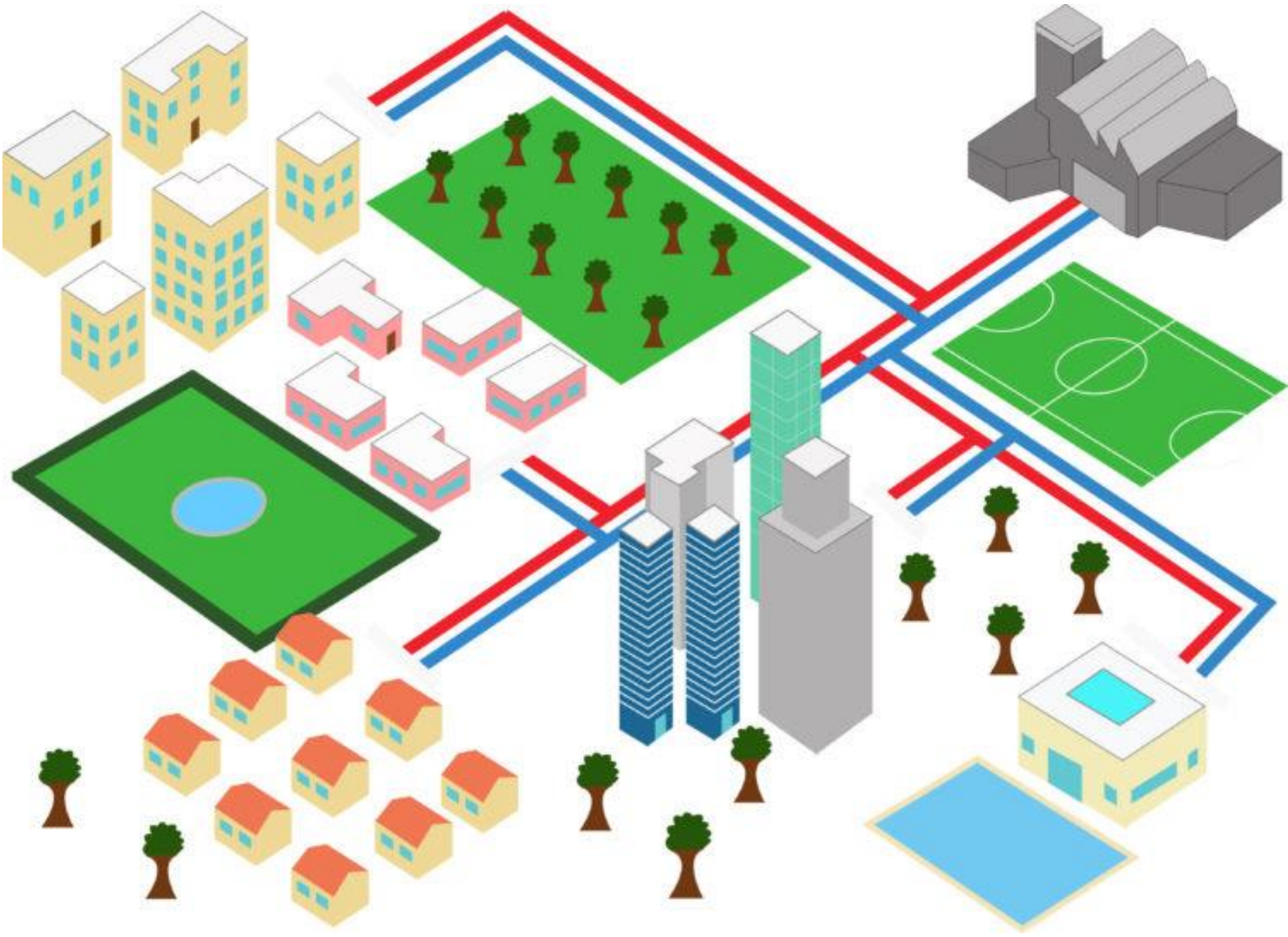
INTERVENTIONS TO SUPPORT THE FORMATION OF DUTCH THERMAL ENERGY COMMUNITIES



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MSC INDUSTRIAL ECOLOGY | TU DELFT & LEIDEN UNIVERSITY

SEPTEMBER 2020

INTERVENTIONS TO SUPPORT THE FORMATION OF DUTCH THERMAL ENERGY COMMUNITIES

By

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to obtain the degree of **Master of Science** in **Industrial Ecology**

at the Delft University of Technology and Leiden University,

to be defended publicly on Thursday September 24, 2020 at 9:30.

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“There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.”

– Niccolo Machiavelli

EXECUTIVE SUMMARY

Thermal energy communities (TECs) are a key element for the transition to a more sustainable heat sector in Europe. These initiatives promote collective citizen action to address various aspects of the heating transition (Gregg et al., 2020). TECs can be defined through three main components: (i) a technology for the generation, distribution and consumption of heat, (ii) involved actors and their roles and (iii) related institutions, formal and informal rules that govern a thermal energy community (Fouladvand et al., 2020).

Overall the technological component of TECs has been thoroughly researched, while the governance and institutional components are relatively understudied. This is problematic since the adoption of sustainable heating technology is not hindered by the technology itself since this can already be considered mature, but by the challenge of redesigning the current institutional context (Busch et al., 2017). Consequently, there is a need to better understand what changes at the institutional and governance level are required to overcome the barriers currently hindering the establishment of these communities and hence, the diffusion of sustainable heating technology in Europe.

As a result, an agent-based model (ABM) of thermal energy communities in the Dutch built environment is developed to provide insights on what techno-institutional conditions enhance the establishment of thermal energy communities. The research follows a case study approach in order to understand the thermal energy transition at the community level and be specifically able to describe how TECs form and progress over time. The study focuses on the case of the Dutch heating sector since the institutional environment of this sector is currently going through a transformation and re-design process to enable the diffusion of sustainable heating technologies.

The theoretical background that serves as the backbone for the conceptualisation, implementation and analysis of the ABM is formed by two frameworks for institutional analysis and three theories. On one hand, this research applies Ostrom's (2005) Institutional Analysis and Development (IAD) framework, and the four layer model of Williamson (1998) to identify and categorise the actors, decisions and actions that are most relevant in the TEC formation process. Then, to identify the factors that better predict the outcome of the decision making processes of actors involved in TECs, the research applies the Behavioural Reasoning Theory, Social Value Orientation Theory and Multi-criteria Decision Making technique.

The model's results show that, regarding the technological conditions, scenarios which combine collective and individual technologies are preferred among Dutch neighbourhoods over fully collective scenarios. Nevertheless, the model also showed that technology selection itself is not the most crucial and determining factor of the success of thermal energy communities but the institutional conditions surrounding it are.

Regarding the institutional context, the model demonstrates that projects are likely to be successful when TEC projects are built on a shared vision across agents that highly and equally values (i) developing energy independent communities, (ii) using environmental friendly heating generation technologies, and (iii) providing heat at an affordable price. Lastly, the results demonstrate that it is crucial to have supportive institutional conditions that are responsive to the local context and needs.

In order to develop such enabling institutional environment in the Dutch context, this research recommends (i) sharing decision making and financial responsibilities among all actors involved in the design and implementation of municipal heat plans, (ii) the design of fiscal structures that focus on supporting those TEC projects that are able to balance out project costs with its potential environmental impact, and (iii) the development of programs that improve the marketing capabilities of TEC boards to increase resident's knowledge about the heating transition and their participation in TECs.

This research expands the knowledge of the use of an ABM approach for providing insights on the institutional factors and conditions that influence TECs and it is the first one to do so for the context of the Netherlands. Additionally, it is first example of an ABM developed through the combination of the IAD framework and the four layer model of Williamson (1998). The research has proven that the combination of the IAD framework and four layer model of Williamson allows (i) to progress from a general to a detailed description of the ABM model concept, and (ii) to move from a detailed interpretation of the model simulation results to a generalisation of such into practical recommendations.

Finally, next steps should involve conducting interviews with experts and practitioners to further validate the results and find ways for the insights to be included in the design of policies related to TECs in the Netherlands. At the model level, further work could focus on incorporating other relevant actors such as social housing associations, energy companies or DSOs. Alternatively, it could focus on better representing the actors already included by conducting surveys to input more concrete and detailed information.

ACKNOWLEDGEMENTS

Writing the master thesis for the MSc of Industrial Ecology has been a seven month journey full of ups and downs. The situation in which the COVID-19 pandemic put us all did not make things easier. However, with the great support of my supervisors, colleagues, friends and family I have been able to overcome all the barriers that came my way.

I would like to specially thank my three supervisors Amineh Ghorbani, Thomas Hoppe and Javanshir Fouladvand. Thank you Amineh for being a role model and for all the attention you have placed in critically assessing my progress to reach to a great level of analysis and in making sure we, your master students, felt supported despite the pandemic circumstances. Thank you Thomas for irradiating your dedication and enthusiasm for the topic of energy communities, for your insightful and critical observations and for always having a door open for spreading out my research within your network of practitioners and researchers. And last but not least, Javanshir, you are the core pillar of what this graduation. Despite your full schedule and dedication to your loved ones and your work, you were always there for me whenever I needed support: you acted as a screening board where all of my crazy initial ideas could be thrown to, as the devil's eye when the research needed a critical eye to move forward, as a mentor when I needed encouragement in the darkest moments of the thesis, but most importantly as a friend that I could always rely on. Thank you to the three of you because you made my thesis very challenging, exciting and enjoyable.

Furthermore, I want to give a special recognition to my family for all the flexibility and support that they have shown when I decided to move back to Madrid in March to spend the lock down and the uncertain times with them. Being close to home definitely made the journey easier. I would like to give a special acknowledgement to Concha Peral, for being the key emotional support in the past half a year. Thank you for creating the safe space I needed and for becoming someone I could be accountable to.

Finally, a shout-out to my fellow students, family and friends whom were always willing to discussed my thesis topic and provided new perspectives that helped the research grow and improve. Thank you.

Maria Aranguren Rojas

Delft, September 2020

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

The deployment and installation of renewable energy technologies (RETs) is considered to make major contributions to the global objective of transitioning to a low carbon energy sector (Fuss et al., 2012; Pacesila et al., 2016). The energy transition is being discussed and executed at different scales: international, national, regional and local (Koirala et al., 2016).

At an international scale, studies have focused for instance, on the role of specific technologies in the future global energy supply mix (Gallo et al., 2016; Breyer et al., 2017; Gielen et al.,2019), on the material requirements for the energy transition (Watari et al., 2019; Valero et al., 2018) or on performing comparative studies of the transition pathways in different regions (Pachauri and Jiang, 2008; Pacesila et al., 2016; Yu et al., 2020). Nevertheless, most of the research on the energy transition has been conducted at a national scale. Studies have focused for instance on forecasting the future national energy mix (Essletzbichler, 2012; Koskinen, 2016), on analysing the key drivers and barriers for the transition (Ren et al., 2015), or on the evolution and transformation of the national energy policy (Kern and Smith, 2008; Li et al.,2020; Shrestha and Dhakal, 2019).

The diffusion of renewable energy technology is not only promoting the transformation of the energy sector at a global or national scale but it is also enabling new local actors such prosumers, groups of citizens and local communities to participate in the purchase and production of energy (Ruggiero et al., 2018). There is not a clear definition of this local approach to the energy transition yet "*energy communities*" is the term most commonly used in the literature to define it (Seyfang et al., 2013).

The literature on local energy communities so far has been dealing with deriving a clear characterisation of the concept. Overall, energy community is an umbrella term that encapsulates all initiatives that promote collective citizen action to address various aspects of the transition to a low carbon energy sector (Gregg et al., 2020). These collective actions involve activities such as the collective procurement of energy technologies and the decentralised generation, distribution and consumption of renewable energy (Walker and Devine-Wright, 2008). Regarding the main characteristics of energy communities, Bauwens (2019) states that there are five key institutional aspects that describe these local energy initiatives which are: (i) technology at local scale, (ii) community engagement, (iii) participatory decision-making, (iv) involvement of local actors and (v) communal distribution of financial actors.

Moreover, the literature on energy communities has looked into the potential impacts of these communities on the energy transition as a whole. In Europe, community energy initiatives have been argued to be transforming the way in which energy is being produced and consumed by promoting the use of renewable energy (Viardot et al., 2013). The discourse around this concept describes it as a phenomenon that is able to disrupt and change the current energy sector (Koirala et al., 2016). On the one hand, it promises to have positive environmental impacts by promoting renewable energy production and consumption and hence, accelerating urban energy transition (Tomor, 2018). On the other hand, community energy projects are also linked to positive societal impacts such as the promotion of democratic values, citizen empowerment, equality, social cohesion, connectivity and inclusion (Cheng, 2016).

Although the energy community concept encapsulates both the electricity and thermal sector, the literature is dominated by studies which focus on renewable electricity. In particular, most of the literature discusses the features and development of wind and solar communities (e.g. Bauwens et al., 2016; Ptak et al., 2018; van der Schoor and Scholtens, 2015; Nolden, 2013).

Nevertheless, the study of the heating and cooling sector at a local scale has been gaining attention in recent years. In particular, the urban heating and cooling sector (H&C) is the largest single energy consumer of the EU accounting for 50% of the continent's annual energy consumption and it is totally reliant on fossil fuels (Nava Guerrero et al., 2019). The annual urban heating supply in 2016 was covered by 13% of oil, 59% of gas, and 68% of gas imports (European Commission, 2016). Given this high dependency on fossil fuels, the research on the energy transition at the local scale and hence, on community energy, has recently expanded from having an electricity focus to delving deeper into defining, characterising and understanding the dynamics of thermal energy communities.

Regarding the definition of thermal energy communities, Nava Guerrero et al., (2019) describe it as "*networks of heating technology interacting with networks of actors in complex ways, where the interactions are governed by a certain set of rules called institutions*". In this line, Fouladvand et al., (2020) defines thermal energy communities through three main components: (i) a technology for the generation, distribution and consumption of heat, (ii) involved actors and their roles and (iii) related institutions, formal and informal rules that govern a thermal energy community.

The literature on the technological aspect can be classified in three elements: generation, distribution and demand. On the generation element, the literature mainly discusses how to optimally design plan and operate local thermal energy communities (Coley and Schukat, 2002; Sameti and Haghighat, 2017; Comodi et al., 2019). In particular, plenty of research has been conducted on the design of thermal energy storage systems (Lorente et al., 2015; Pizzolato et al., 2017; Piché et al., 2020). On the distribution side the literature has comprehensively analysed the role of district heating systems (Persson and Werner, 2011; Lake et al., 2017; Lund et al., 2010). While on the demand side, demand-side management strategies and the importance of thermal insulation is the focal point of study (Wernstedt et al.,2007; Tronchin et al., 2018; Nava Guerrero et al., 2019) Lastly, most of the research on potential future energy scenarios follow a techno-economic approach (i.e. focused on the technological alternatives available, potential costs, and business cases) (CE Delft, 2017; Ecofys, 2016). Nonetheless, these energy scenario hardly consider the governance and institutional aspects related to the different technological alternatives (Sijm et al., 2020).

Regarding the literature on the agents involved in thermal energy communities looks into conducting comparative analysis of different organizational modes (Hawkey et al., 2013; Morlet and Keirstead, 2013; Heldeweg et al., 2017; Peltokorpi et al., 2019) or ownership structures (Magnusson, 2016; Westera, 2018) of district heating systems. Besides, studies have looked at revealing, analysing and addressing the governance challenges related to the heating transition (Patil et al., 2009; Bolton and Foxon, 2015). And lastly, several studies have looked into identifying the key involved agents and the division of responsibilities in urban thermal energy projects (Giebels-Westhuis, 2016; Bush et al., 2017; Li et al.,2017).

Lastly, on the institutional component, some studies have looked at the design or re-design of the regulatory framework for the district heating sector at a country level (formal rules). Wissner (2014) focuses on Germany, Sarma and Bazbauers (2016) in Latvia, Zheng et al. (2018) in China and Heldeweg et al., (2017) and Vitéz and Lavrijssen (2020) in the Netherlands. Moreover, the literature has also looked at the design of the district heating market (Söderholm and Wårell , 2011; Zhang et al., 2013; Liu et al., 2019). With respect to the research on the field of informal rules, few studies have explored the role of value systems on the design and formation of thermal energy communities and technologies (Mahapatra and Gustavsonn, 2010; Correljé et al., 2015) and the level of social acceptance for district heating projects (Achillas et al., 2011; Upham and Jones 2012; Zaunbrecher et al., 2016).

Overall the technological component of thermal energy communities has been thoroughly researched, while the agents and institutional components are relatively understudied. Busch et al., (2017) explains that this is problematic since the adoption of local heat networks is not hindered by the technology itself since this can already be considered mature, but by the challenge of redesigning the current institutional context and of managing the complex agent interactions.

In the institutional analysis field, computational tools are particularly interesting for the study of institutional re-design since they allow for the ex-ante exploration and comparison of the impact of multiple policy alternatives (Dawes and Janssen, 2013). Ghorbani et al., (2014) conduct a comparative analysis of the five major computational approaches to policy analysis namely: Neo-classical Equilibrium Modeling (NEM), Traditional Game Theory (TGT), System Dynamics (SD), Serious Gaming (SG), and Agent-based Modeling (ABM). In their study they concluded that ABM is one of the most instrumental tools for policy analysis. Agent-based modelling is a bottom-up simulation approach that is able to simulate systems where individual agents interact (Bankes, 2002).

ABMs have recently seen much application to the field of climate mitigation policies. Following the trend of the general literature explored above, for energy in particular, most ABM studies have focused on the electricity sector. Sanstad (2015) conducted a review of ABM addressing the energy sector and concluded that most of them looked into the following three topics: (i) the electric power system, and in particular, on the wholesale electricity markets; (ii) consumer behaviour; and (iii) the dynamic pricing in the electricity market. Particularly for policy analysis, Castro et al. (2019) conducted a review of agent-based models of climate-energy policy and out of the 61 ABMs analysed by only two focused on heating technologies.

