Model conceptualization

The model represents a city with multiple neighbourhoods. It assumes each neighbourhood can implement one thermal energy community. In each community, there are individual households who make decisions on whether they are willing to collectively generate and consume renewable thermal energy together. The municipality as a representative of government, has limited budget per year (e.g. subsidy), to facilitate the implementation of thermal energy communities in the city. The model conceptualization is based on the IAD framework as follows.

1.1.1. Participants: agents

The agents included in the model are households, the board of energy communities and the municipality, each representing one of the four layer models of Williamson (see Section 3.1.)

- **Social embeddedness.** Each agent has a particular value system that guides their decision making processes and level of involvement in the formation of thermal energy communities.
- **Institutional environment: the municipality.** This layer comprises the political, legal and governmental formal arranges, the "rules of the game" that shape the activities in the lower layer. In the model, the municipality, which represents the departments of the government that is responsible for the energy transition, is responsible for defining the formal institutions that will be in place to support the neighbourhoods' transition off gas. These include setting eligibility requirements for subsidies, and providing training for the energy community boards.
- **Governance: the TEC board.** This layer looks into the modes of organization which are formalised with contracts and agreements that describe division of roles and responsibilities. In the model, it is assumed that from the start there is already a group of people interested in leading the transition to a natural gas free area in each neighbourhood and who will take ownership of the project. The TEC board is responsible for achieving enough household support, organising the individuals who participate in TEC, initial decision-making regarding to collective technology, negotiating and applying for subsidies as representatives of TEC. The TEC board also has a specific set of values, which define its vision, and it is able to participate in trainings in order to learn how to persuade more individuals to participate in the project.
- **Individual analysis: households.** These are the individual households forming the neighbourhood, who are initially using natural gas to cover the demand for thermal energy in the houses and hold a specific set of value preferences. In a later stage, they can adapt their value preferences influenced by the preferences of their neighbours and can decide to participate in the TEC initiative by supporting the technology scenario, making the required investment and installing the technology.

1.1.2. Action situation and interactions: Model narrative

Agents as representatives of participants, interact with each other and make decisions, which follows a narrative based on the establishment process of TEC initiatives. There are action arenas in which agents interact with each other based on various exogenous variables.

Idea phase

- Individual households decide on whether they support the TEC board' on their role of leading and owning the TEC based on whether their visions align. Before the initiation of the community, the household agents use natural gas to cover their heating demand.

Feasibility phase

- If training is available for the TEC boards and the TEC board has not yet participated in it, the TEC board will go through it in order to gain skills and learn how to better communicate and connect with the households within the neighbourhood.

- When the TEC board has sufficient household support, it goes through a value based multi-criteria decision making process (MCDM) to select the collective system to be implemented in the neighbourhood. In MCDM, different criteria, such as financial gain and environmental concerns will be used to make the final decision. The MCDM results is reported to the TEC board supporters (first MCDM).
- When TEC board supporters receive the information about the TEC board's MCDM, they evaluate this option through an individual MCDM process. Individuals might value criteria such as financial gain and environmental concerns differently than TEC board. If households have the same perception on the collective system, they will support it (second MCDM).
- Once there is sufficient support for the collective technology, households go through a second MCDM process to select their preferred individual technology option to complement the collective system (third MCDM).

The details of three MCDMs are presented in Section 6 and Appendix.

Procurement and building phase

- The TEC board considers the most supported scenario and conducts a technical and investment feasibility analysis for the collective and individual components of the selected scenario. For the technical feasibility, energy generation (input energy), CO_2 intensity technology, and average capacity and load hours are used. For investment feasibility, criteria such as life-time, investment costs, operation costs and availability of subsidies are used.
- Based on the investment required and the total amount the technology supporters are willing to invest, the TEC board calculates how much subsidy they need to request in order to cover the full investment. If this amount does not exceed the maximum amount the government is willing to give to one neighbourhood the TEC board sends the request.
- The municipality receives the subsidy requests and once a year considers the TECs that have applied for the subsidy. The municipality ranks the requests based on their own subsidy distribution strategy and provides the subsidy to those that meet their criteria until all the funding has been used.
- After receiving the subsidy, the thermal energy community goes into a construction state for half a year and once the infrastructure is in place the community is considered to be set up.

Expansion phase

- After the initial set up of the community, "non-supporters" can re-evaluate their participation: check if they support the TEC board, and the selected energy scenario. If their willingness to pay is equal or lower than the investment required per person in the neighbourhood, they will be willing to make the changes and connect to the community.
- Depending on the participation policy of the TEC board, households will be able to make the required changes any time (i.e. under individual participation policy) or they will have to wait until they have gathered enough neighbourhood support for the expansion of the TEC in order to connect to the district heating infrastructure (i.e. under collective participation policy).

