided to maintain the initial assumption of 10% for the opinion dynamics.

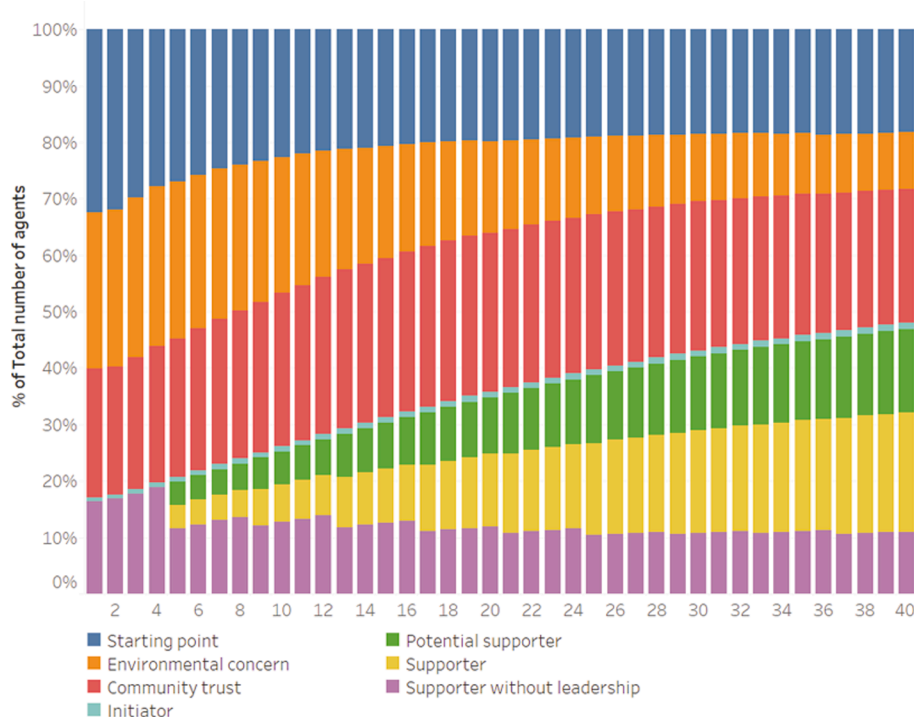


Fig. 5. Evolution of agents state distribution per group over time within simulation runs.

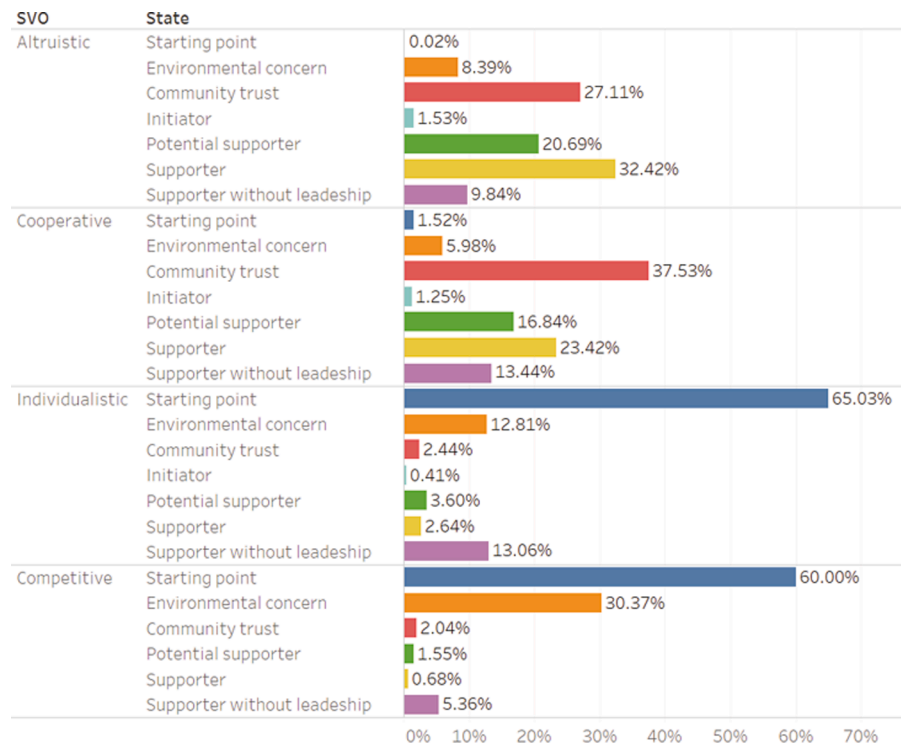


Fig. 6. The distribution of agent states during LEI formation among various social value orientations. Here the starting point is an agent in the simulation who has not yet met the requirements to become a supporter nor an initiator.

As explained earlier, the model covers 30 neighbourhoods [55]. We repeat each simulation experiment 15 times with the same parameter configuration, to take into account the limited number of random values (See Table B.1). We report average values for all 15 runs, unless mentioned otherwise. For all experiments we run the ABM for 40 timesteps [76], each one equivalent to one week (see Table B.1).

5. Results and discussion

We discuss the results obtained from our simulation experiments in steps. First, Section 5.1 presents the *baseline scenario* ('Standard Threshold' in Table 6). In this baseline scenario, the formation of LEI is discussed at three different levels: (1) aggregated dynamics of macro variables such as the total number of communities that initiated LEIs, (2) community variables, revealing the relationship between successful creation of LEIs and community characteristics, and (3) the dynamics at the level of agents.

Second, we explore the role of *Cooperative Orientation* (Section 5.2) and the role of *Leadership* in the formation of LEIs (Section 5.3). For the former, we hypothesize that the existence of agents with cooperative orientation positively influences the creation of community energy projects. Hence, an increase in the number of cooperative agents enhances the likelihood of an LEI being created. For the latter, the hypothesis is that the more people are willing to take responsibility in the incubation of an LEI (i.e., initiators in ABM), the more likely is the formation of an LEI in the community.