It can be concluded that the current literature on the energy transition is lacking a systemic understanding of the concept of thermal energy communities. Although the potential heating technology scenarios have been thoroughly studied from an techno-economic perspective, knowledge is missing on the institutional and governance components of thermal energy communities and, in particular, of the interactions of these latter components with the heating technology alternatives. Thermal energy communities are a key element for the transition to a more sustainable heat sector in Europe. As a result, there is a need to better understand what changes at the institutional and governance level are required to overcome the barriers currently hindering the establishment of these communities and hence, the diffusion of sustainable heating technology. In particular, the field of energy policy analysis is missing the existence of computational models such as agent-based models that allow to fill the identified knowledge gap. As a result, in this research, an agent-based model of thermal energy communities in the built environment is developed to provide insights on what techno-institutional conditions enhance the establishment of thermal energy communities.

In order to understand the thermal energy transition at the community level and be specifically able to describe how thermal energy communities form and progress over time, the research will focus on the heating sector context of a specific European country, the Netherlands. Although Section 3.1 explains more in detail why this country has been selected, in short terms, the main reason is that the institutional environment of the heating sector in the Netherlands, which is adapted to the characteristics of the gas market, is currently going through a transformation and re-design process to enable the diffusion of sustainable heating technologies. This makes the Netherlands a very interesting case to base this research on.

1.2. RESEARCH QUESTIONS

In line with the knowledge gap stated above, the main research question is:

What techno-institutional conditions and factors hinder and enable the success of establishing thermal energy communities in the Netherlands?

The scope of the research is limited to the process of formation of thermal energy communities (TEC). The process of formation of TEC starts when there is a group of individuals that decides to form a group to assess the feasibility of implementing a district heating network in the community. Moreover, once the technology has been installed and it is in operation, the research looks into the potential expansion of the already set up community to include members that decide to join after the first construction phase.

To find the answer to the main questions first the concept of thermal energy communities needs to be clearly defined and understood. Therefore, the first sub-research question is:

1. *What is the definition of thermal energy communities?*
    1.1. *What is the local technology implemented?*
    1.2. *Who are the main actors engaged?*
    1.3. *Which are the key institutions involved?*

Fouladvand et al. (2020) describe thermal energy communities by three core elements: the technology being implemented, the principal actors engaged in the formation of TEC and the institutions that guide the interactions between the actors in the community during this processes. The first step is then to identify the shared characteristics of the sustainable heating systems with the highest diffusion potential in the Netherlands, and who are the key actors and institutions involved in the Dutch heating and cooling sector.

2. *What is the process of establishment of thermal energy communities?*
3. *What are the main factors that lead to the successful formation of thermal energy communities?*

Once the general picture is clear, the next step is to develop a general concept that describes the main steps of the process of forming and sustaining TEC. By understanding the actions and approaches that the actors take and how the institutions guide the process, then the main drivers and barriers can be identified.

The three sub-research questions will provide the necessary context and data to build an agent based model that is able to assess the way in which heating technologies and institutions support the formation of thermal energy communities and hence answer the main research question.

1.3. THESIS STRUCTURE

Chapter 2 elaborates on the theoretical background used to guide the collection of data, conceptualization and analysis of the model. Chapter 3 describes the methodology used to answer the main and sub-research questions. Then Chapter 4 will provide the answer to the three sub-research questions and provide the contextual information and the specific elements that characterise TEC and their formation process for the case of the Netherlands. Chapter 5 and 6 focus on the conceptualization, formalization and verification of the agent based model. Chapter 7 will provide a description and analysis of the experiments conducted with the model. Lastly, Chapter 8 focuses on discussing the simulation results, providing final conclusions, describing the limitations of the research, and reflecting on the academic and societal relevance of the analysis.

CHAPTER 2: THEORETICAL BACKGROUND

In order to be able answer the main and sub research questions, the socio-technical system that will be analysed through this study first needs to be described. In this context, McGinnis (2016) explains that there are two key elements required for a proper description of the functional relationships of a system: frameworks and theories. While frameworks help to identify, categorise, and organise the factors deemed most relevant to understand some phenomenon, theories attempt to explain phenomena with a (limited) set of independent variables. They designate some factors as independent and dependent variables and hypothesise general causal relationships among these variables.

In summary, the theoretical background of this thesis is formed by two frameworks for institutional analysis and three theories. In order to study the favourable conditions for the formation of thermal energy communities, first it is crucial to identify what decision making processes are most relevant and what elements impact the outcome of such processes. To do so, this research applies two of the most commonly applied institutional frameworks developed by Williamson (1998) and Ostrom (2005), whom jointly received the Nobel price on Economics in 2009: the Institutional Analysis and Development frameworks, and the four layer model framework. Theories are then required to understand and identify the most relevant factors that better predict the outcome of the decision making processes of actors involved in thermal energy communities. In this respect, the Behavioural Reasoning Theory, Social Value Orientation Theory and Multi-criteria Decision Making technique have been selected.

This chapter first describes the two overarching frameworks that guide the conceptualisation, implementation and analysis of the agent based model. Then, the last three sections provide a brief description of the theories used to characterise and guide the interactions and decision-making processes of the agents in the model.

2.1. THEORETICAL FRAMEWORKS

The four layer model developed by Williamson (1998) and the Institutional Analysis and Development (IAD) framework developed by Ostrom (2005) provide the structure to describe the elements and factors that are the most relevant to understand and analyse the formation process of thermal energy communities.

2.1.1. FOUR LAYER MODEL OF WILLIAMSON

The four layer model of Williamson (1998) is a general institutional framework that is characterised by distinguishing between different layers and kinds of institutions. In particular, it categorises institutions in four different layers (see Figure 1)

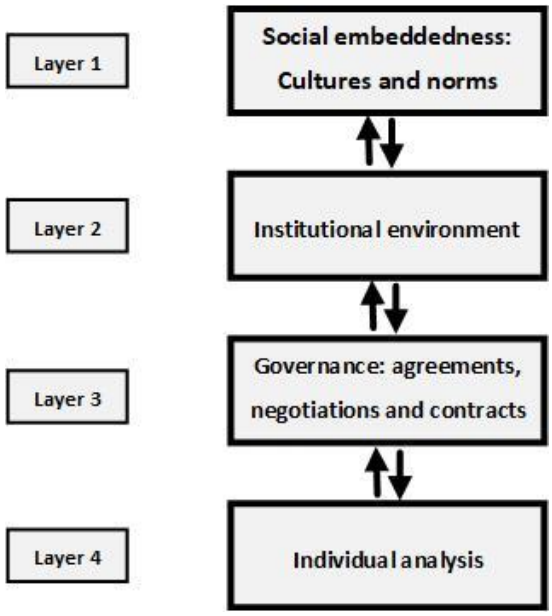


FIGURE 1: FOUR LAYER MODEL OF WILLIAMSON (WILLIAMSON, 1998)

- *Layer 1 – Social embeddedness*: The highest layer includes the informal institutions of norms, customs, traditions, cultures, values and more (Joskow, 2004). They have a large influence on the actor's perception over problem solving approaches to the issue at stake in the institutional re-design process (Koppenjan and Groenewegen, 2005). These informal institutions influence the mindsets of actors and what kind of solution they find acceptable (Ibid.). Regarding the dynamics of these basic social and cultural institutional foundations, they operate at the lowest pace and require hundreds of years to change (Joskow, 2004).

- *Layer 2 – Institutional environment:* This layer comprises the institutional environment, what Williamson (1998) called "the formal rules of the game". It comprises the political, legal and economic institutions such as constitutions, political systems and basic human rights, property rights and basic financial institutions (ibid.). These formal rules determine the legal positions of the actors in the system and the mechanisms available to coordinate their interactions (Koppenjan and Groenewegen, 2005). Change in the basic institutional environment is still relatively slow (can take between 10 to 100 years) and it is constrained by the slow rate of change of the social embeddedness layer (layer 1) (Joskow, 2004).

- *Layer 3 – Institutional arrangements*: This layer looks into what Williamson (1998) calls "the play of the game". It reflects the choices made over the arrangements governing actors' interactions under the constraints of the institutional environment. It comprises for instance of the market structures, the details of contractual arrangements and the organisation of business firms (Ghorbani et al., 2010). Additionally, the informal networks that evolve from the actors' relationships based on trust and reciprocity can also be analysed at this level. Changes in governance arrangements happen faster than those in the institutional environment and can be perceived every 1 to 10 years (Ghorbani et al., 2010).

- *Layer 4 – Individual actors:* This layer refers to the individual actors involved in an institutional system and the day to day interactions between them (Joskow, 2004). It looks at the daily operation of the system, at what individual actors take into consideration when making decisions and at the decision making process itself. This individual layer is the fastest changing level and it is in continuous development and change.

The four layer model of Williamson is relevant for the analysis of institutions for three main reasons. First of all, the categorisation of institutions in layers allows to differentiate between how different institutions evolve and how and to what extent they can be influenced (Koppenjan and Groenewegen, 2005). Secondly, a key aspect of the framework is the feedback loops between layers. This illustrates from a systems perspective the interconnectedness of institutions in a socio-technical system. It shows how a vertical two way relation exists in which (i) high institutional layers steer and restrict the developments and changes at lower layers, and (ii) changes at lower layers open up paths for new institutional arrangements at higher layers (Ghorbani et al., 2010). Lastly, a third important feature of the four layer model is the temporal aspect to the dynamics of the different institutional layers (Baumgartner and Cherlet, 2015). This illustrates the fact that institutions operate at different paces and hence, changes at different layers are perceived at different time scales and some institutions (higher layers) are harder to influence and change than others (lower layers).

Overall, the four layer model of Williamson provides a visual representation of the interconnectedness and embeddedness of institutional systems. In other words, it reveals the fact that institutional arrangements do not exist in a vacuum but that they are the outcome of the interactions of higher institutions which belong to a larger context. Additionally, the model reflects the importance of maintaining institutions of a particular system aligned since otherwise, such system will be unstable and will not function properly (Koppenjan and Groenewegen, 2005). Whatever the pathways of change, the speed, nature and smoothness of any institutional transition will be affected by the time that it takes to make significant adjustments and to align the institutions at the different layers of the system hierarchy (Joskow, 2004).

In the literature, the four layer model of Williamson has been previously used for qualitatively analysing the institutional environment of particular ecological sectors:

Ruijgh-van der Ploeg (2011) provides an excellent example of how the four layer model can be applied for studying the key factors enabling the transformation of a particular institutional system. The research identified at each layer of the model, the following institutions as the ones that facilitated the adaptation of the local water system to climate change impacts:

- *Layer 1:* new principles, norms, and values of local inhabitants with regard to water-system management.
- *Layer 2:* the presence of laws that grant responsibility for adaptation of the physical system to local government.
- *Layer 3:* formal arrangements that can be easily adjusted in response to local changes
- *Layer 4:* a formalised master plan for implementation and a sufficient budget for steering the water board and agents in their interactions.

Moreover, Baumgartner and Cherlet (2015) exemplifies how the four layer model can be used to provide recommendations on how to solve complex environmental issues. The paper applied the model to the topic of land degradation to provide recommendations on what changes to implement at different institutional layers to adjust the institutional system in such a way that land users adopt sustainable land management practises. Some of the recommendations provided at each layer are:

- *Layer 1:* Bottom up policies that recognise and formalised existing traditional institutions such as the recognition of informal pastoralist communities.
- *Layer 2:* Improving cross governmental interaction to reduce conflicting regulations and harmonise national efforts to fight land degradation and the formalising the provision of more responsibilities to actors at the local level (decentralisation); developing new public financing schemes; reformulating property rights.
- *Layer 3:* policy interventions, such as the certification of sustainable production, invest in community-based forest planning, and local resource and knowledge pooling.

- *Layer 4:* sensitisation on the importance of SLM.

Lastly, within the energy field, Kunneke and Fens (2007) is a good example of a paper that applies the four layer model of Williamson for illustrating the institutional features of an energy related system, in particular of the Dutch electricity distribution networks. It concludes that at each layer of the model, this sector is characterised by the following institutions:

- *Layer 1*: the dominant policy is focus is the achievement of three objectives: affordable, clean and sustainable.
- *Layer 2:* For the network, the regulatory framework is sector specific and the work as regulated monopolies.
- *Layer 3:* the exploitation of networks is perceived as a nationally oriented service. The resource allocation.
- *Layer 4:* Network services are based on regulated tariff.

The three literature studies described above show how the four layer model of Williamson is a suitable framework for (i) providing a structured description of the institutional system of a particular sector, and (ii) deriving recommendations over what actions to take to re-design a particular institutional system (van Es, 2017). Thus, they prove that this framework is an appropriate tool to guide the description of the system in which thermal energy communities get formed.

2.1.2. Institutional Analysis and Development (IAD) Framework

Ostrom (2011) defines the IAD framework as a multi-tier conceptual map that enables the identification of the major types of structural variables that are present in institutional arrangements (see Figure 2).

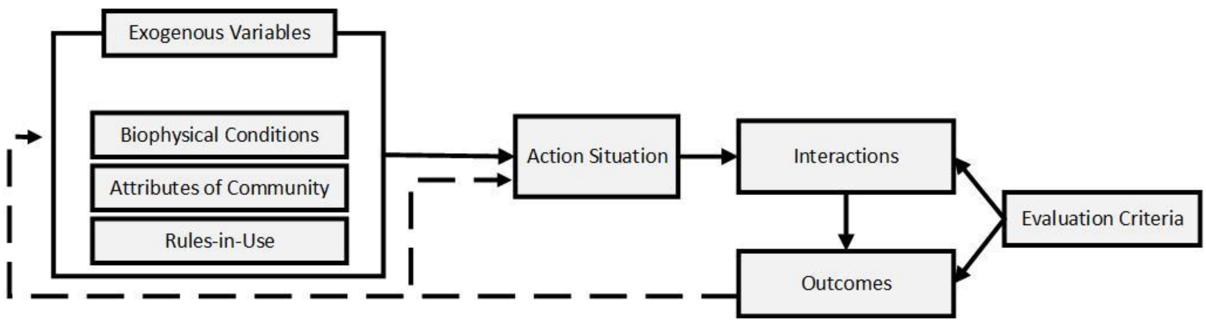


FIGURE 2: INSTITUTIONAL ANALYSIS AND DEVELOPMENT FRAMEWORK (OSTROM, 2005)

Overall, the IAD framework developed by Ostrom (2005) enables the dynamic analysis of decision making processes in socio-technical systems since it breaks and organises these systems in more simple and manageable parts. There are three keywords that need to be fully understood to understand the usefulness and application of the IAD framework: institutions, analysis, and development.

1. Ostrom (2005) defines **institutions** as "*the set of rules that humans use to organize all forms of repetitive and structured interactions*". They shape the individual and collective decision making processes by acting as constraints or opportunities.
2. The framework provides the structure for the **analysis** of the institutional context of a socio-technical system since it breaks down the system into their components and directs the attention to the most important factors to consider under each component.

3. Lastly, **development** brings dynamics to the framework. This framework allows to understand how institutions form and evolve by focusing on the endogenous and external variables that impact and hence influence the development and evolution of institutions (McGinnis, 2016).

The first step in analysing a problem is to identify a conceptual unit which in the IAD framework has been named the "action arena", which includes an "action situation" and the actors (Ghorbani et al., 2012). More specifically, Polski and Ostrom (1999) describe the action arena as "*a conceptual space in which actors inform themselves, consider alternative courses of action, make decisions, take action, and experience the consequences of these actions*" (Figure 3).

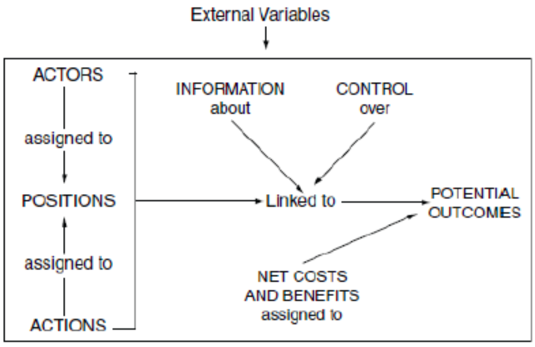


FIGURE 3: EXOGENEOUS VARIABLES INFLUENCING THE IAD ACTION ARENA

The action situation is described by seven key variables (Ostrom, 2011): the characteristics of the actors, their roles the range of actions they can take and the potential outcomes, the cost and benefits of those actions and outcomes, the available information they have, and the level of control over their decisions.

What happens in the action situation is influenced by a series of exogeneous variables that cover all the social, cultural, institutional, and physical contextual aspect in which the action situation is situated (McGinnis, 2016). These are classified in three different categories: biophysical conditions, community attributes and rules.

- The *biophysical conditions* include the physical and material resources and capabilities available within the system's boundaries (Polski and Ostrom, 1999). Resources include, for instance, the technology options, finance, population and labour available.
- The *attributes of community* include the cultural and social context in which the action situation is situated. Two of the most common elements are the concept of trust and reciprocity. The first accounts for the extent to which an actor believes the others will respect and act accordingly to the agreements and rules, the later encapsulates the notion of actors sharing expectations over cooperation (McGinnis, 2016). A third key element under this variable is the shared values and beliefs and preferences over the potential solutions for the problem at stake.
- Lastly, there are seven *rules in use* which define the possibilities of the action situation: boundary, aggregation, scope, pay-off, position, information and choice (see Table 1)

TABLE 1: RULES-IN-USE IAD FRAMEWORK (MCGINNIS, 2016)

Rules	Description
Position rules	specify a set of positions, each of which has a unique combination of resources, opportunities, preferences, and responsibilities.
Boundary rules	specify how participants enter or leave these positions
Authority rules	specify which set of actions is assigned to which position.
Aggregation rules	specify the transformation function from actions to intermediate or final outcomes.
Scope rules	specify set of outcomes.