1.1.3. Biophysical conditions-technology

As described in Section 2.3., biophysical conditions include natural surrounding and human-made infrastructure, which in this study the focus has been on thermal energy technologies. There are several technology scenarios from which the households, TEC boards and the municipality can choose from. For simplification, although in reality the district heating (DH) infrastructure can be of low or medium heat, in this ABM it is assumed that only one alternative is possible. The Heat Expertise Centrum (ECWa, 2020) has identified eight key sustainable heat sources for the Netherlands: aqua thermal energy storage, geothermal, green gas, bioenergy, residual heat, hydrogen and solar heat.

Among all of these sustainable heating technology alternatives, aqua thermal energy storage, waste heat from surface water, and bioenergy are the heat sources which have been included in this ABM model since they are the alternatives which are currently more readily available and the ones which need to overcome the least barriers for implementation. For individual applications, solar thermal (ST) and individual heat pumps (HP) are considered. The information and data regarding these technologies are presented in Section 6.1.

Besides of the technology, another surrounding condition would be the size of the city, which is translated as number of neighbourhoods in the model. According to Netherlands Environment Assessment Agency (PBL) [137], [138], on average each neighbourhood has 660 households and majority of Dutch municipalities have 7 neighbourhoods or less. Although this scale is relatively small (as it does not represent the metropolitan areas), it is insightful to explore the municipality's size in the context of TEC initiatives.

1.1.4. Attributes of community

It is assumed that neighbourhoods are not connected to each other. As a result, each neighbourhood forms a network that is independent from each other. To simulate the social structure of each neighbourhood the model uses a small world network [139], [140]. Within this approach, the nodes represent households, and the edges connect households that interact with each other.

Following the BRT, norms and values are at the core of the factors that influence the final intention and decision making of an actor. [74] concluded that the key values to consider when studying energy community systems are environmental concern, energy independence and sense of community. To these, a fourth one has been included which is that of financial concern [88], [141]. As a result, all agents in the model have a perception of their own internal values and how they are ranked with respect to each other.

Regarding the dynamics within the neighbourhood, the ABM assumes that all households in one neighbourhood can interact with each other. It is assumed that households interact in monthly residents' meetings where it is assumed that 10% of the neighbourhood participate. The dynamics occur based on the following principle as argued in [39]: When two households interact, each will slightly lean towards the opinion of one another attempting to simulate peer pressure. Lastly, it is assumed that households with very extreme values (either high or low) will not be peer pressured and hence will not influenced by the interaction. Table 5 in Section 6.2. presents the data related to the attributes of communities that are used in the simulation.

1.1.5. Rules-in-use

Following Stimuleringsregeling Duurzame Energie (SDE), and the Netherlands Environment Assessment Agency (PBL), the regulations and subsidies related to each technology are implemented.

As in studies such as [69], and [105] mentioned, training leadership skills is considered as a municipality's policy. If the municipality provides training for the TEC initiative's boards, then as skilled boards they are able to persuade more households to join the TEC initiative. Also, it is important to capture the participation policy for individual households who will join the community after it has been created. The two options for participation policy are: (A) participating instantly after the household decides to join, (B) household will join a buffer (i.e. waiting list), and when the buffer is full (i.e. enough households are willing to join), all of them will join the TEC initiative. These two options represent individuals' joining processes for energy community initiatives which are discussed in studies such as [34], [142], [143].

As municipality's budget is limited per year, one of the most important rules for decision-making is how the municipality decide to allocate the available subsidy. Following studies such as [34], [60], [144], In the model, there are four available policies for community initiatives: economy (least economic burden for the municipality), environment (most CO_2reduction option), social (most participants) and trade-off (a balance between the three). Lastly, the amount of municipality's budget is important. In the Netherlands Environment Assessment Agency (PBL) the limitation is 4 million euros per municipality.

1.1.6. Evaluation criteria and outcomes (model's KPIs)

In order to understand and measure performance of the simulations, key performance indicators (KPIs) are defined. Table 1 presents the evaluative criteria that will be used as key performance indicators to analyse the outcomes of the different experiments.

Table 1: Description of key performance indicators used to evaluate the model outcomes

Key performance indicator	Unit	Description
Cumulative CO_2 emission reduction	%	Percentage reduction of the total CO_2 emissions after 10 years in comparison with the reference scenario where 100% of the neighbourhood uses natural gas for heating the houses
Final share of neighbourhood TEC board support	%	Percentage of the neighbourhood households that supports the thermal energy community after 10 years irrespective from whether they are connected or not
Final share of neighbourhood participation in TEC	%	Percentage of the neighbourhood households that is connected to the district heating infrastructure after 10 years
Duration of formation process	months	Time that takes from the moment the TEC board gets stablished to when the thermal energy community starts generating
Collective technology selection	-	The collective technology that the neighbourhood has selected and installed in the neighbourhood (biogas, ATES, heat recovery from wastewater)
Individual technology selection	-	The individual technology that the neighbourhood has selected and installed in the neighbourhood (nothing, heat pump, solar thermal)
Average household investment	euros	Average amount a household from the neighbourhood is willing to invest in the establishment of a thermal energy community.
Share of community investment	%	Share of total investments covered by the neighbourhood. The rest is assumed to be covered by the subsidy dispatched by the municipality.