5.1. Baseline scenario

5.1.1. Aggregated dynamics

Fig. 4 illustrates the time evolution of the number of communities with leadership boards and established LEIs. The maximum number of leadership boards created in a simulation run was 18, while the minimum was 10, resulting in, on average 61.8% of all communities establishing a leadership board. For the number of LEIs, the highest and

lowest are 19 and 9, respectively, resulting in an average of 47.3% of all runs succeeding in establishing an initiative. A 93% correlation was obtained between the curves of each round. Although this result may seem trivial since the leadership board precedes the LEI, it is not a requirement for it. Nonetheless, if a board is created, it is highly likely that an LEI will also be established. Given the strong correlation, from here onwards, we only investigate the creation of an LEI from now onwards.

A summary of results considering the different driver threshold scenarios is presented in Table 8. In the progressive scenario, 78.9% of the communities created LEIs, 2.7% of the community population were initiators and more than 50% were supporters. In the conservative scenario, only 6.9% of the communities created LEIs. Initiators were 0.4% of the population and only 1.0% were supporters. These results serve further to compare the LEI formation outcomes and cooperative behaviour.

5.1.2. Community-level dynamics

In the model, all LEI boards develop a technological and financial plan (Fig. 3). Nevertheless, only the ones that find supporters realise them. Table 9 summarises the characteristics of communities with established boards per technology type in the model. Communities that opted for utility solar have a higher solar yield as compared to those opting for wind.

We perform t-tests comparing the value of these variables (averaged across the 15 runs for each threshold scenario) between the two groups – Communities with and without LEIs. The only variables that returned a p-value lower than 0.05 are the average population and the behavioural drivers. For all the other variables, there was no statistical difference between the two groups. This implies that the size of the community matters, but as Table 9 reveals in contrast to intuition, smaller communities might be more likely to form LEIs in some cases, which makes the analysis inconclusive. In addition, since the behaviour drivers also stand between success or failure of LEIs, we dive into dynamics at the agent level.

Table 10

Difference in the number of LEIs created given the enhanced cooperative orientation, across 3 model scenarios.

Agent Driver Threshold	Baseline Mean (st.dev.)	Enhanced Cooperation Mean (st.dev.)	p-value
60% – Progressive	23.67 (1.63)	26.87 (1.46)	t(28) = 5.66, p < 0.005
90% – Standard	14.13 (2.53)	17.80 (2.86)	t(28) = 3.72, p < 0.005
100% – Conservative	1.67 (1.29)	1.33 (0.72)	t(28) = 0.87, p = 0.81

Table 11

Difference in the number of LEIs created given the reduced cooperative orientation, across 3 model scenarios.

Agent driver threshold	Baseline Mean (st.dev.)	Reduced Cooperation Mean (st.dev.)	p-value
60% – Progressive	23.67 (1.63)	20.47 (1.64)	t(28) = 5.35, p = 1.00
90% – Standard	14.13 (2.53)	12.20 (2.54)	t(28) = 2.09, p = 0.98
100% – Conservative	1.67 (1.29)	1.93 (1.10)	t(28) = 0.61, p = 0.27

5.1.3. Agent-level dynamics

Agents update their opinion regarding their drivers throughout our simulations. This opinion dynamics may push some agents over the driver thresholds and, if other requirements are met, these agents become initiators or supporters. For the sake of analysis we define 7 different states that the agents can be in as illustrated in Fig. 5: initial starting point, having environmental concern, having trust in the community, becoming an initiator, becoming a supporter, becoming a potential supporter but disagreeing with the board's financial or technological proposal, and becoming supporter without the existence of a leadership board.

Approximately 10% of the agents are part of communities where no leadership board was created (therefore, no LEI) – *supporter without leadership* group. The number of *supporters* and *potential supporters* (agents that want to support an LEI but disagree with the board suggestion about technology or financial terms of the project) maintain a steady growth until the end of the simulation runs. These groups combined represent, in the end, around 35% of the total population. At the end of the runs *initiators* represent 1.85% of the total population on average.

Both *environmental concern* and *community trust* driver thresholds are satisfied for an increasing number of agents by the end of the simulations. In order to become initiators or supporters, the agents need to pass the threshold for personal gain as well. However, *personal gain* is the hardest driver to satisfy. Meeting this driver threshold will probably become easier in the future since it is associated with the perception agents have about their potential financial gain. With the existence of more projects and higher return on investment, people would see better financial prospects.

Finally, Social Value Orientation is linked to the final status of the agents (Fig. 6). Since the SVO of agents was not directly taken into consideration in their decision-making processes, it is interesting to see that the final states can actually be categorized based on their orientation. The difference between the pro-social (*Altruistic* and *Cooperative*) and pro-self (*Individualistic* and *Competitive*) orientations is significant. Initiators and supporters mainly have altruistic and cooperative orientations and there are no competitive initiators. Individualistic and competitive agents do not pass the driver thresholds necessary to join the local energy initiative. As Fig. 6 shows, pro-self agents also disagree more rather than agree with the leadership board.

These results suggest that policy strategies should target pro-social

Table 12

Difference in the number of LEIs created given the enhanced leadership, across 3 model scenarios.

Agent Driver Threshold	Baseline Mean (st.dev.)	Enhanced Leadership Mean (st.dev.)	p-value
60% – Progressive	23.67 (1.63)	30.00 (0.00)	t(28) = 15.00, p < 0.005
90% – Standard	14.13 (2.53)	23.80 (1.86)	t(28) = 11.92, p < 0.005
100% – Conservative	1.67 (1.29)	7.33 (2.19)	t(28) = 8.62, p = 0.005

individuals or cultivate the development of these social value orientations. People that participate in LEIs seem to do so because they either seek to contribute to the public good or to directly bring benefits to others.