Information rules	specify the information available to each position.
Payoff rules	specify how benefits and costs are required, permitted, or forbidden to players.

The interactions between the actors in the action arena which are influenced by the exogeneous variables lead to particular outcomes. These outcomes can be objectively assessed on the basis of an evaluation criteria either by the participants themselves or the external observers (Ostrom, 2011). These criteria is used to determine which aspects of the observed outcomes can be considered successful (McGinnis, 2016).

A last element of the IAD framework that is worth mentioning is the presence of feedback loops and learning processes. Outcomes of an action situation may impact any component of the IAD framework. For instance, after participants evaluate the outcomes of their interactions through the evaluative criteria, actors are able to reconsider their personal preferences over which action to take (ibid.).

An important characteristic of the IAD framework is that it accounts for the nestedness present in all socio-technical system. While each action situation is situated on a specific layer of analysis, the IAD framework does explain how each action situation does not exist independently but they are nested within larger action situations (ibid.). Ostrom identified four key layers of analysis which coincide with the layers of the four layer model developed by Williamson (1998) (Ghorbani et al., 2010). The way in which Ostrom represents the vertical and horizontal interconnected of institutions is by describing how each action situation is connected to adjacent action situations (McGinnis, 2016). Ostrom explains how the output of a certain action situation can determine the exogeneous variables of an action situation situated in a lower layer of analysis. As a result, changes in an action arena in a high layer will eventually trigger change in lower institutional layers (ibid.).

With respect to the application of the IAD framework in the literature, Lammers and Hoppe (2019) explained that even though it has conventionally been applied to the study of traditional common pool resource management, its value has recently been more recognized for research on energy transitions as well. Since the IAD framework offers a generic approach in analysing public policies, the literature applies the IAD framework to a variety of topics within the energy field (Milchram et al., 2019).

Lammers and Hoppe (2019) present a great example of how the IAD framework can be applied to identify conditions and enable a specific decision making process within the energy sector. Lammers and Hoppe (2019) first identified the action situations of the decision making processes and most important institutional conditions. Based on this information they were then able to identify patterns of institutional conditions that enable and disable the introduction of smart energy systems in Dutch districts.

Additionally, Shah et al (2020) uses a similar approach to Lammers and Hoppe (2019) and apply the IAD framework following a qualitative case study approach to the renewable energy sector of the Island states. Nevertheless, apart from identifying institutional conditions, their focus is on providing recommendations on what institutional conditions to change or to implement for the studied island states to reach their national renewable energy objectives.

Lastly, Milchram et al., (2019) move away from diagnosing key elements of policy processes and shows how the IAD framework can also be applied to explain how values influence institutional change in the energy transition. In particular, it uncovers how the concept of value applies to each element of the framework. The paper makes explicit how (i) values influence the behaviour of participants in an action situation and (ii) values are embedded in the biophysical/material conditions such as energy infrastructures as well as in the rules creating the institutional environment of an action situation.

The research described above exemplify how the IAD framework helps (i) identifying important actors, contextual settings and rules that apply in energy policy process, (ii) researching how values are embedded in infrastructure and existing regulation and how they influence decisions over the required changes to implement in the energy institutional, (iii) providing recommendations on how to adapt the institutional environment to enable the energy transition. Therefore, the IAD framework serves as one of the basic theoretical framework in this research.

2.2. THEORIES

In the context of environmental-friendly technology decision-making, empirical studies to date have demonstrated that environmentally friendly behaviour are strongly influenced by the values and attitudes of consumers (Eccarius and Lu, 2020; García-Maroto et al., 2020; Wang et al., 2018). For instance, Claudy, et al., (2013) demonstrated that people having strong environmental concerns and reasons for adopting a renewable energy system will also have a positive attitude, and will more likely end up adopting it.

In this content, Social Value Orientation (SVO) theory which classifies people based on the extent to which they have a more pro-social or more pro-self value orientation and the Behavioural Reasoning Theory (BRT), which theorises how people's decisions over which behaviour to have reflect their values and belief systems, have been selected to guide actor's behaviours in the context of thermal energy communities. Lastly, multi-criteria decision making methods (MCDM) have proven to be a good approach to take into consideration local objectives and values when performing holistic analyses of possible energy-related choices considering .

2.2.1. BEHAVIOURAL REASONING THEORY

The literature on factors influencing sustainable behaviour distinguish between contextual influences (i.e. external conditions) and personal factors (i.e. attitudinal factors, personal capabilities and habits or routines) (Lewin, Strutton, and Paswan 2011).

When focusing on the personal factors, Claudy et al., (2013) state that there are two key frameworks which are commonly use in attitude related research: (i) the value-belief-norm (VBN) theory (Stern 1999); and (ii) the theory of planned behaviour (TPB) (Ajzen 1991). Many researchers have a preference over TPB because when actors are involved in extreme or challenging situations the explanatory power of values can be weakened (Stern, 2005).

TPB postulates that attitudes are strong predictors of behavioural intentions (Ajzen 1991). Nevertheless, surveys on sustainable consumption show that the reality is different. Although consumers report positive attitudes towards renewable energy, the diffusion of this technology is slow (Claudy et al., 2011). As a result, recent advances of behavioural theories attempt to explain the attitude-behaviour gap that TPB fails to address (Westaby 2005).

The Behavioural Reasoning Theory (BRT) addressed the attitude-behaviour gap by extending the TPB to include context specific reasons (for and against) as a key variable influencing behavioural attitudes (ibid.). Reasons are generally defined 'as "the specific subjective factors people use to explain their anticipated behaviour'' (Westaby 2005). This new variable allows to incorporate the fact that although values are an important predictor of consumer behaviour, consumers also rationally evaluate reasons for and against adoption which may influence their final attitude towards a decision. This is especially relevant for costly and high involvement products such as renewable energy systems. (Westaby 2005; Westaby, Probst, and Lee 2010).

Presented in Figure 4, BRT offers a more complete understanding of consumer decision-making by including context-specific reasons as important linkages between consumers' values, attitudes and behavioural intentions (Westaby 2005).

FIGURE 4: BEHAVIOURAL REASONING THEORY (WESTABY, 2005)

1. *Intention → Behaviour:* As menionted above, BRT postulates that intentions are strong predictors of behaviour. Research in this regard proves that the more consumers intend to adopt a new product, the more likely they are to actually purchase it in the future (Ajzen 2001; Reyes-Mercado, 2017). For instance, Westaby, Probst, and Lee (2010) use intentions as a dependent variable for renewable energy adoption. Additionally, Irfan et al., (2020) investigate the impact of consumers' intention factors on willingness to pay (WTP) for renewable energy (RE) in Pakistan.
2. *Attitude → Intention:* BRT then theorises that attitudes are a key antecedent of the adoption of behavioural intentions (Westaby 2005). Ajzen (1989) defines attitudes as "an individual's evaluation of a particular behaviour as favourable or unfavourable ". The relationship between attitude and intention is the one that has been more carefully and throughout studied in the literature. Several studies claim that consumers' pro-environmental attitudes constitute an important antecedent of green behaviour and that these are clearly influenced by the dominant social paradigm (Bruner and Kumar 2007; Dabholkar and Bagozzi 2002). Thus, pro-environmental attitudes also reflect the mainstreaming of the sustainability discourse in society (Prothero, et al., 2010). For example, Wiser (2007) measured U.S households' willingness to pay for green energy and found that including attitudinal factors improved the accuracy of predicting adoption significantly. Moreover, Hansla et al. (2008) found that positive attitudes were the main predictor of buying green electricity in Swedish homes.
3. *Reasons → Attitude:* Most behavioural theories stop at the study of factors influencing consumers behaviour. However, as mentioned earlier, the identification of a gap between attitude and behaviour has led to the exploration of other factors influencing consumer's sustainable behaviour. In this regard, BRT includes the relevance of context specific reasons for and against a decision (Westaby 2005). Westaby, Probst, and Lee (2010) explain how consumers use reasons for and against to resolve potential cognitive dissonance and be confident in their purchasing decision. Chatzidakis and Lee (2013) explain how these reasons come from the available social, public, and cultural narratives or discourses and Claudy et al., (2013) that they are specifically influencing purchasing decision instead of the attitude of a consumer towards a product.
4. *Values → Reasons:* Lastly, BRT further proposes that people's processing of value information is the most important factor and directly affects people's behavioural choices. In this line, following the BRT theory, Westaby et al., (2010) argue that leaders, in the search of a decision on which action to take and the most justifiable reasons to support or not this action, they scan their values and belief systems and find the action that better aligns to this. Lastly, BRT claims that, resulting from a desire for simplified information processing, often values can directly influence actor's final behaviour (Claudy et al., 2013). In the context of environmental-friendly technology decision-making, empirical studies to date have demonstrated that there is a strong influence of values and/or attitudes on consumers' adoption intentions and environmentally friendly behaviour (Eccarius and Lu, 2020; García-Maroto et al., 2020; Wang et al., 2018).

As a general practical application of BRT, Claudy et al., (2013) demonstrated that people having strong environmental concerns and reasons for adopting a renewable energy system will also have a positive attitude, and will more likely end up adopting it.

2.2.2. Social Value Orientation Theory

The Social Value Orientation (SVO) theory groups individuals based on their internal values and hypothesizes the relationship between these groups and their motivations with specific behaviours under study (Griesinger and Livingston, 1973; Forsyth, 2006). In general, SVO makes the distinction between proselfs and pro-social individuals:

- Pro-self individuals: they are more focus on self-interest and place more weight on their own outcome and benefit. The assumption of narrow self-interest is central to rational choice theory
- *Pro-social individuals:* they place more value on collective benefits and to contributing to the well-being of everyone.

Considering that SVO corresponds to how much an individual is willing to sacrifice in order to make another individual better off, it could considered a continuous construct (Murphy, Ackermann, Handgraaf, 2013). Nevertheless, SVO to date has been most commonly used in categories. Although there are multiple lists of social orientation groups in the literature, this research will only include the most common idealized social orientations reported in the literature (ibid.):

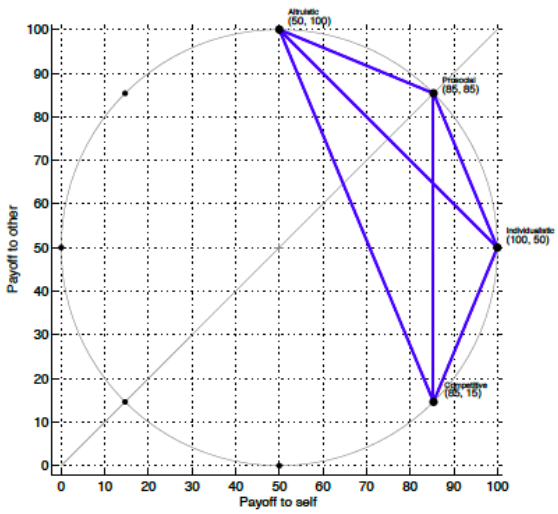


FIGURE 5: FOUR KEY SOCIAL VALUE ORIENTATION TYPES (MURPHY, ACKERMANN, HANDGRAAF, 2013)

5. *Altruistic*: they solely focus on maximising joint benefits regardless of the impact on their own payoff.
6. *Cooperative*: they will work for the joint payoff while also looking for their own benefit.
7. *Individualistic:* they will focus in their own payoff without having a specific need of minimising other's benefits.
8. *Competitive*: On the other side of the spectrum, competitive people focus only in the maximisation of their own benefit even if this means minimising the joint benefit.

This four group categorisation has been used by Nascimiento (2019) on the study of the creation of local energy initiatives. However, other studies have adapted the framework into different categories. For example, Murphy & Ackermann (2014) describes eight subgroups of social orientation, while Sütterlin, Brunner & Siegrist (2013) uses three groups to analyse the impact of SVO on the adoption of energy conservation measures.

In the context of environmental behaviour, SVO theory is used to assess the extent to which more pro-social value orientation can be used as an indicator of pro-environmental behaviour. For example, Garling et al., (2003) demonstrated that the behaviour of pro self individuals are more influenced by how environmental issues can impact their own lives while pro social individuals tend to respond when becoming aware of the potential impact of their behaviour on the collective and on the ecosystem balance. The study concludes that when pro-environmental behaviour explicitly requires cooperation with others, pro-socials are more likely than are pro-selfs to engage in this behaviour. In this line, Sutterlin et al., (2013) and Hoppe et al., (2019) tested the relationship between social value orientations and level of energy conservation and confirmed that prosocial oriented people reported more energy conservation. Moreover, Kastner and Matthies (2016) use the SVO theory to analyse household's investment decisions in solar thermal energy. They conclude that households with strong eco-social value orientations are more likely to make an investment while strong pro-self value orientations reduces investment likelihood.

2.2.3. Multi-criteria decision Making (MCDM)

There are plenty of considerations to take into account during the decision making processes happening in the planning and design of energy communities. To ensure the successful establishment of energy communities, Karunathilake (2019) explains that such decision making processes should consider (i) technical elements (the quality of energy supply and the generation output), (ii) financial feasibility evaluation (costs) and, (iii) environmental and social evaluations (the environmental impacts of energy generation, and the impact on the communities). These objectives are usually conflicting and decision makers need to decide how to weight and balance them against each other. Karunathilake (2019) explains that through a MCDM a finite number of alternatives can be prioritised and ranked against based on a set of criteria.

MCDM can be classified into two groups: multi-objective decision making (MODM) and multi-attribute decision making (MADM) (Pohekar and Ramachandran, 2004). The key differences between them is on whether the alternatives are predefined. In MODM the alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints (Ervural et al., 2017). In MADM a small number of alternatives are to be evaluated against a set of attributes (Vinogradoba, 2019). For this research, the latter, MADM, is the most suitable technique given that the focus is on evaluating and selecting a technology scenario within a set of scenarios that have been previously developed (see Section 5.3.1).

Within the field of MADM, value-driven MADM techniques in particular allow to rank the alternatives based on the internal values and belief systems of the actor's involved in the decision making process (Zhuang et al., 2017). Value-driven MADM techniques methods have been widely applied in the energy field to analyse different energy scenarios considering competing objectives and values (Pohekar and Ramachandran, 2004). Tsoutsos et al., (2009) explores the process of sustainable energy planning on the island of Crete in Greece and demonstrate the importance of involving multiple actors in the derivation of the criteria to be used in the planning process. In this regard, McKenna et al., (2018) presents the results of how to use a participatory value driven MCDM approach for the planning of a rural energy community in Germany in an attempt to bring together the traditional techno-economic energy system analysis with social aspects such as individual preferences. Moreover, focusing on thermal energy communities, Denarié et al., (2017) presents a clear step by step approach to apply MCDM to compare the feasibility of several sustainable district heating configurations against technical, economic, environmental and social criteria.

Wang et al., (2009) describe the steps of applying a MADM to a specific decision-making processes. Table 2 shows how these steps have been adapted to the specific decision making processes involved in the establishment of thermal energy communities. The further explanation on how the steps have been incorporated into the agent based model are explained in Chapter 6.

TABLE 2: MULTI-CRITERIA DECISION MAKING PROCESS STEPS (WANG ET AL., 2009)

Step	Description	Adaptation to TECs
1	Goal identification	Alignment with internal values and beliefs of the actor making the decision following the Behavioural Reasoning Theory

2	Definition of alternatives	Different renewable heating technologies technically feasible taken into consideration the local context
3	Identification of criteria	Financial, environmental and social criteria
4	Scoring	Calculation of performances for every alternatives according to chosen criteria based on data gathered from literature
5	Criteria weighting	According to the internal values and beliefs of the actor
6	Application of multicriteria decision analysis methods	Find alternative with the highest score.

CHAPTER 3: RESEARCH METHODS

This chapter elaborates on the methods used and the reason why they have been selected to guide to answer the research questions. Section 3.1 explains why the Netherlands has been selected as the country of study for the case study. Section 3.2 explains the role of conducting desk research for this thesis and the themes it has been applied to. Section 3.3 supports the choice of using agent based modelling as the fundamental method for answering the main research question. And lastly, Section 3.4 describes the method used for the analysis of the agent based simulation results.

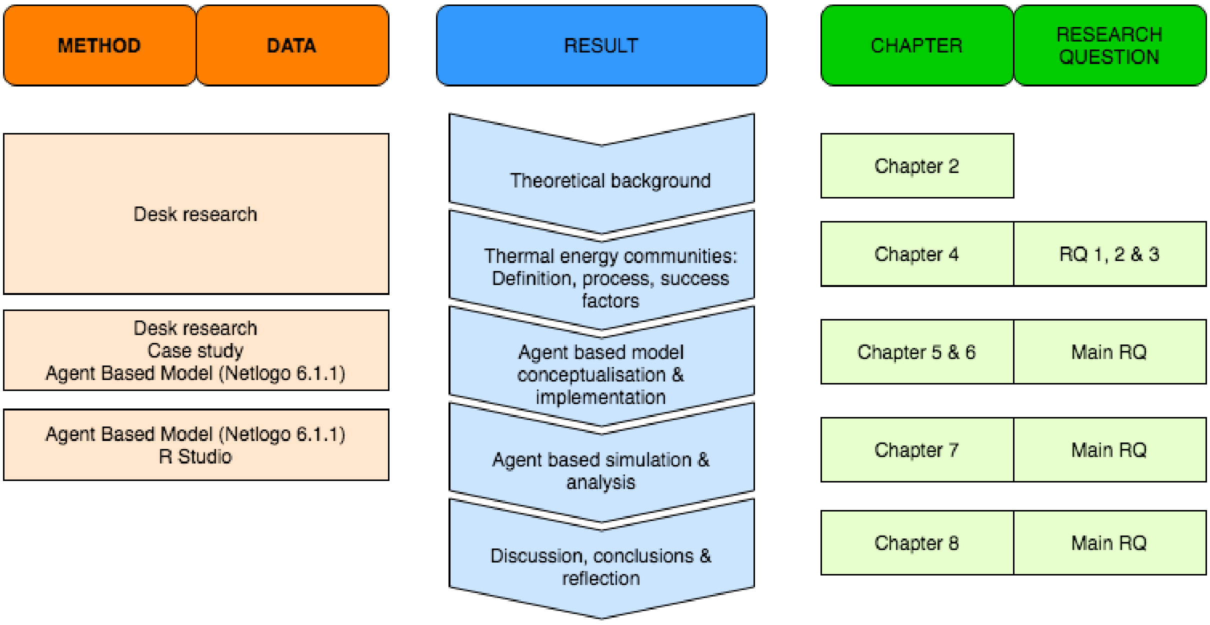


FIGURE 6: RESEARCH METHODS FRAMEWORK

Figure 6 displays the research flow followed in this thesis to arrive to answer the main research question. The theoretical background and the literature review on thermal energy communities together through literature review serves as the basis for the conceptualisation and implementation of the model. Then the analysis of the results from the agent based simulation lead to the discussion on the factors that influence the formation process of thermal energy communities in the Netherlands. From this discussion several conclusions and reflections are derived which are reflected in the last chapter of the document.