Table 2 summarises the key characteristics of the agents in the model as well as the key tools they have to influence the decision-making process simulated in the ABM. Figure 4 also illustrate the model's narrative.

Table 2: Agents, their roles and characteristics

	Agents		
	Municipality	**TEC board**	**Households**

Role	CO_2 emissions monitoring and policy implementation	TEC project decisions and leadership	Level of project participation land investment
Biophysical conditions	Municipality size	Skills	Annual heat consumption and CO_2 emissions
Attributes of the community	*Heat vision objective:* cost minimisation, autonomy maximisation, participation maximisation and emission minimisation	*Values ranking*: environmental concern, energy independence and financial concern	*Values ranking*: environmental concern, energy independence and financial concern *Social value orientation* *Payback time and willingness to pay*
Rules in use	Subsidy schemes Subsidy allocation strategy Provision of workshops CO_2 tax	Technology decision policy Minimum neighbourhood participation policy Process duration policy Expansion policy Household persuasion	Technology decision policy Investment decision strategy

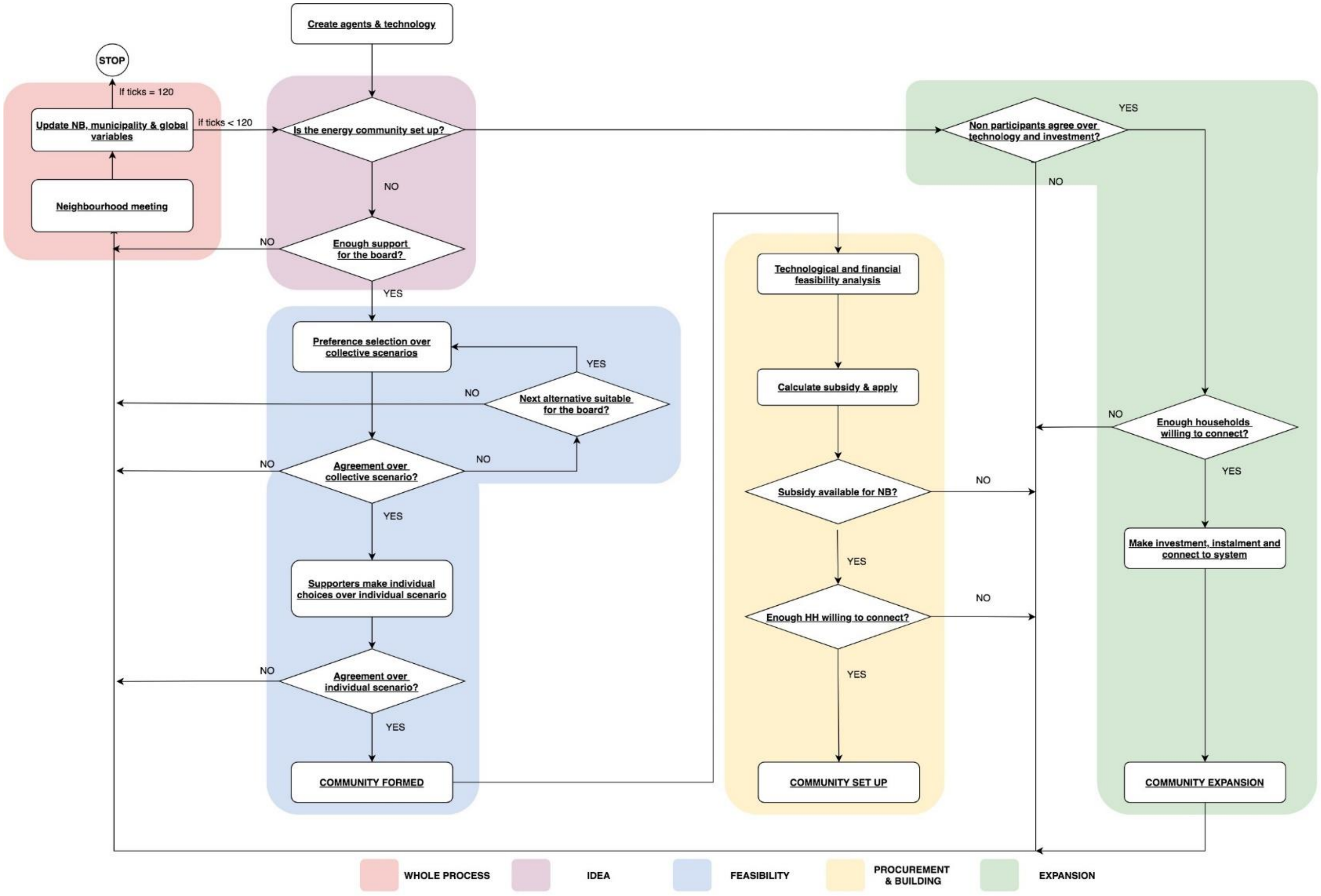

Figure 1: Overview model structure