5.2. The role of cooperative orientation

It is commonly accepted that cooperative action is the cornerstone of LEIs [3,17]. Nevertheless, the fact that stakeholders work together does not mean that they have a cooperative orientation. It only elucidates that they choose to cooperate to achieve a certain goal, perhaps because it also satisfies individual goals. Therefore, it is relevant to understand what type of agents engage in cooperative action in LEIs (see Section 5.1) and to assess the relationship between cooperative social value orientation and the establishment of these initiatives.

We formulate hypotheses to test the positive effect of cooperative SVO in the creation of LEIs:

- H₀: The mean number of LEIs created is **the same** when there is an increase in the share of cooperative agents.
- H_A: The mean number of LEIs created is **higher** when there is an increase in the share of cooperative agents.

Table 10 summarizes the results for the three driver threshold scenarios, indicating how difficult it is for agents to meet the necessary behavioural driver thresholds – from progressive (easy) to conservative (hard).

These results suggest that increasing the share of cooperative agents has a positive impact on the establishment of LEIs in a situation where the community threshold is *Standard* or *Progressive*. However, increasing the share of cooperative agents does not have an impact on the creation of LEIs in the *Conservative* threshold scenario. This means that in highly connected communities with a high level of environmental concern, trust and personal gain, increasing the number of cooperative agents leads to the creation of more initiatives. Or, in other words, in communities where the population is already aware of the benefits of an LEI, cooperative agents might catalyse the creation of LEIs.

It is important to know if having fewer cooperative agents can have a negative impact. Our two hypotheses here are:

- H₀: The mean number of projects created is **the same** when there is a decrease in the share of cooperative agents.
- H_A: The mean number of projects created is **lower** when there is a decrease in the share of cooperative agents.

The *t*-test indicates **no** significant difference in the scores of the normal and reduced share of cooperative orientation; t(28) = 2.09, p 0.98. This suggests that reducing the share of cooperative agents does **not** affect the success of established LEIs, independently of the threshold value of the drivers (Table 11).

An increase in cooperative orientation is associated with an increase in the number of projects in the *Progressive* and *Standard* threshold scenarios but not necessarily in the *Conservative* one. Nevertheless, when no cooperative agents are present, an LEI is still established with no

significant statistical difference as compared to when cooperative agents are in the community. These results suggest that cooperative orientation is not a necessary requirement for the creation of LEIs. In such circumstances, altruistic agents tend to represent a higher share among initiators and supporters: when cooperative agents are absent, altruists take their role. Hence, it is not a requirement that agents personally benefit from an LEI provided that the community benefits from it.

5.3. Leadership and its role in LEI formation

Leaders or initiators are key agents in the creation of LEIs. These agents are willing to take responsibility and to share their time and expertise to run local energy projects. They bring information from outside their communities, paving the way for supporters to join.

In our standard scenario (Section 5.1), 21% of the population on average disagrees with the vision of the board; 11% on average is ready to support an LEI but is not able to do so due to the lack of a leadership board in their communities. To test the role of leaders, we increase the number of possible initiators in a community to assess its impact on the number of projects. The results are measured using t-tests for two independent samples.

The number of possible leaders is the number of people who are willing to take significant responsibility, e.g. being a part of the foundation/leadership board. This concept is modelled through the *responsibility* parameter (Section A.3), which we modify here to explore the role of leaders. Our null and alternative hypotheses, respectively, become:

- H_0 : The number of projects created is **the same** when there is an increase in the share of possible initiators.
- H_1 : The number of projects created is **higher** when there is an increase in the share of possible initiators.

In the base scenario, the agents' value distribution for the *responsibility* parameter is (based on survey): *No interest in joining an LEI* (25%), *Little Responsibility* (30%), *Not Organizational* (37%) and *Leadership* (8%). In the experiment, we triple the share of leaders while maintaining the relationship among the other responsibility levels. The distribution in the simulation runs for all driver threshold scenarios for this *enhanced leadership experiment* is therefore: *No interest in joining an LEI* (21%), *Little Responsibility* (25%), *Not Organizational* (30%) and *Leadership* (24%).

A summary for all scenarios in this experiment is presented in Table 12.

These results suggest that increasing the number of initiators positively effects the creation of LEIs in all cases, irrespectively of the threshold scenarios for the behavioural drivers. Hence, focussing on initiators is advisable due to several reasons. First, while enhancing cooperative orientation was not useful in the *Conservative* scenario with high driver thresholds, increasing the number of initiators raises the number of LEIs formed in all driver threshold scenarios. Second, most of the non-realized projects in our ABM fail due to the lack of leaders. Finally, a strong correlation between the creation of a leadership board and an LEI exists which highlights that community support is usually found after the board is created.

6. Conclusions and policy implications

Community energy initiatives represent a significant change in how people interact with energy systems due to their decentralized and citizen-lead nature. LEIs increase societal acceptance of renewable energy technologies, speed up their adoption and scale of implementation. Therefore, LEIs are valuable enablers for energy transition.

This research aimed to explore factors that influence the formation of LEIs in a dynamic context, thereby considering social networks and opinion dynamics that play a decisive role in such settings. To address

this goal, we presented the design and simulation results of a theory- and data-grounded agent-based model permitting us to trace the formation of LEIs from the bottom-up. We employ a wide array of data – ranging from individual surveys to statistical databases in the Netherlands – to represent environmental concerns, trust, norms and personal gains as well as social value orientation for simulating agents' behaviour in the model. Specifically, we focused on simulating factors that influence the formation of LEIs in communities and generated insights into the role of behavioural aspects of various agents in this process.