3.1. CASE STUDY SELECTION

In order to understand the thermal energy transition at the community level and be specifically able to describe how thermal energy communities form and progress over time, the research focuses on the heating sector context of a specific European country. Within Europe, the Netherlands has been chosen as the country to be analysed through a case study approach for several reasons. Firstly, the Netherlands is one of the European countries with the highest number of energy communities (Bauwens et al., 2016). Moreover, TECs in particular, have gained momentum in recent years since they are seen as one of the key pathways to achieve the energy security and sustainability targets for 2030 (MEZ, 2018). Since 1950s the Netherlands has been in a comfortable position regarding the security of their heating and cooling sector when they started exploiting the gas fields available in the north of the Netherlands (van Foreest, 2010). However, since 2018, due to the changing climate discourse at a global level and the more frequent earthquakes around the gas fields, the Dutch government has started to focus on the heating sector as one of the key elements of the energy transition to achieve the climate targets in the efforts to mitigate climate change effects (Ligtvoet et al., 2016). Even through the availability of natural gas has dis-incentivised up until recently the improvement of the heating sector’s sustainability, it now has the advantage of having left behind a robust and mature grid infrastructure that can be potentially used to reduce the costs of the transition. On a governmental level, which is explained more in detail later on Section 4.1.2, municipalities are the institutions responsible for leading and facilitating the heating transition with an ambitious plan to become natural gas free until 2030 (MEZ, 2016). As a result, the changing Dutch institutional landscape within the heating sector is an unique and interesting context to explore through the case study approach since lots of radical changes are required for achieving this goal.

3.2. DESK RESEARCH

The information gathered through desk research has constructed the backbone of this thesis. In particular, desk research was used to gather relevant information on the technologies, actors and institutions involved and the key enablers and barriers for the formation of thermal energy communities in the Netherlands. Policy documents, academic articles, student thesis studies and relevant websites have been used to gather information on the key actors and institutions involved in the Dutch urban heating transition and to conduct an analysis of how the transition has developed in recent years and how it is expected to evolve. Additionally, the data used as input for the agent based models were gathered from academic articles and official websites such as the European and Dutch National Statistics Agency (Eurostate, CBS), the Dutch government (RVO), the Dutch Environmental Agency (PBL), and websites from other institutions (e.g. CE Delft).

3.3. AGENT-BASED MODELLING AND SIMULATION

In order to answer the main research question, modelling and simulation is the preferred research approach. Simulation of social processes presents a new way of studying complex social phenomena. The success of this approach relies on its capability to construct virtual laboratories to test hypotheses of social phenomena that otherwise would be impossible to test in real life or would require a lot of resources (M'hamdi and Nemiche, 2018).

The main reason why this approach has been selected is the exploratory nature of the research. Given that the goal is to understand the enabling conditions of the formation of thermal energy communities, social simulations provide the necessary freedom to explore the interactions driving this process. Additionally, in the Netherlands most of the thermal energy communities are still in their early stages of formation. As a result, the simulation approach allows to conduct an ex-ante analysis of this formation process by using the limited data on the Netherlands and complementing this with data from other countries where these communities are more mature.

There are two approaches for social simulation: top down and bottom up. Top down approaches assume the behaviour of a system can be analysed by defining the relationship between elements through mathematical equations (e.g. system dynamics) (Bonabeau, 2002). Bottom up models, on the other hand, assume that it is only through the interconnection between the elements that the behaviour of a system can be understood (Ibid.). Hence, bottom-up models focus on modelling the behaviours of the individual agents and exploring the dynamics that emerge from the interactions between the agents (e.g. agent-based model). M'hamdi and Nemiche (2018) argues that bottom-up social simulation approaches are able to explain through simple local interactions how global models such as participation in collective action occur. Thus, this approach seems appropriate to explore the main research question of this thesis.

M'hamdi and Nemiche (2018) explains that there are two key approaches to bottom up social simulation: cellular automata and agent-based models. Cellular automata are adequate when the interactions are planned just between a cell and its neighbours. In general, it is a set of cells interacting locally in a simple way, but with a complex global behaviour. Each cells has a state that evolves over time according to the state of its neighbours. Cellular automata has been used for instance to simulate land-use change for urban environments. Agent based models on the other hand, allow the modelling of agents that are more complex in their internal processes and hence in their behaviour and interactions with other agents. As a result, given that fact that the simulation to be developed in this thesis aims at representing the interaction between the agents involved in thermal energy communities, agent based modelling is the preferred alternative.

Agent based modelling (ABM) has been selected as the bottom up simulation approach for studying the establishment of thermal energy communities since it allows:

1. To grasp the complexities of decision making processes where multiple agents are involved (Busch et al., 2017).
2. Actors to be represented as heterogeneous, autonomous and individual decision-making entities that are able to learn and interact with each other and their environment (Grimm and Railsback, 2005). This allows to capture the individual behavioural choices while also allowing to understand and analyse the emergent behaviour of the system (Bonebeau, 2002).
3. To study the outcomes that emerge from the complex social interactions between the different agents. Emergence is defined as "*the arising of novel and coherent structures, patterns, and properties through the interactions of multiple distributed elements*" (Wilensky and Rand, 2015). In other words, emergence relates to the idea of "the behaviour of the system" which is the result of the behaviour of individual actors on lower layers and their interactions (Bonebeau, 2002).
4. Simulate alternative strategies through experimentation Additionally, given the uncertainty over the effectiveness of different institutional conditions, agent based models allows for different institutional changes and policy interventions to be analysed and to be compared against each other (Busch et al., 2017).

ABM has been used multiple times to conduct institutional analysis of energy communities and the impact of policy interventions. For instance, Rosales-Carreón and García-Díaz (2015) built an ABM to study the growth of near-Zero Energy Buildings (nZEB's) in the Netherlands. Busch et al., (2017) developed an ABM to assess the impact of different policy interventions on the scale up local heating infrastructure in the UK. Lastly, Nava Guerrero et al., (2019) explored what socioeconomic conditions could support the Dutch heating transition at the neighbourhood level.

The conceptualization, operation and analysis of the ABM was developed following the 10-steps approach proposed by Van Dam, Nikolic and Lukszo (2013). The steps are (1) problem formulation and actor identification, (2) system identification and decomposition, (3) concept formalisation, (4) model formalisation, (5) software implementation, (6) model verification, (7) experimentation, (8) data analysis, (9) model validation, and (10) model use.

The first three steps are taken based on the relevant information found in sub-questions 1, 2 and 3. The outcome of these steps was a concept model and flowchart that structured the relevant concepts, agents, actions, states and interactions to answer the problem that model addresses (see Chapter 5). In the following two steps, the flowchart is translated to the agent based model software, NetLogo (Version 6.1.1). This software is used because it can be used in any operating system, it is open source and there is a large amount of documentation available. Hence, using Netlogo enables the model to be readily used, adapted and improved by future research

(Abar et al., 2017). The model developed was then used to conduct computational simulations to assess the effectiveness of several institutional conditions affecting the formation of thermal energy communities. In order to do so, the implementation of model was first verified and then validated through literature and sensitivity analysis to fix part of the parameters and set the range for the others (Chapter 6). Each unique set of input parameters of the model is an scenario and each scenario was run 100 times. In total, 96 scenarios were initially included in the simulation. The outcome of the simulation were analysed and visualised (Chapter 7) to gather key insights on the influence of institutional conditions on the formation process of thermal energy communities (Chapter 8).

3.3.1. THEORETICAL BACKGROUND FOR ABM

This section presents how the theoretical background presented in Section 2.1 serves as the backbone for the conceptualisation, implementation and analysis of the agent based model and simulation developed for answering the main research question.

THEORETICAL FRAMEWORKS

Regarding the theoretical frameworks, there are multiple examples in the literature where the four layer model of Williamson and the IAD framework have serve the conceptualisation of agent based models of socio-technical systems. Ghorbani et al. (2010) conclude that both frameworks are suitable for conceptualising the complexity of real world systems in agent-based models and provide an example case on how to develop the ABM concept of an economic network using both frameworks independently. Additionally, Zellner et al., (2014) developed an ABM based on the IAD framework to understand the mechanisms of collective decision making in ecological restoration.

Regarding the complementarity of the IAD and Williamson frameworks for the analysis of institutional environments of socio-technical systems, Van Es (2017) innovatively combined these two frameworks to perform a qualitative analysis of the institutional re-design of the regional water cycle in Delft. Through his research he was able to demonstrate that combining these two frameworks you provide a more in depth and dynamic analysis of the institutional system in place.

Nevertheless, no paper has been found in which an agent-based model is developed based on the combination of the IAD and Williamson frameworks. This research aims at combining these two frameworks for the conceptualisation of the agent based model in the following way:

- Given the high-level conceptualisation of the four layer model of Williamson, this framework provides the structure to identify the key action arenas that hinder and drive the decision making processes of establishing thermal energy communities. Additionally, it will support the classification of these action situations into different institutional layers.

- Once the key actions that drive the formation of thermal energy communities have been identified, the IAD framework will support a more in depth analysis of these actions through the identification of the components that shape them and the important external and internal conditions that influence their successful conduction. This will provide the required depth of understanding for the proper representation of the action within the model.

THEORIES

The theories explained in Section 2.2, (Behavioural Reasoning Theory (BRT) Theory, Social Value Orientation (SVO) Theory, Multi-criteria Decision Making (MCDM) technique) support the hypothecation and implementation of the general causal relationships among the main variables of the four layer model of Williamson and the IAD framework.

Regarding BRT (Section 2.2.1), Rai and Robinson (2015) develop a theoretically-driven behavioural model agent-based model of energy technology adoption based on the Theory of Planned Behaviour (TPB) which is a consisted version of BRT. However, although no ABM application of BRT has been found. Nevertheless, the literature of BRT described in Section 2.2.1 has proven that BRT is a suitable theory for explaining how values are good predictors of people's final attitude and decision over renewable energy technologies.

By linking this finding with the four layer model of Williamson and the IAD framework, it can be concluded that the BRT is suitable for explaining:

- the interconnectedness between the first layer of the four layer model of Williamson with the second, third and fourth layer independently. On the one hand, the first layer accounts for the values and belief systems, and the social norms and discourses influencing the reasons for/against thermal energy communities. On the other hand, the others layers capture the outcome of the collective behaviour of the actors involved in thermal energy community projects. However, the collective behaviour under study can belong to different layers of analysis which correspond to different layers of the institutional framework.
- how the attributes of community within the IAD framework influence the decisions and interactions of actors in the action area. While the attributes of community include the shared values and beliefs and preferences of actors, the action area in this thesis encapsulates the decision making processes in the formation of thermal energy communities.

While BRT is suitable for understanding the final decision and behaviour of the individual agents in the model, the Social Value Orientation (SVO) theory is appropriate to better understand the final behaviour at a collective level instead since it allows the classification and categorisation of individuals in groups.

Lastly, the value-driven MCDM technique combines within the other frameworks and theories of the theoretical background in several ways. Firstly, in IAD framework terms, the MCDM technique provides the aggregation rules (see Section 2.1.2) actors use to assimilate and use the information on the biophysical conditions and the community attributes to decide on their renewable heating technology of preference. Secondly, this technique is able to illustrate one of the key hypothesis of the Behavioural Reasoning Theory explained in Section 2.2.1 which is that values and context specific reasons directly influence actor's final behaviour and choice. Hence, the value-driven MCDM technique provides the vehicle through which the Behavioural Reasoning Theory is applied to the agent based model.

As a whole, through the combination of the two theoretical frameworks (four layer model of Williamson and IAD framework) together with the two theories (BRT and SVO) and the value-driven MCDM , the goal is that the agent based model is able to (i) analyse the way in which a certain combination of institutional, governance and operational conditions influence the establishment of thermal energy communities, and (ii) provide recommendations on changes on the institutional system and in which layer these should be made to foster the success of the TECs formation process.

3.4. R FOR EXPERIMENTATION ANALYSIS

The data from the different experiments were exported from Netlogo (Wilensky, 1999) into a CSV file and the free and open sourced statistical computing software R project (R Core Team, 2020) and R studio (R Studio Team, 2020) were used to visualize and analyse the experimentation results. Visual inspections of graphs and nonparametric statistical tests were used to analyse the results and derive conclusions from the experiments on the effectiveness of different policy interventions.

CHAPTER 4: DUTCH THERMAL ENERGY COMMUNITIES

This Chapter focuses on providing an in depth analysis of the concept of thermal energy communities by first elaborating in Section 4.1 on the definition of TECs through their main components (technology, actors and institutions) with a particular focus on the case study of the Netherlands. Then the following two sections (4.2 and 4.3) describe the process of establishing thermal energy communities and the factors and conditions that favour their successful establishment.

4.1. DEFINITION OF THERMAL ENERGY COMMUNITIES

This section is structured following Fouladvand et al. (2020)'s classification of thermal energy communities (TECs). Each section describes one of the three main components of TECs: (i) the technology for the generation, distribution and consumption of renewable energy, (ii) involved actors and their roles and (iii) related institutions, formal and informal rules that govern an energy community.

4.1.1. TECHNOLOGY

According to HIERverwarmt (2020) the future of sustainable heating in the Netherlands will concentrate among three technology alternatives: green gas, electrical solutions, and district heating.

The Dutch built environment which is characterized for being densely clustered makes district heating especially attractive for achieving the objectives of the Dutch urban heating transition. Because constructing heat network is a relatively expensive, the building density will have to be quite high to keep the costs of the infrastructure reasonable. Due to the high growth potential of district heating in the Netherlands (expected to represent 15 % and 45 % of the total heat supply by 2030 (Epp, 2020), this research focuses on district heating (DH) as the representative of the technology component of thermal energy communities.

In 2012, the share of collective heat supply using district heating network was only 3%. With respect to the built environment, It is estimated that in 2015, 4 to 5% of total dwellings in the Netherlands was connected to a large scale heat network and that there were more than 50.000 dwelling-connections and approximately 2PJ of heat supplied by small networks (ECN, 2017). Regarding the small scale networks, there are only three low heat networks (Ecofys and Greenvis, 2016).

Since all low temperature district heating networks in the Netherlands are small scale this will be the focus of the study (ECN, 2018). Small scale heat networks are as those supplying less than 150 TJ per year (ECN, 2018). Overall, the heat value chain of a general small scale district heating system can be divided in three sub-systems: generation, distribution and demand (Burch, 2012).

GENERATION

Generation includes the source of heat. The heat source partially determines the temperature in the network (Lund et al., 2014). A back up heat source is sometimes required to deal with the fluctuating heat demand of consumers (ECN, 2018).

Currently, the main primary energy source for small scale district heating in the Netherlands is natural gas for fuelling the power plants and cogeneration plants (Daniels et al., 2011). Waste incinerators, biomass and biogas and heat pumps play a smaller role (Niessink and Rösler, 2015). Nevertheless, in order to meet the 80% CO_2 emissions reduction target this landscape needs to change. In this regard, the Netherlands does have a large technical potential for supplying their district heating networks with sustainable energy (Knobloch et al., 2019).

For the built environment in particular the Dutch government is focusing on three sustainable alternatives to natural gas: (i) electrification (renewable, coal/biomass + CCS, gas and biogas + CCS), (ii) ambient heat (heat pumps, solar collectors) and (iii) ground source heat (ATES, geothermal) (ibid.). The Dutch Environmental Agency (PBL) has developed several scenarios to provide insights into the Netherlands' future energy supply in which it is calculated that there is around 200-550PJ of potential heat from renewable sources considering ambient (geothermal and air), residual heat and solar (Niessink and Rösler, 2015).

More specifically, the Heat Expertise Centrum (ECWa, 2020) has identified eight key sustainable heat sources for the Netherlands: aquathermal, thermal energy storage, geothermal, green gas, bioenergy, residual heat, hydrogen and solar heat.

- *Aquathermal* uses the heat and cold extracted from surface water, wastewater or drinking water.
- *Thermal energy storage* has a long history in the Netherlands which uses the soil and the aquifers to extract and store heat and cold to a maximum depth of 500 meters.
- *Geothermal energy* refers to the extraction of heat from deep subsurface from 500 meters and deeper. The feasibility of these options is very context dependent. The condition and composition of the subsurface in the neighbourhood needs to be suitable for the extraction of geothermal energy.
- *Green gas*: Biomass is upgraded to meet natural gas standards so that it can be distributed to end consumers. Having similar properties to natural gas it has the advantage that little modifications are then required in the grid infrastructure. However, its availability is limited.
- *Bioenergy:* This refers to the combustion of solid or liquid biomass. Examples of fuels are wood chips and pellets and waste biogas from organic waste.
- *Residual heat*: This refers to the heat released during industrial processes that is not recovered by the factory itself. The feasibility is very content dependent since the availability of sources, the temperature and the distance to an (existing) heat network are important parameters for the feasibility of a residual heat project.
- *Hydrogen*: Similar to green gas, the use of hydrogen would require only small modifications of the gas network however, its sustainability depends on the production method and green methods such as electrolysis are still very expensive.
- *Solar heat*: use of the sun's energy to provide heat to the consumers. Solar thermal systems have a limited potential in the Netherlands.