As a typical virtual social science laboratory, this ABM enables experimentation with relevant behavioural attributes, focusing on leadership and cooperative orientation. Our results reveal that leadership is fundamental for the creation of LEIs and that cooperative orientation contributes positively to their development. However, the simulation results demonstrate that higher cooperative orientation does not necessarily increase the number of LEI projects in situations where the community is not receptive (conservative scenario). Therefore, cooperative orientation is not a necessary condition for the formation of LEIs. Both cooperative and altruistic agents constitute a significant part of supporters or initiators. When communities lack participants with cooperative orientation, altruistic citizens replace them. This substitution does not lead to a significant reduction of successful LEI projects. Therefore, **prosocial social value orientations are essential for the establishment of community energy projects**. This result supports the assumption that agents engage in community energy for the benefit of the public good and of others.

The modelling results demonstrate that an increase in leadership impacts the creation of these initiatives positively, irrespectively of other key model settings. Our simulation experiments show that **leaders can be the main bottleneck for the establishment of LEIs**. When a board is created, it is likely that it finds support provided that the leadership takes the characteristics of the communities into account when deciding on technology and size of the project. Governments or third parties interested in the development of community energy systems could support the creation of community leadership practices to support reducing initiators' workload. These could include guidelines concerning applications and permits, or tools to facilitate decision making. Providing this information in a centralised and organised way is paramount.

These modelling outcomes have implications for policies aimed at supporting LEIs. Policies should target small group of individuals who can lead a project. These results highlight the role of initiators and how important it is that these individuals feel safe to come forward and voice their vision to their communities. If anything, this shows that the power for change is in the hand of people from the community.

This research faced some limitations. First, due to limits in computational power, the number of experiments that were explored were limited. Furthermore, one of the important roles of the leadership is networking. The leaders are still able to interact with the community after they become part of the leadership board. So, as individuals, they are still interacting and enhancing the likelihood of other agents surpassing the drivers' thresholds. Nonetheless, networking in an organisational level was not considered. The leadership board as a single entity does not interact with agents or other organisations. Therefore, an area worth further investigation is to assess if leadership interaction with SMEs or the government, for example, may impact agent's perception of the LEI and its creation.

Another limitation of the model is that the agents share their drivers to join an LEI. However, agents may also share their opinion on the technology or on the amount of money they are willing to invest. The focus of this research was on dynamics of behavioural drivers, nevertheless, experimentation with those factors would enhance the comprehension of how other variables impact the creation of LEIs.

A final consideration here is the time dependency aspect. In this model, all communities start evolving simultaneously. Also, the networks are considered static in time. People do not make or break

connections during the simulation timespan, which is unlikely. Since the time dependency is not considered, it is harder to assess the cumulative effect of LEIs in society. By enabling the board to interact with other LEIs and triggering the start of the dynamics in a community by factors associated with neighbouring communities or policy changes, the role of networking and time on the emergence of these initiatives can be further studied.

Finally, we would like to stress that the model presented in this research was extensively driven by Dutch data. We believe that the

model at its core can be applied to other cases around the world given its theoretical underpinning, provided that it is recalibrated with the data of that country leading to tailored insights.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A Data

A.1 Driver values and thresholds

The agent drivers (environmental concern, trust and personal gain) for joining or supporting an initiative are populated with data from the empirical survey [53]. In this dataset, there is direct reference to the **Environmental Concern**: individuals were asked if they agree with certain statements using a 5-point Likert scale. The statements are:

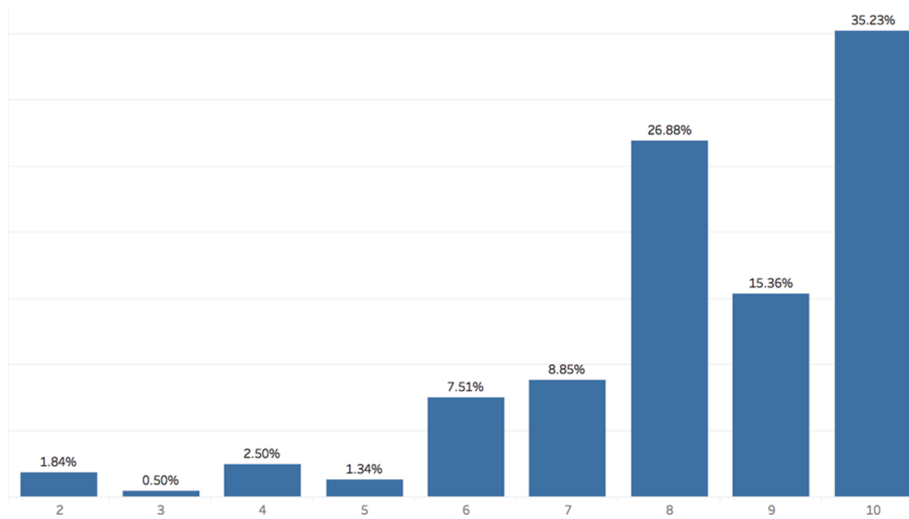


Fig. A1. Environmental Concern Distribution.

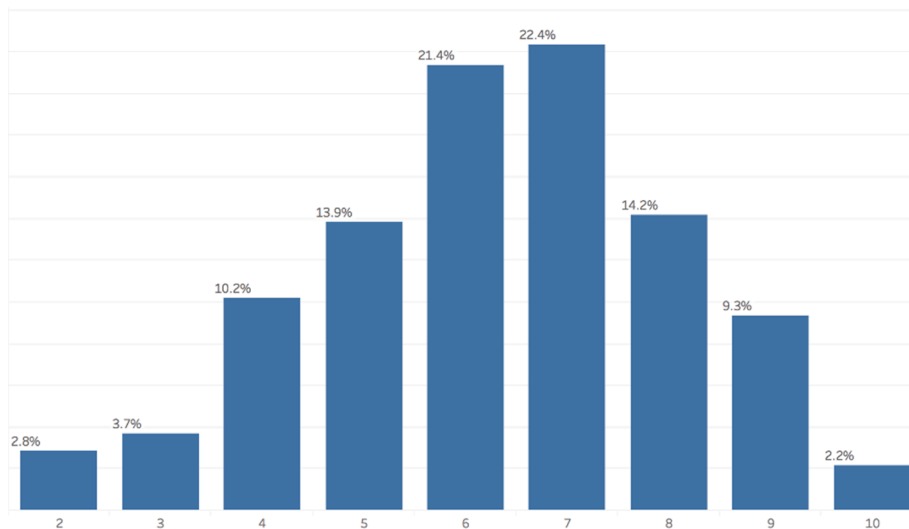


Fig. A2. Trust Distribution.



Fig. A3. Average Scenario Ratings.

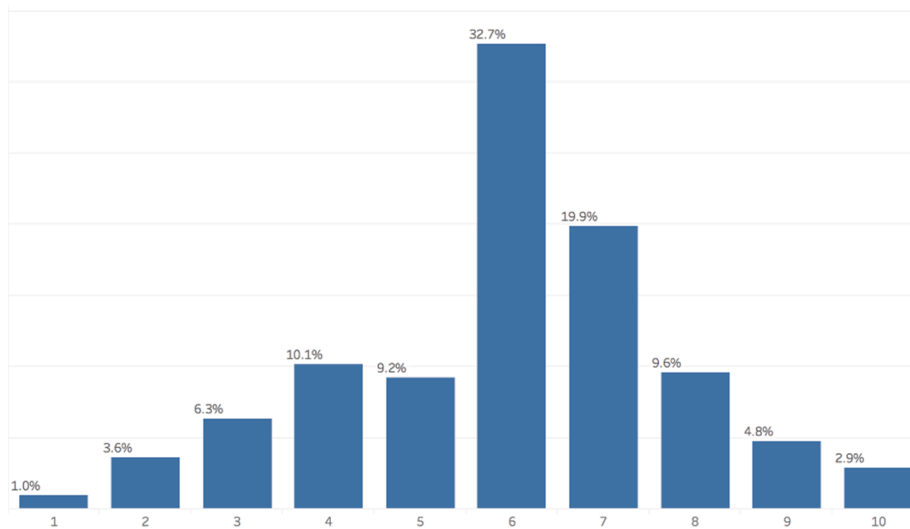


Fig. A4. Personal Gain Distribution.

- I. "I think CO₂ reduction is important".
- II. "I think it is important that the use of fossil fuels is reduced".
- III. "I think climate change is a major problem".
- IV. "I would like for my energy consumption (electricity and heating) to be independent of big energy companies".

Two of these statements are directly related to Environmental Concern, these being I and III. By summing the answers of statements I and III, considering 1 as totally disagree and 5 as totally agree, an indicator ranging from 2 to 10 is obtained. The result is presented in Fig. A.1.

It is important to notice that a large part of the population (86.3%) has environmental concern above average.

It is also necessary to set up **Trust** in the community, in a similar fashion as Environmental Concern. To assess the trust distribution of the community two variables of the survey are combined, Community Involvement and Community Trust. Individuals were asked to rank from 1 to 5 their involvement and trust in the community, so, their sum can be a value between 2 and 10.

Differently from environmental concern, which is clearly shifted in the direction of higher values, trust has a shape closer to a normal distribution as illustrated in Fig. A.2. Still, around 70% of the population possess trust above average. A high level of trust is related to a high level of involvement.

The **Personal Gain** dimension can be modelled using the social return on investment theory (SROI) [56]. In the survey, participants were asked to state the amount they can invest and, also the range of hours they are willing to work with the LEI. The average value of these ranges is used for the calculations except for the latest, in which the floor value is used. The distribution obtained from the survey is presented in Table A.1.

More than 95% of the survey respondents are willing to invest less than 2 h a week in the LEI. There is a clear peak in the range of investment ranging from €2,000 to €5,000, 43% of the respondents are contained in this group. Also, by making an analysis of the level of income of the respondents, no correlation was found between income and investment.

The hours invested must be converted into monetary value, this is done by considering the income of the household and the usual workload of the participant. Also, since one household has, on average, more than one person with income, the income of the household must be adjusted. This correction factor is 1.7 [77].

$$\text{Costhour} = \frac{\text{YearlyHouseholdIncome}}{\text{YearlyWorkload} * 1.7} \quad (\text{A.1})$$

By considering the average number of hours the participant is willing to invest in an LEI and the cost of their hour, the time investment is converted

Table A1

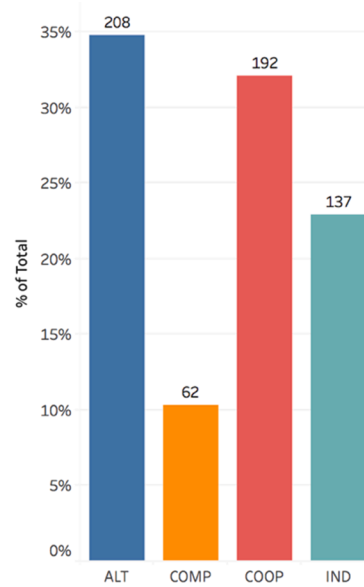
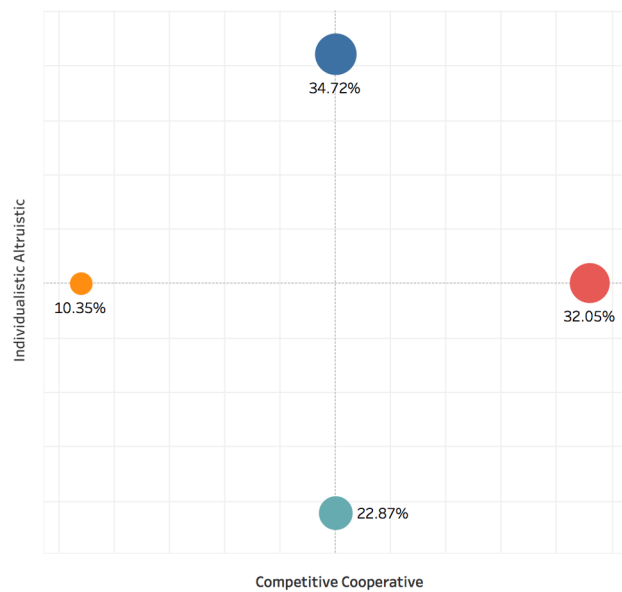
Investment Availability vs Time Availability.