Among all of these sustainable heating technology alternatives, aquathermal, thermal energy storage and bioenergy are the heat sources which have been included in this thesis 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 and individual heat pumps will be considered.

DISTRIBUTION

Distribution consists of the technology responsible for making the heat available for consumption, the distribution network of insulated pipes with water (or steam) as a heat carrier and the two connections points between the heating technology and the demand side (Westera, 2018).

In general, small scale heat networks can be classified based on the temperature of the distribution network in medium and low temperature (ECN, 2018):

- *Medium temperature networks* are the most commonly used systems which supply heat at a temperature ranging between 65 and 90 ºC. The advantages is that the initial investment is lower than for the other two types, not many changes are required at the household level since the common radiators still serve, and lastly, it prevents the growth of Legionella bacteria. On the contrary, the sustainability of the system may be reduced since there are less incentives to improve the insulation of the houses and higher temperature leads to higher heat losses.

- *Low temperature networks* provide heat at a temperature of less than 55ºC and the return temperature is about 20-30°C. There are plenty of advantages of these networks. Firstly, the range of potential heat sources increases since these networks make use of renewable heat sources such as shallow geothermal, low temperature waste heat from industry, solar thermal plants, heat storage, waste heat from commercial buildings. Secondly, networks are more efficient and distribution losses are reduced. Additionally, it also incentivises the reduction of heat demand. However, on the contrary, the transition to low temperature networks requires additional measures. Buildings must have an energy label of at least label B, low temperature radiators need to be installed at the household level, and individual heat pumps are required to supply hot temperature at a temperature that prevents legionella could be a problem. All these measures make these networks more resource intensive and financial intensive in the short run which makes it harder to gather the needed support.

The Dutch Environmental Agency (PBL) has developed five strategies that neighbourhoods could follow to achieve the vision of gas-free neighbourhoods (ECW, 2020b). Two of these strategies focus on the implementation of collective heat networks, medium and low temperature respectively. Table 3 briefly describes the strategies with its different variants.

TABLE 3: COLLECTIVE HEAT SCENARIOS DEVELOPED BY THE DUTCH ENVIRONMENTAL AGENCY (PBL) (ECW, 2020)

Strategy	Variant	Description
1.Heat network with medium and high temperature source	A	Heat network fed by heat sources with heat of 70 ° C or higher, such as residual heat from industry
	B	Heat network fed by geothermal sources that supply geothermal heat of 70 ° C or higher.
	C	
	D	Heat network fed by a cogeneration installation (CHP) with renewable gas as fuel (70ºC)
2.Heat network with low temperature source	A	Network fed by heat supplied at 30ºC and individual buildings heat pumps. Radiators are replaced.
	B	Heat network fed by collective heat pump that upgrades temperature 70ºC with a collective heat pump.
	C	Heat network fed by collective heat pump that upgrades temperature 50ºC with a collective heat pump. Radiators are replaced.
	D	Thermal energy storage as heat source and temperature upgraded to 50ºC with collective heat pumps. Radiators replaced and individual heat pump
	E	Surface water and ATES as heat sources for network. Temperature upgraded to 70ºC with collective heat pump.

The main difference between the variants under the first strategy is in the sources of heat. With respect to the second strategy, the main difference is in the temperature at which the heat is supplied.

After assessing the availability of the heat sources at the local level and the technical feasibility of the scenarios, it is then important to assess their financial feasibility. They focus is on finding the trade-off between reducing the heat losses in the network by keeping the temperature low until the household and minimising the changes at the demand level for upgrading the heat to be delivered at the temperature of 70ºC. Since the higher the temperature the less efficiency the system is, the variants of the second ranking on sustainability from the most sustainable alternative is A, C, B, E and D.

Demand

Demand focuses on the heat consumption which in this study is represented by the household thermal energy consumption. It is important to stress that the suitability of different heat networks greatly depends on the features and insulation level of buildings. Having thermally well-insulated homes and individual heating technologies reduce the overall demand and the required capacity of the collective generation and distribution infrastructure and hence the capital investment of the heating network.

In the Netherlands, the use of heat in total accounts for 40% of the primary energy demand out of which 50% goes for space heating and hot tap water in the built environment Hekkenberg and Verdonk, 2014). All homes and other buildings in the Netherlands must have an energy performance certificate that indicates the heat demand and energy quality of buildings (energy label A accounting for the most efficient houses) (NEA, 2020).

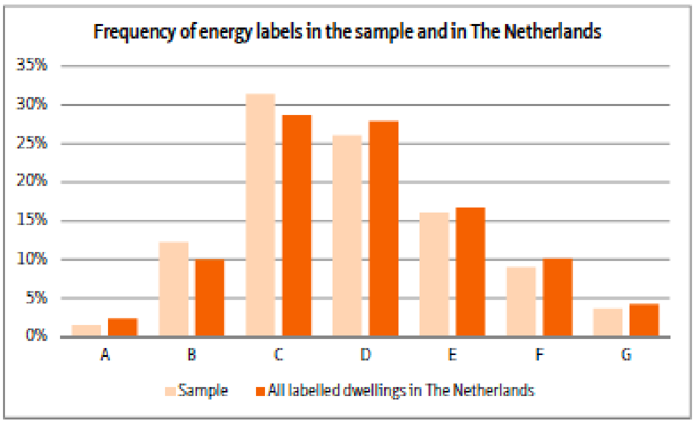


FIGURE 7: ENERGY LABEL DISTRIBUTION FOR DUTCH DWELLINGS (MAJCEN, 2016)

As can be seen from Figure 7, only around 15% of households in the Netherlands have an energy label B or higher. However, the strategy to achieve gas-free neighbourhoods, especially for those considering collective heat networks, states that all households must first reduce their heat demand through improving the insulation of their houses to level B to be able to connect to a low temperature heat network (ECW, 2020). Additionally, further changes are required at the demand side such as replacing the radiators to fit with the lower temperature of the supplied heat (ibid.).

As mentioned above, sometimes the collective heating systems need to be supported by an individual heating technology in order to meet the demand (ECN, 2018). This is especially relevant for low temperature heating networks where the temperature of the heat needs to be upgraded when reaching the house through a heat pump to supply hot water to the buildings. Nevertheless, solar thermal systems present themselves as an alternative to heat pumps for avoiding the temperature upgrade of the heat work.

4.1.2. Actors

This section brings a general understanding on the literature of the different actors involved and the roles they take and a particular look to the agents in the Netherlands. In general, communities, government, market parties or associations need to cooperate to enable energy communities to develop (Oteman, 2014). Key actors involved in thermal energy communities fall under one of the following categories: (i) public actors, (ii) private heat actors, and (iii) intermediaries (Bush et al., 2017).

Public actors

Regional and local authorities in particular have a key role to play in the local energy communities landscape. Hoppe et al., (2015) argue that the success of local energy initiatives are largely influenced by local governments acting as change agents and process managers. In this regard, Kona et al., (2019) concludes that the four main enabling modes of urban governance derived by Bulkeley and Kern (2006) can also be used by local public actions in the energy communities landscape: municipal self-governing (demonstration projects in public buildings), municipal enabling (partnerships, awareness raising), governing through provision (provision of incentives and grants), governing by regulation and planning.

The main public actors involved in the Dutch heating sector are at the European level the EU Commission, at the national level, the Ministry of Economic Affairs and Climate Policy and the Netherlands Enterprise Agency, and at the regional level the provinces and municipalities. Their vision and governance instruments are described in Table 4.

TABLE 4: OVERVIEW OF DUTCH PUBLIC ACTORS INVOLVED IN THE HEATING SECTOR

Actors	Vision	Agency
EU commission	Securing a reliable, accepTable and affordable heat provision	Allocate funding for district heating and renewable energy in buildings
National government (Ministry of Economic Affairs and Climate Policy)	Securing a reliable, accepTable and affordable heat provision	Building Decree: Compulsory connection for new buildings. Policies for stimulating demand reduction and renewable energy generation (subsidies, obligations, prohibitions)
Netherlands Enterprise Agency	Securing the highest market efficiency for heat delivery	Surveillance and enforcement of the Heat Act (tariffs, service level quality, license granting & consumer protection)
Provinces	Reaching their renewable energy and CO_2 objectives	Providing resources (finance, knowledge, expertise, network)
Municipalities	Reaching their renewable energy and CO_2 objectives	Development of municipality heat plans, granting permits and provision of subsidies

PRIVATE HEAT SYSTEM ACTORS

The roles of private actors involved in the heat sector can be discerned into: developers, financiers, investors, corporations, and communities, (Brandon, 2019). The agents that fulfil this role in the Netherlands are described in Table 5.

- *Developers:* They are responsible for constructing and delivering the infrastructure. When development is performed by large corporations (heat companies) they are also involved in the distribution and supply of heat.
- *Financers and investors:* They provide capital for investment and costs.
- *Energy corporations*: The roles that these actors take are that of heat products, distributor and supplier. The distributor role is usually taking by the infrastructure operator who is responsible for managing the varying heat demand with the heat supply.
- *Communities*: Three types of community organisations can be involved in thermal energy communities: energy cooperatives and homeowner associations. Energy cooperatives when involved are legal entities that own and manage some or the full heat supply chain at a local level. Additionally, homeowner associations and housing corporations play a crucial role in the development of thermal energy communities since they are the final legal entity in charge of making the improvements and installing the technology at the household level.

TABLE 5: : OVERVIEW OF DUTCH PRIVATE ACTORS INVOLVED IN THE HEATING SECTOR

Actors	Vision	Agency
Energy companies: Eneco, Nuon, Ennatuurlijk	ProfiTable growth of district heating areas	Explore opportunities to build and own heating networks
DSOs: Stedin, Alliander, Enexis	Securing reliability	Explore opportunities to build and operate heating networks
Consumer organizations: housing corporations, owner associations	Securing affordability	Use of financial instruments to make heat networks financially attractive
Investors	ProfiTable growth of district heating areas	Provide necessary capital and supporting the development of business cases.
Heat consumers	Affordable, reliable and sustainable heat provision	Getting together to initiate transition forming cooperatives

INTERMEDIARIES

Hoppe et al., (2015) stress the importance of having an actor taking the role of conflict mediator between actors involved in the establishment of local energy communities. Intermediaries are defined by Bush et al., (2017) as those "*actors that facilitate relationships between key actors and enable sharing and pooling of knowledge*". Apart from conflict mediation and process facilitation, Warbroek at al., (2018) explains that intermediaries are responsible for (i) connecting lessons learnt from different initiatives and developing standardised toolkits, and (ii) taking an advocating role for policy reforms. A special category has been created for these actors since they can be individuals or a group of people within organisations that range from public bodies, to trade associations, nongovernmental organisations (NGOs), or consultancies.

4.1.3. INSTITUTIONS

Institutions comprise a set of formal and informal rules that constrain and guide the behaviours and interactions of the actors within the development of thermal energy communities (Ostrom, 2005). Formal rules include the policies and strategies that officially govern the TEC. Whereas informal rules relate to the values and norms held by the actors involved in TECs that have an influence on their behaviour.

Ghorbani et al., (2010) explain that when these informal and formal rules are not adapted to support decision-making processes required to provide stability to a system, they reinforce incumbent power relations and institutional systems. Institutional re-design then becomes relevant to bring changes into the system and bring the stability back.

This is especially relevant for the case of the development of thermal energy communities focusing on district heating technology. Busch et al., (2017) argues that the adoption of local heat networks is not hindered by the technology, already considered mature, but by the challenge of overcoming the lock-in of the current infrastructure and institutional setting and of complex agent interactions. Hence, a crucial factor for the achievement of the heat transition in urban areas is the activation and empowerment of local actors to take action and reach consensus on the re-design of the system. This requires a better understanding of the dynamics, and more specifically, the institutional factors and conditions that stimulate the formation and continuation of thermal energy communities.

Since the institutional environment is very context specific, the following paragraphs elaborate on the key institutions involved in the formation and continuation of thermal energy communities in the Netherlands by classifying them according to the four layer model of Williamson.

LAYER 1: EMBEDDEDNESS

This layer includes the informal institutions of norms, values and cultures.

Regarding the norms, in the Netherlands the government is the one responsible for the availability of heat for its citizens at an affordable price for everyone (Kamp, 2017). Additionally, as a norm the provision of heat in the Netherlands is done by gas which has led to building standards to represent this norm and require houses to be designed with radiators that need water of 70 to 90ºC (Milieucentraal, 2018). Due to this, large readjustments at the building levels need to be made to adapt the system for heating networks. Moreover, the Netherlands has a market traditions and consumers are accustomed to being able to have the choice of their heat (gas provider) since the gas market is formed by multiple competing market parties (Rutte, 2017). However, in recent year there has been a great shift on public values and perceptions related to sustainability. This has been reflected on the signing of the Climate Accord and the Energy Agreement which aim at better aligning the Dutch society to sustainability values by reducing the country's climate change impact. The Climate Accord (Klimaatakkoord, 2019) aims to reduce CO2 emissions in the Netherlands by setting a national reduction goal of 49% by 2030 compared to 1990 and the Energy Agreement (MEZ, 2013) in particular is an agreement signed by key agents involved in the Dutch energy sector which contains provisions on energy conservation, boosting energy from renewable sources and job creation. Regarding the heating sector, this has led to district heating becoming an optimal solution despite of the "gas norm" and the long market tradition which contrasts with the usual monopoly structure of district heating networks (Bouw, 2017).

Layer 2: Institutional environment

This layer comprises the political, legal and governmental formal arranges, the "rules of the game" that shape the activities in the lower layer (international treaties, national law and constitutions, fiscal structures and market design).

Regarding the design of the Dutch heat market, it is important to distinguish between the natural gas environment and the district heating environment. The main difference is that whereas the gas can be transported over long distances, there are multiple competing parties involved and it is a well-known and regulated market, the heat market is local and decentralised by nature, often supplied by local monopolies and the legislative framework has not yet been fully defined yet (Westera, 2018; Bouw, 2017).

With respect to the national law, the most important ones are the gas law and the Heat Act. On one hand, the gas law restrict the new connections to the gas network since new houses are not allowed to connect to the gas infrastructure (ClimateXChange, 2016). However, the current built environment is not included under this law. The Heat Act, was amended in 2019 to provide more clarify the roles and responsibilities of the different actions (ACM, 2019). The Heat Act 2.0 focuses mainly on tariff regulation, market organization and sustainability (Vitez and Lavrijssen, 2020). Up until now the regulation of the tariff has focused on the "no more than otherwise" principle (NMDA) which ensures that the heat price does not surpass the gas price for consumer protection (ACM, 2015). However, other pricing methods are being under study such as providing a range of pricing methods depending on the nature of the district heating network to guarantee the investment's feasibility. Regarding the market organization, the new Heat Act focuses on clarifying the role options for ownership and operation. The debate is on whether it is a good idea to re-design the system to that of the gas market by allowing open networks in which multiple heat generators and supplies can participate (Bouw, 2017). The last element is sustainability aims to be achieved through the promotion of sustainable and low carbon energy generation technology.

Another important law is the Building Decree which focusing on regulating the improvement of the energy efficiency in the built environment. It enforces new buildings to be energy neutral, all rental homes of housing associations to arrive to an average energy rating B or better, and 80% of private rental homes to have energy rating C or better (ClimateXChange, 2016).

Regarding fiscal structure, there are three key instruments used by the Dutch government: the energy tax, the ETS and the national subsidy and loan schemes. A tax on natural gas consumption is to be gradually increased in the following years while those on electricity to be gradually decreased. Moreover, the CO_2 price established by the European Emission Trading System (ETS) is expected to increase and start having a visible impact on the market. Lastly, the government has put together several subsidy and loan schemes to incentivize the development of local heat networks in the Netherlands: The SDE++ subsidy, the PAW living labs subsidy and the ISDE subsidy are the most known schemes. The SDE++ subsidy (Stimulation of Sustainable Energy Production) is an operating subsidy focused on the generation of energy through renewable energy sources which compensates for the unprofitable component of the generation for a period of time (RVO, 2020a). Moreover, the ISDE subsidy (sustainable energy investment subsidy scheme), focused on compensating for the investment of individual heating technologies at a household level (RVO, 2020b). Lastly, through the PAW living labs subsidy scheme the Cabinet wants to make approximately 100 existing neighbourhoods free of natural gas together with municipalities (Programma Aardgasvrije Wijken, 2020). The first tranche of 27 testing grounds was started in 2018 and the application for the second round closes in May of 2020. This subsidy is distributed every 2 years and gives around 4 million euros to a maximum of 25 neighbourhoods. This grant can be used to finance the additional costs in the implementation of the project compared to the continuation of the current situation.

Layer 3: Governance

This layer looks into policy implementation and the modes of organization which are formalised with contracts and agreements that describe division of roles and responsibilities.

In general, heating networks have a local character and are local monopolies traditionally (Bouw, 2017). It is the heat company who is responsible for the ownership of all the heat value chain. In the Netherlands, the regional government and municipality play an important role in the heating transition in the built environment. On one hand, they are the ones responsible for giving out permits, drawing the environmental plans and arranging cooperation agreements and contracts to facilitate the development of heat network projects. Additionally, there are the ones responsible for implementing the Regional Energy Strategy (RES) and the municipal heat plans which map current and future heat demand of regions and make suggestions of sustainable heating technologies to implement in the municipality scale (Ten Haaft, 2019).

Layer 4: Resource allocation

This layer accounts for the analysis of the operation and management of the system. It looks at what individuals take into consideration when making decisions and how they make these decisions.

This layer relates to the different stages and actions of the establishment of thermal energy communities which are described in Section 4.2. These actions and decisions mainly comprise: the organisation of meetings with the residents and participants, conducting feasibility studies, deciding on the technology, governance arrangements and ownership structure, drawing up a feasible business plan and building, operating and expanding the heating infrastructure.

Overall, through the TEC framework developed by Fouladvand et al. (2020), this section explains how on the technological component aquathermal, thermal energy storage and bioenergy are the most feasible heat sources for collective networks currently. With respect to the actors, in the Netherlands, local public actors (municipalities) are given the responsibility to make decisions over the urban heating transition pathway. Additionally, private companies so far have been leading on taking up the ownership of heat networks yet, community ownership is now emerging as an important alternative to private ownership. Lastly, on the institutional component, the challenge of overcoming the lock-in of the current infrastructure and institutional setting is one of the key barriers for the diffusion of TECs.

4.2. ESTABLISHMENT PROCESS

The development of a viable local heating networks requires main actors to navigate through a series of project stages. Busch et al., (2017) and Hooimeijer et al., (2016) define the key phases of a heat network process development in a similar way and they have been combined into the following phases:

- *Idea phase*: This phases focuses on the initial mobilization of the TEC actors. Initiators (project champions) are those who take on the lead and ensures that actors are engaged project and they develop a vision that is common and validated by all of the actors involved. The outcome of this phase is the shared approval of a vision and a first plan. Key points in this phase are: a vision, a new technology, a new partnership between the actors around the TEC project.
- *Feasibility phase:* This phase focuses on building consensus over the project characteristics with the underlying condition that this must feasible. A key requirement is that the project is linked to both the spatial characteristics of the region and the socio-economic characteristics of the residents. Additionally, the financial and organisational arrangements needs to be agreed upon the TEC actors.
- *Procurement and build phase*: Once the consensus has been reached on the local heat network project, finance needs to be secured, customers contracts arranged and the infrastructure needs to be built.
- *Expansion phase:* Lastly, this phase includes the daily operation of the local heat network once it is in place and its expansion to involve a larger share of the community.

4.3. FACTORS AND CONDITIONS FOR SUCCESS

This section focuses on understanding the important economic, social and institutional factors that impact the formation and continuation of thermal energy communities. Since the literature on TEC is not very extensive, most of the literature mentioned in this section studies the concept of energy communities in a more general way.

Following the meta categorisation derived by Warbroek et al., (2019) of the social, organisational and governance factors that positively impact local energy initiatives, these factors can be divided in three different groups related to (i) the leadership TEC board in charge of the project, (ii) the local community, (iii) external agents. Since the focus is on the local operational layer, technological and macro-level factors are not included in this analysis.

Regarding the factors related to the energy leadership TEC board, the key factors are having project champions, the required knowledge and expertise, and access to funds. (Warbroek et al., (2019) defines project champions as those actors who are specially committed to the project who effectively manage the process and provide direction to the group. In this line, Walker (2008) states that having a couple of very committed participants is essential for its success. Regarding the skills, Martiskainen (2017) proves that energy projects benefit from community leaders having the right set of skills to overcome impediments and take the required actions and decisions to establish the energy communities. Lastly, energy community projects are very financially intensive. Therefore, an important element for the project to be affordable is having the capital or if not access to external funds through subsidies to cover the required investment (Dvarioniene et al., 2015).

With respect to the interactions between the TEC board and the local community, it is important to secure high level of local community involvement which is translated into a high willingness to participate and to invest in the project (Warbroek et al., (2019). Yong and Brans (2017) claim that this can be achieved through early direct involvement of the neighbourhood and open decision-making processes. In addition, Dvarioniene et al., (2015) assert that alignment with the needs, expectations and values of the local community is key for ensuring their active engagement. Additionally, Boyd (2018) explains that another key factor is that there are strong social networks within the local community which are reflected on a high level of cohesion and trust . A low level of involvement can lead to discouragement in the participants side and a lack of trust over the technology, actors and institutions.

Lastly, regarding the actors external to the communities, it is important to be linked to intermediaries and local government for external support in order to complete the overall skill set, capacities, information, and expertise required for the formation and operation of an energy community (Dvarioniene et al., 2015). Additionally, establishing partnerships and information sharing networks is important for enhancing learning from the experience of other cases (Martiskainen, 2017). Lastly, it is crucial to have supportive policy frameworks that easy the provision of planning permits, provide the required extra funding and are responsive to the needs of the energy communities by, for example, altering regulations if required (Boyd, 2018). Van der Schoor and Scholtens (2015) explain that, for instance, in the case of the Netherlands, the national energy policies are one of the key barriers for the slow transformation of the energy system However, all these can only be achieved if the discourses and visions across agents are shared and aligned with each other (Yong and Brans, 2017). Only through this collaboration can be achieved.

CHAPTER 5: MODEL CONCEPTUAL FRAMEWORK

In this Chapter, the socio-technical system of the thermal energy communities in the Netherlands, as perceived from the academic and professional literature is conceptualized. Section 5.1 describes the problem formulation that will be analysed through the agent based model. Section 5.2 elaborates on how the actors described in section 5.1 interact forming the model narrative. Section 5.3 identifies and decomposes the system in its basic elements. Section 5.4 explains the evaluative criteria that will support the analysis of the simulation outcomes. Section 5.5 presents the hypothesis to be validated with the model simulation and the last part of this Chapter, Section 5.6 describes how the model concept was formalised in the agent based model software.

5.1. PROBLEM FORMULATION

Problem. The problem we are addressing in this research and with the agent-based model particularly, is the lack of insight on what technological and institutional settings and factors affect the formation of thermal energy communities within a municipality in the Netherlands.

The model looks at understanding how the different institutional layers of Four layer model of Williamson interact and influence each other through the study of the loops linking the four different layers. On one hand, the model focuses on analysing how value systems (layer 1) and external institutional conditions (layer 2) affect the outcome of the TEC formation process (layer 4). On the other hand, it also explores the influence of lower layers on higher ones. In other words, the impact of actors interactions (layer 4) on the effectiveness of the different policy alternatives (layer 2 & 3) and values and beliefs of actors (layer 1). Each layer is then further decomposed and analysed independently through the Institutional Analysis and Development framework.

Timeline. The timeline that is addressed in the model is from 2020 to 2030. This has been selected following the guidelines from the Natural Gas Free Areas Program (*Programma Aardgasvrije Wijken,* translation by the author) of the Dutch national government, in which they state that neighbourhoods should finalise their implementation plans within a time period of 8 years. Moreover, extending the timeline further would undermine the validity of the model due to the uncertainties regarding technology advancements and price fluctuations.

Emergent patterns. Following Williamson's four layers framework, the *current observed emergent pattern* is that neighbourhoods are trapped in the TEC formation process (layer 4) and unable to agree on a common TEC project to implement (layer 3) due to the mismatch between the values held by the agents (layer 1), and the absence of an enabling institutional environment adapted to the TECs needs (layer 2). As a result, TECs experience low level of household participation and low CO_2 emissions reduction.

Initial proposition The desired emergent pattern is that when the values held by the agents involved in the thermal energy communities are aligned with each other (layer 1) and the institutional environment is adapted to these values (layer 2), an agreement of the TECs projects is found across agents (layer 3) and they achieve a high share of the neighbourhood engaged in the thermal energy community and the level of GHG emission considerately decreases with respect to the reference scenario (layer 4).

Whose problem are we addressing? There are three main involved in the formation of thermal energy communities: (i) the governmental department responsible for the transition to gas-free neighbourhoods, in the model represented as the municipality; (ii) the TEC boards of the thermal energy communities to be formed; and (iii) the households in the neighbourhoods. Each of them are representing a layer of *Four layer model of Williamson.*

- *First layer - values:* Each of these actors have a particular value system in place and hence different objectives to meet.
- *Second layer - 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 responsible for the development, is responsible for putting together the formal institutional environment that will be in place to support the neighbourhoods transition off gas. Questions that can be asked in this regard are: What technology and strategy should we promote through different policy instruments in each municipality in order to achieve the highest layer of household participation and CO_2 emissions avoided by 2030? What policy instrument has a large positive impact on the formation of thermal energy communities?
- *Third layer – 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. TEC boards are the ones responsible for formalising the agreements with the other two agents, the municipality and the households. The questions that can be posed by these are: What vision and values will support me to attain my goal of forming a thermal energy community faster? What do I take into account when selecting the technology for the project to be successful? What participation policy allows me to finalise the formation process faster?
- *Fourth layer - households:* In the hands of the households is the final decision of whether the thermal energy communities will be formed or not. They have the final word on whether they are willing to invest or not in the residential heating transition. As a result, the question that this model can support in answering are the following: Which technologies align better with my values? How much do I need to invest for the thermal energy community to be successful? What is the minimum payback time that I should expect when participating in such as project?

Agents. Each of the three actors mentioned above will be represented as separate agents in the model. First, there are the individual households forming the neighbourhood, initially using natural gas to cover the demand for thermal energy in the houses and with 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 by supporting the technology scenario, making the required investment and installing the technology. The second type of agent is the TEC board which also has a specific set of values, and are in charge of achieving enough household support, selecting the technology, participating in trainings, applying for subsidies and ensuring investment costs are covered. Lastly, the third agent type is the municipality who is in charge of developing a policy framework that enables the formation of Dutch thermal energy communities.

5.2. MODEL NARRATIVE

This section explains the actions taken by the agents through the model run following the phases of the establishment process described in Section 4.2. These mainly represents the two lower layers of the Williamson's framework. The general actions are depicted in the flowchart (see Figure 8).

Idea phase

- Individual households decide on whether they support the TEC board's vision and their role on leading and owning the thermal energy community to be developed.

Feasibility phase:

- If the persuasion training is available and the TEC board has not yet participated in the, it will go through it in order to gain persuasion skills and learn how to better communicate and connect with the neighbourhood.
- When the TEC board has enough household support, it goes through a value based multi-criteria decision making process (MCDM) to select the collective system to implement in the neighbourhood. This is then reported to the TEC board supporters.
- When TEC board supporters receive this information, they evaluate this option through an individual MCDM process. If households have a positive perception on the collective system, they will support it.
- Once there is enough support for the collective technology, households go through a second MCDM process to select their preferred individual technology alternative.

Procurement and building phase

- The TEC board considers the scenario with the most supporters and conducts a technical and investment feasibility analysis for the collective and individual components of the selected scenario.
- 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 local government 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, the selected scenario and the demand changes required. If their WTP is equal or lower to 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).

Throughout the whole process:

- 10% of the neighbourhood households interact with each other. In these interactions they evaluate the level of sense of community and values of the neighbours they are in contact with and modify their preferences based on this.
- If the TEC board goes through the persuasion training and gather the skills, it is able to reach 10% of the neighbourhood to influence their internal value system for it to better align to the TEC board’s strategy.

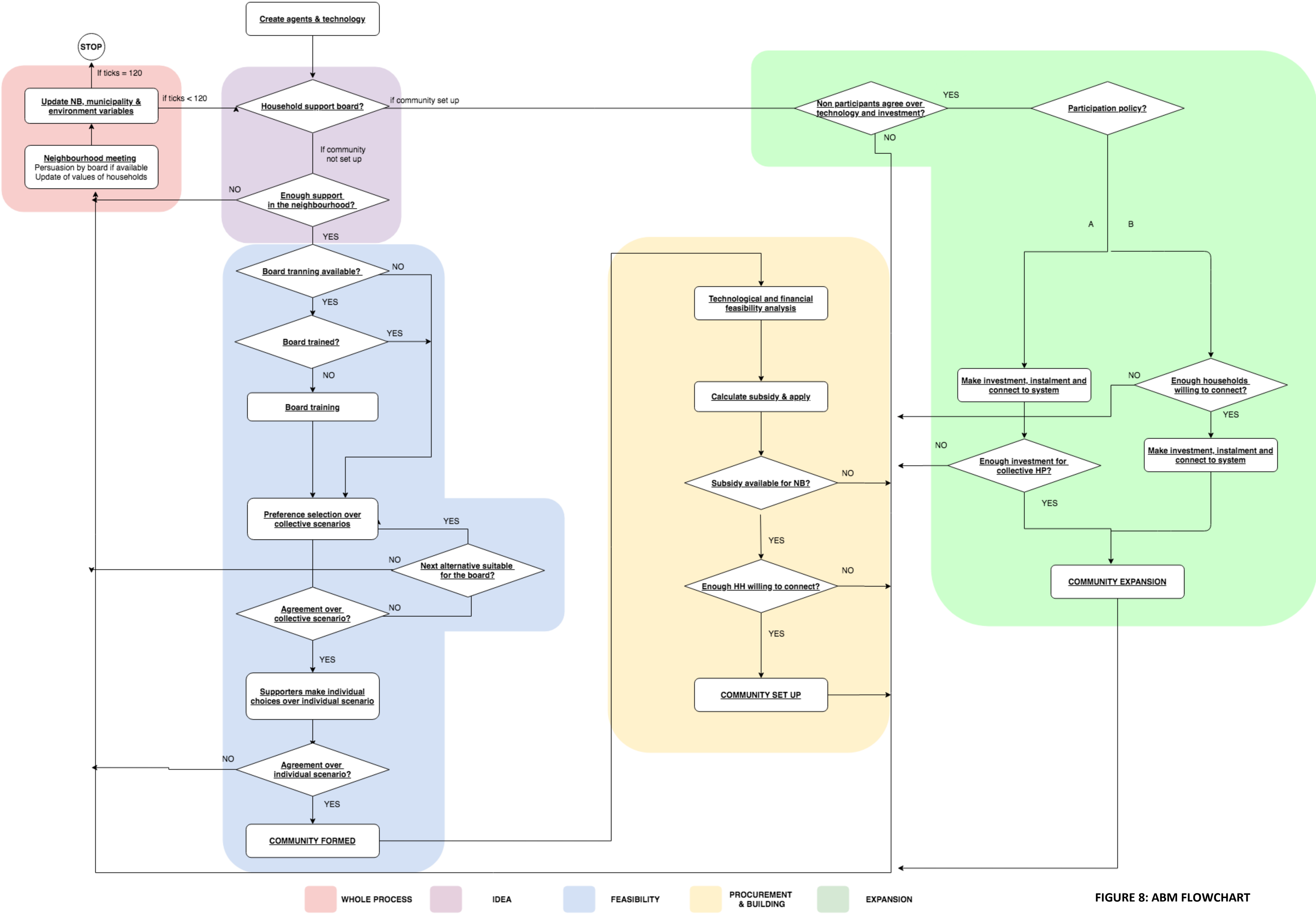


FIGURE 8: ABM FLOWCHART

5.3. System decomposition

The decision-making process the municipality together with the different actors go through in order to achieve the transition to gas-free neighbourhoods is what the agent based model attempts to represent. The outline of the municipality transforming to a gas-free municipality was established by applying frameworks for institutional analysis and theories for decision making and for social interactions between households, TEC boards and municipalities. The system has been first decomposed through the four later model of Williamson and the IAD framework has been used to further describe each of the four layers. Some elements of the IAD framework's external variables "biophysical conditions" and "attributes of the community" are considered to be similarly represented in the different layers of Williamson's framework. As a result, Section 5.3.1 and 5.3.2 describe the components that can be generalised for all the layers (values and technology) and sections 5.3.3 , 5.3.4, and 5.3.5 expand on the IAD for different layers of Williamson's framework. Lastly, Section 5.3.6 explains the way in which the neighbourhood network is formed.

5.3.1. Biophysical conditions – technology

In general, biophysical conditions include the physical and material resources and capabilities available within the system's boundaries. Factors that can be considered under this category are, for instance, the technology that is technically feasible, the climate conditions (e.g. temperature, humidity), the sun radiation, and the temperature of the sub-surface. The focus of this study has been on the technology.

There are several technology scenarios from which the households, TEC boards and the government can choose from. The final decision is based on the outcome of the multi-criteria decision making processes conducted by the TEC board and the households. These scenarios are composed of three elements: (i) the collective heating technology (generation); (ii) the district heating infrastructure (distribution); and (iii) insulation and an individual heating technology (demand/consumption). For simplification, although in reality the district heating infrastructure can be of low or medium heat, in the model it is assumed that only one alternative is possible. The collective technologies options that are included in the model are biogas, aquifer thermal energy system (ATES) and waste heat from surface water (TEA). The individual technology options are heat pumps and solar thermal systems. Following PBL scenarios described in Section 4.1.1, improving insulation is a compulsory measure household must take if they want to connect to the district heating infrastructure. The impact on the heat demand of this changes is that it will reduce by 50% following the estimation and assumption of Nava Guerrero et al., (2019). Lastly, since the time scales for the construction phase will be project specific it is assumed that the installation of the technology infrastructure will take half a year to be completed. A further description of the technical, financial and environmental characteristics of each technology can be found in Section 6.2.1.

5.3.2. Attributes of community – values

This category looks at the characteristics of the community that can potentially affect the final outcome of the interactions. Important elements are the size of the community, the level of trust and cohesion, and the cultural norms accepted by the community. The latter element, cultural norms, can be generalised for all actors represented in the model. Moreover, they are represented as "attributes of community" in the IAD framework and as the first and overarching layer in Williamson's framework. When looking at the way in which cultural norms are represented in the two theoretical frameworks used in the model. As a result, when describing the concept of the model, the first layer of Williamson's framework is integrated in the description of the other three layers of the framework as part of the IAD of each layer.

Following the Behavioural Reasoning Theory, values are at the core of the factors that influence the final intention and decision making of an actor. Koirala et al., (2015) concluded that the 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. 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.

5.3.3. LAYER 2 – INSTITUTIONAL ENVIRONMENT: MUNICIPALITY

Actions. Municipalities monitor the heat demand and CO_2 emissions of the neighbourhoods and have a choice over certain rules-in use (institutional instruments available) to empower and support TECs.

Bio-physical conditions. In the model, the municipality has a certain size based on the number of neighbourhoods.