Money availability	0 h	0–1 h	1–2 h	2–4 h	+5 h
0 – €2,000	16.25%	7.16%	1.55%		
€2,001 – €5,000	7.74%	22.24%	12.38%	0.77%	0.19%
€5,001 – €10,000	2.13%	10.25%	9.28%	2.32%	0.19%
+€10,000	1.16%	3.09%	2.71%	0.39%	0.19%

Table A2

Parameters for Social Network Specification – Watts-Strogatz.

Variable	Variable Value	Target	Final
Neighbourhood	5	0.03	0.03
Rewiring Probability	0.028 * Trust Percentile	6.00	5.95

**Fig. A5.** Social Value Orientation.**Fig. A6.** SVO Distribution.

into a monetary value (Eq. (A.1)).

To calculate the return on investment, the 4 ranked scenarios in the survey are used (Fig. A3). The participants were asked to rank the following in a 10-point scale:

- I. **SCENARIO 1:** Based on an investment cost of 5,000 euros, employment of 10 h setting up the LEI in a month with 50% energy savings.
- II. **SCENARIO 2:** Based on an investment cost of 10,000 euros, employment of 10 h setting up the LEI in a month with 80% energy savings.
- III. **SCENARIO 3:** Based on an investment cost of 5,000 euros, employment of 30 h setting up the LEI in a month with 80% energy savings.
- IV. **SCENARIO 4:** Based on an investment cost of 10,000 euros, employment of 30 h setting up the LEI in a month with 50% energy savings.

Table A3

Level of Investment Distribution per SVO.

Category	0 – €2.000	€2.001 – €5.000	€5.001 – €10.000	+€10.000
ALT	18%	64%	91%	100%
COOP	16%	65%	90%	100%
IND	36%	74%	96%	100%
COMP	69%	95%	98%	100%

Table A4

PBT Limit Distribution per SVO.

Category	1–5 years	5–10 years	10–15 years	15–20 years	20–25 years
ALT	29.78%	82.58%	98.31%	100.00%	100.00%
COOP	30.95%	82.74%	97.02%	98.81%	100.00%
IND	46.72%	86.89%	98.36%	100.00%	100.00%
COMP	72.73%	96.36%	100.00%	100.00%	100.00%

Table A5

Agent's Level of Acceptance of Wind Technology.

Category	1.0	1.5 & 2	2.5 & 3	3.5 & 4	4.5 & 5
ALT	3.37%	23.08%	60.58%	86.06%	100.00%
COOP	14.06%	34.90%	67.19%	90.63%	100.00%
IND	16.06%	40.88%	69.34%	87.59%	100.00%
COMP	16.13%	45.16%	75.81%	93.55%	100.00%

Scenario 1 is the most well ranked (6.43) and it assumes energy savings of 50% while scenario 3 is the second best (5.97) assuming saving of 80%. Both scenarios assume the same monetary investment and differ considering the number of hours the person would be willing to employ in the project. While the difference between these scenarios, in terms of rating, is relatively low, scenario 3 is based on an hour commitment of 30 h a month, this is not realistic considering participants' availability presented above. Considering that, the return is assumed to be 50% of their energy costs that are also presented in the survey².

Furthermore, to include some other possible benefits everyone may have from the participation in the LEI a random bonus is added to the savings and may range from 0 to 50% of their energy bill. The threshold value of 50% was defined because 50% of savings would cover the time investment of the majority of the population surveyed. This is an attempt to other social benefits like enhancing citizen well-being or the feeling of belonging to the community since these cannot be quantified in this work.

The time investment was arbitrarily limited to five year to consider the fact that people lose motivation with time to work on these types of projects with the passing of years. Also, each participant, in the survey, chose which is their PBT threshold. By comparing the calculated payback time with the threshold, it is possible to design an indicator ranging also from 0 to 10 as illustrated in Fig. A.4.

A.2. Social network parametrisation

Every agent has an intrinsic environmental concern, a level of trust in the community and a perception of their personal gain. But, since they are embedded in a network, they are also subject to opinion dynamics. This is one alternative to model **social norms** by looking at peer interaction. It is possible to calculate the trust percentiles to generate the random network. Three parameters need to be defined: network size, neighbourhood, and rewiring probability.

The number of actors in the community defines the network size. To implement the concept of trust in the social network to use both the diameter and the density. We keep the neighbourhood variable constant and use the trust percentile to define the rewiring probability. The neighbourhood variable is adjusted to obtain an average density of 0.03, which is the survey obtained a density of 60 villages [78]. The rewiring probability is used to simulate the community trust and is defined to maintain the thumb rule of 6 degrees of separation, that states that everything in the actor's world in within six steps of him/her [79]. Which implies that the mean diameter considering all networks in the simulation should be 6. Table A.2 summarizes the key values.

The minimum diameter is 2.99 while the maximum is 10.79. The minimum and maximum densities are 0.065 and 0.0952, respectively.

A.3 Data for social value orientation

To use the SVO framework there is need to classify our individuals into one of the four groups. Although the data was not specifically collected for this purpose, in this work, it is enough for a proxy using a multi-stage classification method.

The first step is based on the identification of altruistic and individualistic orientations. This is done by using the scores each agent gave to the reasons to join an LEI. It is assumed that if the agent has a higher score for environmental and community reasons than for financial and independency reasons he is altruistic, if the opposite happens than he is individualistic. It is important to state that there is no scale within the group, an individual

² One important remark is that some respondents did not know their level of income of energy monthly expenses. These participants will result in an SROI with value zero and are excluded when calculating the indicator.

Table A6

Agent's Level of Acceptance of Solar Technology.

Category	1	2	3	4	5
ALT	5.77%	15.38%	31.25%	60.10%	100.00%
COOP	4.17%	17.19%	35.42%	61.46%	100.00%
IND	7.30%	16.79%	35.04%	54.01%	100.00%
COMP	11.29%	22.58%	45.16%	66.13%	100.00%

Table A7

Level of Responsibility and Agent is Willing to take in an LEI.

Category	No interest	Little Responsibility	Not organizational	Considerable Responsibility
ALT	16.3%	54.3%	89.4%	100.0%
COOP	14.6%	48.4%	91.7%	100.0%
IND	32.1%	55.5%	92.7%	100.0%
COMP	74.2%	80.6%	100.0%	100.0%

cannot be more altruistic/individualistic than other (see Eq. (3)).

Moving to the second step, the variable that contains information about the willingness to work with the community is assessed, since this is an indication of cooperative behaviour. If the agent is willing he is classified as cooperative, otherwise competitive. The results of the classification are presented in Fig. A.5.

As it can be seen most of the population in this community presents prosocial orientation, amounting to 67% of the total number of participants in the survey.

It is also expected, considering the pro-self group, that individualistic orientation is more significant than competitive in this context. In a community, an individual will not benefit directly from a negative outcome for others, which can be different in a business context. This said, if an individual is pro-self, it is more likely that he will be individualistic than competitive.

All in all, it is assumed that these results support the use of this proxy methodology to classify the agents into the four groups of social orientations presented above and this information can be used to add heterogeneity to the agents in the model. To combine the information of social value orientation and the behavioural drivers, a different distribution is used for each SVO.

The first step is to give the agents their social value orientation by using the distribution in Fig. A.6.

Most individuals are altruistic (34.7%) or cooperative (32.1%), which are *prosocial* orientations. This is assumed to have a positive impact on the formation of LEIs. The remaining agents are individualistic (22.9%) or competitive (10.4%); *pro-self* orientations. The SVO of the agent is not used in the decision-making process. This attribute is responsible for giving heterogeneity to the agents, enabling further description of results and experimentation.

For each SVO a different distribution of drivers and attributes is given. Besides the drivers discussed in detail previously: Community Trust, Environmental Concern and Personal Gain, other important attributes are assigned to the agents in this step. These are given below with their description and running total percentage per SVO:

- o INVEST: Amount the agent is willing to invest in a Local Energy Initiative (Table A.3)
- o PBT_LIMIT: Maximum amount of time an agent is willing to wait to have their return on investment (Table A.4)
- o WIND: To which extent is the agent disturbed by wind energy technologies, considering both sight and noise factors. This indicator ranges from 1 (very disturbed), to 5, (not disturbed at all). Since noise and sight factors were considered separately in the survey, the average value was taken in the model (Table A.5)
- o SOLAR: To which extent is the agent disturbed by the sight of solar panels. This indicator ranges from 1, very disturbed, to 5, not disturbed (Table A.6).
- o RESPONSIBILITY: the level of responsibility an agent is willing to take after joining a Local Energy Initiative (Table A.7)

Finally, after assigning these attributes that are dependent on the SVO, the income is assigned to the agents. There are five possible income values. The lowest household income is *Bijstandniveau*, or Assistance, meaning that the agent's only income comes from governmental assistance, this group represents 3% of the population and is assumed to have an annual income of €16,800, based on the maximum income of € 1,404 per month [80]. The second group represents 5% of the community and ranges from Assistance to Average, or *Modaal*. The average income value was given in the question and is taken as €28,500 per year. The other three levels are defined based on the average. The third level is Average (12%), the fourth from Average to Twice Average (29%), and the fifth Above Twice Average (51%)³.

³ Agents that did not provide income information were filtered in the analysis.

Appendix B: Assumptions, Parameter Setup and Calibration

B.1 Assumption and parameter values

Table B.1 summarizes the employed parameter values in the ABM of LEI formation. To avoid duplication, we omit here the financial information about solar and wind energy calculations already summarized in the main text.

Table B1

ABM settings: Parameters' Summary.