Attributes of community. The municipality holds a certain value system and vision over the heating transition which directly influences their choices over the institutional environment in place. In practise, following the findings of Mc Kenna et al., (2016), the key elements forming the value systems of municipalities are: cost minimisation, autonomy maximisation, participation maximisation and emission reduction maximisation. This has been implemented in the model by developing different subsidy strategy alternatives the municipality can select from. These are further described below.

Rules-in-use. The rules-in use (institutional instruments) the municipality has available in the model for influencing the TEC formation process are the following:

- *Subsidy schemes (pay-off rule)*. The use of subsidy schemes developed to enhance the heating transition has been included in the model by replicating the dispatch of the PAW living labs subsidy. Thus, the municipality, on average, has 4 million euros available per neighbourhood. Per year, the municipality will only have the equivalent to the subsidy available for one neighbourhood (4 million euros).
- *Subsidy distribution strategy (boundary rule)*. Apart from the amount of subsidy available, the municipality sets a certain criteria that the TEC projects need to fulfil in order to receive the subsidy. The criteria alternatives represented the value system of the municipality (attributes of community) and in total there are four alternatives the municipality can select from: (i) environment focused (emission reduction), (ii) affordability focused (cost minimisation), (iii) acceptability focused (maximization of participation) or (iv) a balanced strategy looking at the trade-off between the three criteria.
- *Provision of persuasion workshops (information rule)*: Mahapatra and Gustavsson (2008) studied how the Swedish government influenced homeowners to adopt district heating system and conclude that a marketing campaign based on information provision was vital for motivating homeowners to adopt the district heating. Following this, the model includes the option of municipalities offering TEC boards the opportunity to attend persuasion workshops that aim at enhancing the interactions between the TEC board and the households so that their can better influence their attitudes towards thermal energy communities. This is something which is starting to occur in the Netherlands through the Natural Gas Free Area Program (PAW) which are available for all municipalities in the Netherlands.
- *CO_2 tax (pay off rule)*: Additionally, the municipality must monitor the implementation from 2020 onwards of a carbon tax which initially has a price of 22 euros that is expected to increase by 2.5 euros each year until 2030 (Borenstein, 2019). This CO_2 tax will increase the gas market price of natural gas and therefore increase the affordability and feasibility of TEC projects.

5.3.4. LAYER 3 – GOVERNANCE: TEC BOARDS

Actions and formation states. Throughout the run, the TEC board needs to go through five different phases in which certain actions and agreements need to be made that allow them to move from a lower to a higher state (see Section 4.2). Table 6 briefly explains the different phases the TEC board needs to go through in order to complete the formation process and the key outcome of each of the phases.

TABLE 6: TEC BOARD STATES DURING THE FORMATION PROCESS

Stage	Description	Outcome
Idea	Households decide whether they support the vision of the TEC board.	TEC board gathers enough support from the neighbourhood households and are formally established. From now on they can formally engage in organisational and project affairs.
Feasibility	TEC board can attend the persuasion trainings if available and they need to decide on a technology scenario to be implemented in the neighbourhood.	TEC boards, together with the households, makes a final decision over technology scenario.
Procurement	TEC boards send a subsidy request and the participating households and municipality agree on their level of financial contribution to the TEC.	An investment plan is finalised with an agreement on the level of financial contribution of actors
Building		The technology and infrastructure have been constructed, contracts have been arranged with the participants and they are connected to the district heating infrastructure.
Expansion	After the set-up, households can connect to the TEC. The rules for when they will be allowed to connect to the already existing district heating network depend on the participation policy that is in place.	TEC is expanded and more households are connected to the district heating infrastructure.

Attributes of community. From the start, each neighbourhood in the model has a TEC board that has already developed their vision for the TEC project. This is translated by assigning each TEC board a certain ranking for their internal values which is further explained in Section 6.2.4 (environmental concern, energy independence and financial concern). Apart from the value ranking TEC boards have a certain level of persuasion skills. Initially, since at the beginning of the run the TEC board is considered to be recently formed, it is assumed that they do not have these skills. They can acquire these skills when the TEC board participates in the training provided by the government and allow the TEC boards to better reach the households in the neighbourhood and influence their level of TEC support.

Rules in use for technology selection:

- *Minimum neighbourhood participation policy (boundary rule)*: TEC board needs to agree with the neighbourhood on the technology scenario to be implemented. At least 10% of the neighbourhood must be participating in this decision making process.
- *Technology decision policy (choice rule):* TEC boards will choose the collective technology with the highest score and highest support and the most popular individual technology alternative.
- *Technology ranking (aggregation rule)*: Each collective alternative is ranked on the basis of three criteria with several sub-criteria. The technology decision making process is explained in detail in Section 6.2.2.
- *Process duration policy (scope rule):* Regarding the duration of the technology choice process, it is assumed that there is a maximum time of 18 months for the selection of both the selection of the technology scenario (Busch et al., 2017).

Other rules in use. Apart from the policies regarding the technology selection, TEC boards have available the following instruments to guide the TEC formation process:

- *Participation policy (aggregation rule).* This represents the mechanisms through which TEC expands after it has been initially set up. The participation policy alternatives differ to the extent to which the decision is made at an individual level or at a collective level.
    - *Individual participation policy*: The first option is that once households have made the decision to participate, they can make the insulation changes and connect to the existing TEC at any time. However, when they connect at first they will be having their heat supplied from natural gas. Only once enough new participants have joined to cover for the investment on the collective sustainable heating technology to cover their heat demand, they will be receiving heat from a renewable energy source.
    - *Collective participation policy*: The second connection option is that households who decide to participate after the initial set up of the heating infrastructure will have to wait until there are enough households to cover the investment for upgrading the capacity of the collective heating technology. Once the new capacity is installed, they will make the required thermal insulation changes and installations in the houses and connect to the district heating infrastructure.
- *Household persuasion (information rule).* Once the TEC board is recognised by the neighbourhood (i.e. has gathered enough support) and formalised, TEC boards can participate in the workshops organized by the municipality to train them on how to better talk with the neighbourhood to convince them to participate in the thermal energy community. Replicating the marketing campaign used by the Swedish government for increasing the diffusion of district heating networks researched by Mahapatra and Gustavsson (2009), after gaining this skill, TEC boards will be able to reach part of the neighbourhood to persuade them to align their values closer to those of the TEC board and chance their perception about the project. This attempts to reflect the impact of broad reach out and informative campaigns actors may use in TEC projects such as newsletters and open letters. TEC boards will only be able to influence those households whose values rankings are different from the TEC board's value ranking. Another important consideration is that those households that have very extreme value concerns (either very high or very low) will not be influenced by this initiative of the TEC board.

5.3.5. Layer 4 – Individual analysis: Households

Actions and participation states: Throughout the model run, households are constantly making decisions about the extent to which they are participating in the thermal energy community of their neighbourhood. Table 7 describes the potential 7 levels of household participation in the thermal energy community:

TABLE 7: LEVELS OF HOUSEHOLD PARTICIPATION IN TECS (ORDINAL SCALE)

Participation level	Description	Household heating characteristics
0	Household does not engage in the TEC project	Household is not thermally insulated but is connected to the natural gas network
1	Household's values align to those of the TEC board and hence, supports the TEC board leading the TEC project	
2	The collective technology chosen by the TEC board aligns to the household's preferences.	
3	Household supports the individual technology preferred by the community's majority.	
4	Household is willing to make the required investment for the construction of the infrastructure and instalment and operation of the heating technology	
5	Household is connected to the district heating network and their heat is generated by the selected sustainable heating source	Household is thermally insulated, and is connected to the sustainable district heating network

6	Household is connected to the district heating network and their heat is generated by natural gas.	Household is thermally insulated, and is connected to the natural gas network

When the values of the households align with those of the TEC board, they become TEC board supporters (level 1) and decide whether they support the TEC board's technology scenario on the basis of whether the selected collective heating system by the TEC board is align with their values (level 2). After the collective scenario has enough support, the households decide on the individual technology and further concretes the technology scenario (level 3). Then households decide whether they are willing to make the investment required (level 4). When the infrastructure is installed, households make the required investment and connect to it (level 5 and 6).

Biophysical conditions: Households have an annual heat consumption which depends on whether the house has been insulated or not and annual yearly CO_2 emissions which depends on the heat demand and the heating technology they are connected to.

Attributes of community:

- *Values*: Households have a value system formed by four key values which influence their decision over their degree of participation in a thermal energy community: environmental concern, financial concern, energy independence concern and sense of community.
- *Social value orientation:* Following the social value orientation theory, households are categorized in four different SVO groups according to their internal value system (altruistic, cooperative, individualist and competitive).
- *Payback time and willingness to pay*: Each household is assigned an expected payback period (PBT) and amount willing to invest (WTP). Following the results from studies that researched the link between SVOs and willingness to invest, the level of the PBT will increase the more altruistic the household is (see Table 8). Then, the WTP of each household will be assigned based on their expected PBT by calculating the accumulated expected savings for the PBT period of the household.

TABLE 8: EXPECTED PAYBACK TIME ASSIGNED TO HOUSEHODLS BASED ON THEIR SOCIAL VALUE ORIENTATION TYPE

SVO group	1 - Altruistic	2 - Cooperative	3 - Individualistic	4 - Competitive
Expected PBT (years)	15-20	10-15	5-10	1-5

A further description of the biophysical conditions and attributes of community of households can be found in Section 6.2.4.

Rules in use for TEC participation:

- *Technology criteria: (aggregation rule)*: Each individual technology alternative is ranked on the basis of three criteria with several sub-criteria (see Section 6.2.2).
- *Technology selection (choice rule):* Households will choose the collective and individual technology with the highest score (see Section 6.2.2).
- *Investment decision (payoff rule):* Households are willing to invest in the TEC when the average investment required is lower than their own WTP (see Section 6.2.4).

5.3.6. NEIGHBOURHOOD STRUCTURE AND DYNAMICS

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. In a small world network which models social interactions, the nodes represent people and the edges connect people that know each other. Their key property is that most nodes can be reached from every other by a small number of hops or steps. Section 6.2.4 provides a further explanation on how the small world network has been implemented in the model.

Regarding the dynamics within the neighbourhood, the model assumes that all households in one neighbourhood can interact with their neighbours. It is assumed that households interact in monthly residents meetings where 10% of the neighbourhood participates.

The interactions occur based on the following principle: When two households interact, each with 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 influenced by the interaction.

5.4. EVALUATIVE CRITERIA

This section describes the evaluative criteria that will be used to analyse the outcomes of the different experiments described in Chapter 7. This evaluation criteria in the form of key performance indicators allows to compare the results from different experiments to then arrive to providing insights to the problem described under Section 5.1.

The key performance indicators have been developed at a neighbourhood level which later can be calculated at the municipality level for a broader and systemic analysis (see Table 9).

TABLE 9: DESCRIPTION OF KEY PERFORMANCE INDICATORS USED TO EVALUATE THE MODEL OUTCOMES

Key performance indicator	Unit	Description
Neighbourhood final SVO distribution	%	Distribution of households in the different social value orientation groups after 10 years.
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.

5.5. HYPOTHESES OVER POTENTIAL OUTCOMES

This section presents a set of ten hypotheses on how the three external variables of the IAD framework are expected to influence the outcome. These are expected to be either accepted or rejected with the analysis of the simulation results. The hypotheses related to the biophysical conditions aim at testing the impact of the extent to which the collectiveness of the technology scenarios matter and to understand the influence of choosing very environmentally friendly technology in the final outcome of TECs. Moreover, the hypothesis on the attributes of community aim at testing whether the assumptions made through the application of the Behavioural Reasoning Theory and the Social Value Orientation Theory hold true for the outcome of the agent-based model. Lastly, the hypotheses developed for the rules-in-use have been developed to structure the discussion over which instruments are the most effective for the successful formational of thermal energy communities.

BIOPHYSICAL CONDITIONS (TECHNOLOGY)

- H1.1.: Fully collective scenarios are more popular than individual/collective scenarios.
- H1.2: Neighborhoods with fully collective scenarios are more successful than collective/individual scenarios.
- H1.3: Neighborhoods installing the most environmentally friendly technology are not necessary the most successful ones.

ATTRIBUTES OF COMMUNITY (VALUES)

- H2.1: Neighborhoods with households with pro-social value orientations are more successful than those with pro-self-orientation.
- H2.2: Neighborhoods with pro-self-orientations prefer those technology scenarios that mix individual and collective technologies.
- H2.3: TEC boards with environmental concern as the higher ranking are more successful than the rest.
- H2.4: The most successful municipalities are the once that prioritises environment in their decision making process.

RULES-IN-USE (POLICIES)

- H3.1: Individual participation policy leads to higher neighborhood participation and CO_2 emissions avoided.
- H3.2: Persuasion training leads to higher neighborhood participation and hence CO_2 emissions avoided.
- H3.3: Municipality needs to support the TEC boards by covering at least 30% of the transition costs.

5.6. CONCEPT FORMALIZATION

Once the system has been decomposed into its most basic elements, it must be formalized to fit the data structures of the agent based modelling software Netlogo (Wilensky, 1999). All states and actions of the agents and the states of the objects are respectively shown in Table 10 and Table 11. In the following paragraphs, the most formalization of the most important states and why they have been formalized in such a way is explained.

Integers. Integers are whole numbers that are used in the model to group the agents in various groups. For instance, agents, TEC boards and technologies are grouped into neighbourhoods and households are grouped into SVOs (1-4). Moreover, integers are used for identification and monitoring: through integers, technology types to be selected by the agents, the level of participation of each households (0-6), and the number of subsidies dispatched are monitored. Furthermore, integers are also used for providing a ranking to the values of the TEC boards (1-3) and a certain expected payback time period for the households. These PBT period ranges from 1 to 20 years depending on the households SVO group.

Floats. Floats are numbers with decimals. They have been used to monitor the importance households assign to each value type. Initially, each household gets assigned a value from 0 to 10 on each value type and through interactions this initial value changes transforming into a decimal number. This formalisation provides a big enough range for measuring different level of importance assigned to each value and allows for comparison between each other. Floats have also been used for monitoring the

Lists. Lists are used to store integers or floats together. In the model, lists have been used to store the technical and financial characteristics of the individual and collective technology options. Each position of the lists belongs to a specific characteristics. For instance, the first item refers to the amount of investment required per kilowatt of capacity. Another relevant way in which lists have been used in the model is to store the rankings calculated based on the outcome of the multi-criteria decision making for the technology choice by the households and TEC boards and for the neighbourhoods for the subsidy distribution by the municipality.

Booleans. The two most important Booleans in the model, which can either be true or false, represents two different formal institutions options: the availability of persuasion trainings and the establishment of a CO_2 tax that affects the gas price.

TABLE 10: OVERVIEW OF THE STATES AND ACTIONS FOR THE KEY AGENTS IN THE MODEL: HOUSEHOLDS, TEC BOARDS AND GOVERNMENT

HOUSEHOLDS	TEC BOARDS	MUNICIPALITY
States	**States**	**States**
Neighbourhood *(integer)* SVO *(integer 1 to 4)* Values: environment *(float)* Values: independence *(float)* Values: costs *(float)* Values: Sense of community *(float)* Expected PBT *(integer 5 to 20)* Willingness to pay (float) Yearly heating consumption *(float)* Share space heating *(float)* Collective type support: none, biogas, ATES; DW *(integer 0 to 3))* Individual type support: none, solar thermal, heat pump *(integer 0 to 3)* Participation level (integer 0 to 6) CO_2 emissions *(float)*	Neighbourhood *(integer)* Values: environment *(integer 1 to 3)* Values: independence *(integer 1 to 3)* Values: costs *(integer 1 to 3)* Neighbourhood trust *(float)* *Neighbourhood CO_2 emissions (float)* *Skills (yes/no))* Rank collective scenario *(list)* Selected collective scenario *(integer)* Preferred individual scenario *(integer)* Number of TEC board/scenario supporters *(integer)* Number of participants *(integer)* Formation state: not built, built, formed, investment covered, set up *(string)* TEC RE share (*float*) TEC investment share (float)	Subsidy amount *(integer)* *Subsidy not used (float)* Subsidy distribution (list) Subsidy requests *(list)* SDE number *(integer)* PAW training cap *(integer)*
Actions	**Actions**	**Actions**
Heat demand CO_2 emissions TEC board support decision Collective technology support decision Individual technology support decision Investment decision Connection to infrastructure	Collective scenario decision Training request & participation Feasibility analysis Subsidy request Infrastructure building Meeting (with supporters) Persuade	Subsidy decision Subsidy dispatch Training provision

Update preferences (households interactions, TEC board interactions		

TABLE 11: OVERVIEW OF MAIN STATES OF THE COLLECTIVE AND INVIDIVIDUAL TECHNOLOGY OPTIONS MODELED AS OBJECTS IN THE ABM

Collective technology (object)	Individual technology (object)
States	**States**
Neighbourhood *(integer)* Collective heating system: biogas, ATES or DW *(string)* Technical and financial characteristics *(list)* MCDM ranks (*integers*) WP value TEC board *(float)*	Neighbourhood *(integer)* Individual heating system: none, individual heat pump, solar thermal *(string)* Technical and financial characteristics *(list)* MCDM ranks (*integers*)

CHAPTER 6: MODEL IMPLEMENTATION

This Chapter describes most of the data used for the development of the model and the experimentation phase. Section 6.1 explains the data sources used and Section 6.2 describes by agent type the preparation done with the data before inputting it in the model. Section 6.3 illustrates the validation done through literature and sensitivity analysis for the parameters to resemble the reality of the Netherlands. Section 6.4 describes the most relevant assumptions taken from the model which do not relate to specific data and the last section provides an overview of all the parameters used as input.

6.1. DATA SOURCES

For the model to be able to provide relevant insights, the decisions made throughout the model runs must be backed up through reliable information. Since the agent based model aims to exemplify a prototype case of a development of a thermal energy community in the Netherlands and it does not attempt to provide insights to a specific case study, the priority has been to use official sources that provide general information on the Netherlands: Statistics Netherlands (CBS), Netherlands Environmental Assessment Agency (PBL), Netherlands Enterprise Agency (RVO), CE Delft, official websites from the Dutch Climate Programs (e.g. Expertise Centrum Warmte and Programma Aardgasvrije Wijken) and academic articles that focus on Dutch energy communities.