Parameter	Type	Value	Source	Comments
Number of Communities	Numeric	30	[55]	Total number of communities in a simulation.
Population Range	Range	100–10,000	[55]	Factors defining the exponential probability distribution to attribute the population size.
Exponential Factor	Numeric	0.0035	Sensitivity analysis	The exponential parameter specifies how fast the probability drops with the possible size of the community.
# Altruistic	%	35	Survey	Social Value Orientation assigned randomly (using these percentages) among the total number of agents in a simulation
# Cooperative	%	32	Survey	Social Value Orientation assigned randomly (using these percentages) among the total number of agents in a simulation
# Individualistic	%	23	Survey	Social Value Orientation assigned randomly (using these percentages) among the total number of agents in a simulation
# Competitive	%	10	Survey	Social Value Orientation assigned randomly (using these percentages) among the total number of agents in a simulation
Environmental Concern	Distribution	1–10	Survey	The environmental concern of an agent. It is dependent on the SVO with average of 8.34.
Trust	Distribution	1–10	Survey	The trust an agent has in the community. It is dependent on the SVO with average of 6.31.
Personal Gain	Distribution	1–10	Survey	Contains the perception of personal gain based on a preliminary PBT calculation. It is dependent on the SVO with average of 5.97.
Invest	Distribution	1,000–10,000	Survey	Amount, in euros, an agent is willing to invest. It is dependent on the SVO and has four possible values.
Payback time Limit	Distribution	5–25	Survey	Maximum time, in years, an agent is willing to wait to have his/her investment returned. It is dependent on the SVO and has five possible values.
Wind Discomfort	Distribution	1–5	Survey	5-point Likert scale containing the level of discomfort an agent has with wind technology. It is dependent on the SVO.
Solar Discomfort	Distribution	1–5	Survey	5-point Likert scale containing the level of discomfort an agent has with PV technology. It is dependent on the SVO.
Responsibility	Distribution	1–4	Survey	Attribute containing the level of responsibility an agent is willing to take, ranging from not interested in participating (1) to management responsibility (4). Depends on the SVO.
Income	Distribution	1–5	Survey	5 categorical groups containing the level of income of the agent ranging from 16,800 to 57,000 per year.
Consumption per Capita	Distribution	2,300–3,900	[77]	9 groups containing the level of consumption per capita in the Netherlands.
People in a household	Numeric	2.17	[61]	Average number of people living in a household for community consumption calculations.
Inflation Rate Factor	%	1.11	[78]	Factors used to define the discount rate in the NPV calculation for the board technology decision.
	%	0.13		
Neighbourhood	Numeric	5.00	[78,79]	Used by the Watts-Strogatz method to obtain a mean network density of 0.03.
Rewiring	Numeric	0.028	[78]	Used by the Watts-Strogatz method to obtain a network mean diameter of 6.
Probability				
Thresholds	%	60, 90, 100	Sensitivity check	Percentages applied to the average of each driver distribution to contemplate unusual situations for opinion dynamics.
Weeks	Numeric	40	[76]	Timespan of the simulation, in weeks. One week is one tick
Dynamics	%	10	Sensitivity check	How much an agent leans towards the opinion of a neighbour he/she interacts at each time step.
Percentage				
Agents in the board	Numeric	5	[8]	Minimum number of agents for a leadership board to be created.
Weeks until meeting	Numeric	4	[76]	At the end of every month (4 weeks) the community gathers and checks for the existence of a leadership board.

B.2 Calibration of discount rate

The relationship between the discount rates of wind and utility solar is altered to replicate the distribution of these technologies. Both wind and utility solar, in the NPV calculation, start being discounted using the current inflation rate in the Netherlands, 1.1% per year [81]. Wind energy is, in general, more profitable. In order to avoid wind power from winning over utility solar in all runs and also, to try to encompass social elements into the leadership board's technological decision, the discount rate is adjusted. The discount rate is increased for wind energy, while decreased for utility solar. The starting value of the factor is 0.00 and is increased by 0.01 in every loop until the wind energy has twice the number of communities of utility solar.

This simulation runs 1,000 times for the calibration of the exponential factor and the discount rate factor. The exponential factor parameter specifies how fast the probability drops with the possible size of the community. The results are presented together with the standard deviation of the value distribution in Table B.2.

The discount rate is attributed to the communities using a normal distribution with the same average and standard deviation⁴ presented above.

⁴ The discount rate for solar rooftop is only the current inflation.

Table B2

Calibrated parameters to match technology distribution.

Parameter	Average	Standard Deviation
<i>Exponential factor</i>	0.0024	0.0003
<i>Discount rate factor</i>	0.1301	0.1429

Table B3

Parameters for Social Network Specification – Barabási-Albert.

Item	Control Variable	Control Variable Value	Item Target	Item Final
Density	<i>Number of Links</i>	4.00	0.03	0.03
Diameter	<i>Degree Exponent</i>	1.25	6.00	6.04

Table B4

Comparison Watts-Strogatz vs Barabási-Albert.

Situation	Threshold	Number of LEIs Watts-Strogatz	Number of LEIs Barabási-Albert	p-value ¹
<i>Standard Threshold</i>	90%	14.00	14.20	0.82
<i>Conservative Threshold</i>	100%	1.92	1.91	0.56
<i>Progressive Threshold</i>	60%	22.27	22.80	0.50

¹ The condition of homogeneity of variance and independence are satisfied in all three cases and the data is assumed to follow a normal distribution.

B.3 Network sensitivity analysis

It is possible to use other methods than Watts-Strogatz to build the social network; one well-established algorithm is the Barabási-Albert one. The mechanism behind is simple; it adds new connections using the number of links one actor already possess to elevate the probability to connect to that agent. It simulates the fact that, in a social network, new players tend to link to the more connected ones. While, in random networks, like the Watts-Strogatz, agents randomly choose their interaction partners [82].

At each time step, the algorithm adds a new node with m connections to other nodes, the higher the number of connections the higher the density of the network. Also, the final network has a degree distribution that obeys a power law with degree exponent γ , which impacts the mean diameter of the network. Therefore, a similar calibration to the one performed for the Watts-Strogatz is done using a method with preferential attachment in Table B.3.

The simulation ran 1,000 times to calibrate each item. The number of links and exponent degree were changed to obtain the target values for network density and diameter. The simulation is executed using the parameters defined in Table B.3. That is done to assess if the application of a social system with a preferential attachment would impact the results. It is noteworthy that the social network created by this new method has the same density and diameter as the ones before. Therefore, the only difference is in the structure of the social network with hubs. Table B.4 summarises the results using a Barabási-Albert network.

The results in Table B.4 show the mean number of LEIs created per threshold situation. There is no significant statistical difference between the average number of LEIs created using distinct networks structures. All comparisons resulted in a p-value higher than 0.05 in a two-sample t -test. Therefore, the fact that the Watts-Strogatz method does not contemplate the preferential attachment does not impact the creation of LEIs.

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