The statistics on average household energy consumption and on residential building stock from the Dutch governmental institution, Statistics Netherlands (CBS) were used to build neighbourhoods in the model that resemble the average physical characteristic of a Dutch neighbourhood. Moreover, In order for the households in these neighbourhoods to represent the values held by Dutch households, the model extrapolated the results from a survey conducted by Koirala et al., (2018) to 599 Dutch citizens to assess how demographic, socio-economic, socio-institutional and environmental factors affect the willingness to participate in community energy systems.

Furthermore, the Netherlands Environmental Assessment Agency (PBL) is a research institute that advises the Dutch government on environmental policy and regional planning issues. Part of their role is to advise the Ministry of Economic Affairs and Climate on how to shape the next issue of the Sustainable Energy Transition Incentive Scheme (SDE++). For this, they have drafted several reports on the different technologies that fall into the subsidy scheme in which the cost price of the various technologies are determined (PBL, 2020). The technical and financial data found in these reports have been used to shape the characteristics of the technology scenarios for these to align to the Dutch context. Additionally, as part of the Dutch Climate Act, PBL must publish every year a climate and energy outlook which provides insight into the development of Dutch greenhouse gas emissions. The data on the gas and CO_2 price development from 2020 to 2030 from the report published in 2019 was used in the model (PBL, 2019).

The Netherlands Enterprise Agency (RVO) is a department of the Dutch Ministry of Economic Affairs, that implements government policy for sustainability within other topics. The public information found on their website on the Renewable Energy Investment Subsidy (ISDE) contains valuable information on technical and financial characteristics of the individual heating technology options in the Netherlands (heat pumps and solar thermal systems). Additionally, the CO_2 emission factors used in the model were taken from the fuel list published by this department.

Lastly, CE Delft is an independent research agency and consultancy that support institutions in achieving structural sustainable change. As an outcome of their research on the sustainable heating transition, they developed factsheets with an overview of all individual and collective heating techniques that residents can choose from to heat their houses. The model uses the financial information found in the factsheets for collective heat networks.

6.2. Data collection and preparation

This section shows how the data gathered in the sources explained above were extracted and prepared for them to be used in the model. This section is structured by agent type and the last sub-section focuses on the data preparation for the multi-criteria decision making processes.

6.2.1. Biophysical conditions – technology

The technology scenario in the model is composed by a collective system (biogas, ATES and TEA) and an individual system (heat pumps, solar thermal and no system). The following two sections describe the technical, financial and environmental data used to characterise each technology alternative represented in the model.

Collective technology

Technical & financial data

All the technical and financial data related to the collective technologies modelled (biogas, ATES and heat recovery from wastewater) have been extrapolated from the advisory reports PBL has published on the SDE++ subsidy. The technical data required to calculate the capacity of the technology for a neighbourhood knowing the heat demand the technology must cover are the average load hours which differs per technology option. Additionally, the calculation also accounts for the peak demand of the neighbourhood which was assumed to be 10% above the average heat demand (Airaksinen and Vuolle, 2013). The financial information used to calculate the required investments was about the capital and operating costs as well as the lifetime of the technology. With respect to the latter, in reality the SDE++ report assumed 20 years for the biogas and 30 years for the other two technology options. As a result, the capital cost information for the biogas was recalculated to account for a reinvestment after 20 years. The data used per technology option is summarised in Table 12.

Table 12: Data input for collective technology alternatives

Attribute	Units	Biomass	ATES	TEA	Reference
Investment costs	EUR/KW	415	2401	2364	SDE ++ (PBL)
O&M costs	EUR/KW/yr	25	113	170	
Load hours	h	3000	3500	6000	
Lifetime	yr		30		
Peak demand	%		10		Airaksinen and Vuolle, 2013

CO_2 emissions

In order to account for the difference in CO_2 emissions in the different scenarios , the CO_2 emissions intensity of each technology had to be estimated. For the biomass technology, the CO_2 emission intensity was assumed to be 0.25 Kw/kWh which accounts for the CO_2 emissions of the wood pellets and the boiler for the whole lifecycle. For the ATES and the TEA system, the CO_2 emission intensity was calculated taking into account the information on the electricity consumption of the system, the average capacity and the load hours included in the SDE++ reports and the current CO_2 emissions intensity of the electricity mix in the Netherlands (Moro and Lonza, 2018). The following equation shows how it was calculated and Table 13 the data used for the calculation and the results.

$$CO2_{int,tech} = \frac{annual\ elect\ consump}{average\ capacity} \times CO2_{int,elect} \div load\ hours$$

TABLE 13: DATA INPUT FOR CALCULATION OF COLLECTIVE TECHNOLOGY CO2 EMISSION INTENSITY

	CO_2 intensity (electricity)	Average capacity	Annual electricity consumption	Load hours	CO_2 intensity technology
	Kg/kWh	Kw	KWh/yr	h/yr	Kg/kWh
Biomass	0.429	-	-	-	0.26
ATES		800	994000	3500	0.152
TEA		10000	1935000	6000	0.138

Individual technology

Technical & financial data

The technical and financial information related to the individual technologies included in the model (heat pump and solar thermal) has been compiled from multiple data sources. In the model it is assumed that the individual technology will cover the demand for hot what (16.5% of total heat demand). Once knowing the heat demand, similarly to the collective technology, the technical data required to calculate the capacity of the individual technology for one household are the average load hours which differs per technology option. The information used to calculate the required household investments was about the capital and operating costs, and the lifetime of the technology. With respect to the lifetime, the average lifetime of the heat pump is 15 years as oppose to 30 years for a solar thermal system. As a result, the capital cost information for the heat pump was recalculated to account for a reinvestment after 15 years. The data used per technology option is summarised in Table 14.

TABLE 14: DATA INPUT FOR INDIVIDUAL COLLECTIVE ALTERNATIVES

Attribute	Units	Heat pump	Source	Solar thermal	Reference
Average capacity	KW	1	-	2	-
Investment costs	EUR/KW	1770	Sandvall, Ahlgren and Ekvall, 2017	1666	The Renewable Energy Hub, 2018
O&M costs	EUR/KW/yr	35.4	Sandvall, Ahlgren and Ekvall, 2017	22.5	GREBE, 2017
Load hours	h/yr	1500	Kontu et al., 2020	700	Epp, 2020
Lifetime	yr	15	Sandvall, Ahlgren and Ekvall, 2017	30	Sandvall, Ahlgren and Ekvall, 2017
Total costs	EUR	4602	-	4680	-

CO_2 emissions

Figure 9 taken from Klip (2017) on the CO_2 intensity of a heat pump and a gas boiler for various electricity mixes was used to assume the CO_2 intensity of the individual heat pumps in the model. Considering a COP of 3 and an electricity mix with a $C0_2$ intensity of 471 kg CO_2/KWh (red line) which resembles that of the Dutch electricity mix where used to select the CO_2 intensity of the heat pump. As a result after converting the CO_2 intensity, this is assumed to be 0.14 kg CO_2/Kwh for the heat pumps in the model.

For the calculation of the CO_2 intensity of the solar thermal systems, it was assumed that the solar water heater is used to supply hot water 80% of the time, and the rest 20% will be supplied by the electric water heater (Patel et al., 2012). In other words, this 20% will be covered by the electricity grid. By calculating 20% of the CO_2 intensity of the grid we arrive to a CO_2 intensity for the water heater systems of 0.086 kg CO_2/KWh.

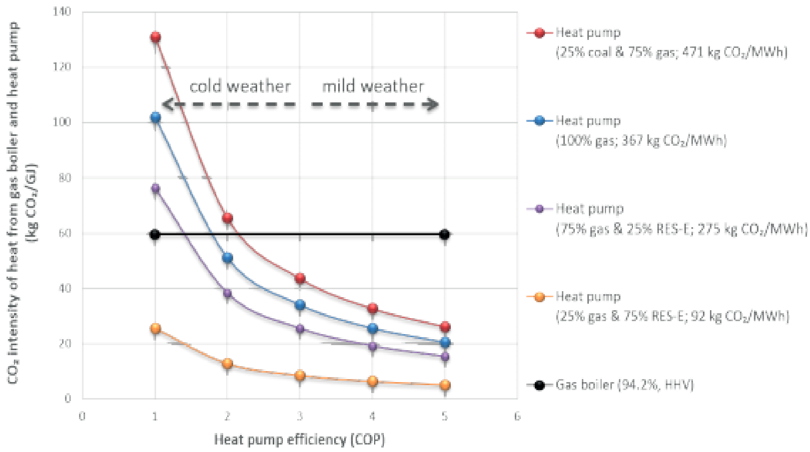


FIGURE 9: CO2 INTENSITY OF HEAT PUMPS IN THE NETHERLANDS BY ELECTRICITY MIX ALTERNATIVE (KLIEP, 2017)

6.2.2. ATTRIBUTES OF COMMUNITY - VALUES

The value system of each agent type in the model is the key factor influencing the preferences of agents over the technology decision making. This has been taken into consideration by implemented a values based multi-criteria decision making technique for the decision over the technology alternatives.

Table 15 describes the criteria and sub-criteria used to conduct the multi-criteria decision making of the agents with respect to the technology scenario. The three criteria are directly linked to the values included in the model (environmental concern, cost concerns and independence concerns).

TABLE 15: CRITERIA AND SUB-CRITERIA USED FOR MULTI-CRITERIA DECISION MAKING PROCESSES

Criteria	Sub-criteria	Unit	Description	Reference
Financial criterial	CAPEX	Euros	Investment costs	Dénarié et al., 2018
	OPEX	Euros	Operational and maintenance costs during the lifetime of the system	Tsoutsos et al., 2009
	Payback time	Years	Years for the investment and maintenance cost to equal the accumulated energy savings from the change	Karunathilake et al., 2019
	Subsidy coverage	%	Percentage of the capital costs covered by the SDE++ subsidy	Tsoutsos et al., 2009
Environmental criteria	CO_2 emissions	Kg CO_2eq	CO_2 emission intensity of technology based on capacity	McKenna et al., 2016
	Land use	HA	Amount of land use required for technology based on capacity	Dénarié et al., 2018
	Social acceptance	1 to 10	Degree to which that technology is accepted, recognized and implemented in the Netherlands	Tsoutsos et al., 2009
Independence criteria	Energy input to the system	KWh	Amount of energy input required for the technology to produce the heat to cover the neighbourhood heat demand	McKenna et al., 2016

The criteria for each alternative was calculated on the basis of the required capacity to cover the heat demand per household by alternative. Since the load hours is lower in the biomass technology (A1) than in the ATES (A2) and the TEA system (A3), the capacity required per household is also higher.

Financial criteria

The investment and maintenance costs were calculated by multiplying the capacity per household by the investment costs from Table 16. The operating costs were calculating in the following way:

$$Costs_{main} = Cap_{tech} \times Operating\ costs_{fixed} + heat\ demand \times Operating\ costs_{var}$$

The payback time period of the technology was calculated by dividing the total costs for a period of 30 years by the savings

$$PBT_{tech} = \frac{total\ costs}{Annual\ energy\ cost\ savings} = \frac{invest_{cost} + operating_{costs} \times 30}{heat\ demand\ reduction_{annual} \times price_{gas}}$$

For the percentage of subsidy coverage, the following information on the SDE++ subsidy amount per technology found in the reports published by PBL were used (PBL, 2020):

TABLE 16: DATA INPUT FOR SUBSIDY COVERAGE SUB-CRITERIA FOR EACH COLLECTIVE TECHNOLOGY ALTERNATIVE

	Units	Bio-boiler	ATES	TEA
Subsidy amount	EUR/KWh	0.030	0.080	0.042
Subsidy time	yr	12	15	15

The share was calculated by dividing the total subsidy amount dispatched through the SDE++ subsidy scheme by the total cost of the technology throughout its lifetime.

$$Subsidy_{coverage} = \frac{total\ subsidy}{total\ costs} = \frac{heat\ demand + subsidy_{SDE++} \times\ subsidy\ time}{investment_{costs} + operating_{costs} \times lifetime}$$

Environmental criteria

The annual CO_2 emissions per household were calculated by multiplying the $C0_2$ emissions intensity of the technologies (Table 13) by the annual household heat demand.

The data for the second environmental sub-criteria, land use, was taken from the study conducted by Dombi, et al., (2014) on the sustainability assessment of renewable power and heat generation technologies. They describe land use as the “amount of technological demand on land used for agricultural, forest or nature conservation purpose”. Information for the land demand of a district heating system connected to a wastewater treatment plant was not found and it was then assumed to be similar to that of the ATES system (see Table 17).

TABLE 17: DATA INPUT FOR LAND USE SUB-CRITERIA FOR COLLECTIVE TECHNOLOGY ALTERNATIVES

	Bio-boiler	ATES	TEA
Land demand (km^2 /kwh)	59.5	2.68	No info

For the third environmental criterial, awareness on the technology a more qualitative assessment was done. Godschalk and Bakema (2009) conducted a study on how to stimulate the scale up of aquifer thermal energy storage in the Netherlands and stated that usually proven and common technologies are preferred since these are more easily accepted by the residents. In this line, Hoppe (2012) on a study about the adoption of innovative energy systems in social housing also affirmed that due to a lack of knowledge on the benefits of new technology, tenants prefer heating systems they are familiar with. Thus, in the model it is assume that the more a heating technology has been used in a sustainable heating project the more easily accepted will be by an actor and the higher it will score in the awareness sub-criteria. The technologies are given a score from 1 to 10 on how aware Dutch households are about each technology.

To develop the awareness sub-criteria for the collective technology, a score from 1 to 10 was given to each technology by normalising the number of district heating projects that use each technology and multiplying the final value by 10. The data set on the current testing grounds of the PAW program, the 25 neighbourhoods that received the subsidy was used to count the number of projects that were planning on installing each collective technology. Out of the 25 projects, a total number of 14 projects were planning on installing one of the technologies incorporated in the model. In particular, there were 8 biomass projects, 4 ATES project and 2 aqua thermal projects.

Regarding the individual heating technologies , Kleefkens (2011) estimates that in the Netherlands an average of 17000 heat pumps and 8000 solar thermal systems are installed per year. This shows that the market size of solar thermal systems in comparison with that of heat pumps is rather small in the Netherlands (IEA-SHC, 2017). In this line, Fouladvand (2017) conducted a study on the social acceptance of solar thermal energy systems in the Netherlands and from the results of the survey showed that only 16% of the respondents were using these systems in their houses. With all this information, a score of 3 and of 8 were given respectively to the solar thermal systems and heat pumps for the level of awareness in the Netherlands (see Table 18).

TABLE 18: SCORE GIVEN FOR LEVEL OF SOCIAL AWARENESS TO EACH HEATING TECHNOLOGY.

Heating technology	Bio-boiler	ATES	TEA	Heat pump	Solar thermal system
Awareness score	7	5	2,5	8	3

INDEPENDENCE CRITERIA

The third criteria used for the multi-criteria decision making process is the energy dependence criteria. In this thesis, this criteria is defined as the amount of energy that is imported into the thermal energy community of study (Mc Kenna et al., 2016). With respect to the bio-boiler technology, this refers to the amount of energy stored in the wood pellets that are imported to the thermal energy community for the generation of heat. Regarding the ATES and TEA systems, since most of the heat is considered to be located within the boundaries of the thermal energy community, this energy refers to the amount of electricity consumed by the systems for the generation of heat.

For the bio-boiler, the energy import is calculated by dividing the annual household heat demand by the efficiency of a wood pellet bio-boiler (85%). For the ATES and the TEA system, the energy input to the system was derived by dividing the annual electricity consumption of the technology by the average capacity installed of the technology.

CRITERIA CALCULATION

Table 19 shows the calculation in absolute terms of each sub-criteria for each collective technology alternative. For the results of the individual technology refer to the Appendix A.

TABLE 19: RESULTS FOR CALCULATION OF DATA INPUT ON EACH SUB-CRITERIA FOR MULTI-CRITERIA DECISION MAKING PROCESSES FOR SELECTION OF COLLECTIVE-TECHNOLOGY ALTERNATIVE

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings		
					A1	A2	A3
C1	Financial	Investment costs	Min	€/HH	1402	4635	2668
		Maintenance costs	Min	€/yr	77	231	204
		PBT tech	Min	yr	4	13	10
		Subsidy coverage	Max	Fraction	0,99	0,70	0,48
C2	Environmental	CO_2 emissions	Min	t/HH/yr	1757	1029	935
		Land use	Min	KM^2/kwh	60	3	3
		Awareness	Max	number	7,0	5,0	2,5
C3	Energy	energy independence	Min	KWh/yr	7949	2399	2179
		Tech capacity	Min	kw/HH	2,25	1,93	1,13

CRITERIA RATING

Once the parameters for each alternative have been calculated, the rating of each alternative on each criterion is calculated by normalising the absolute values on the basis of whether the goal is to maximise or minimise such criteria.

When the goal is minimisation, a value of 0 is given to the alternative with the highest score in the sub-criteria and a value of 1 to the alternative with the lowest score. For the third alternative which sub-criteria falls between the other two, the following expression is used to arrive to a value between 0 and 1:

$$value_{norm,AX} = \frac{value_{abs,AX} - value_{abs,Amax}}{value_{abs,Amin} - value_{abs,Amax}}$$

When the goal is maximisation, a value of 0 is given to the alternative with the lowest score in the sub-criteria and a value of 1 to the alternative with the highest score. For the third alternative which sub-criteria falls between the other two, the following expression is used:

$$value_{norm,AX} = \frac{value_{abs,AX} - value_{abs,Amin}}{value_{abs,Amax} - value_{abs,Amin}}$$

Table 20 show the results for the normalisations of the criteria for the collective technology alternatives.

TABLE 20: RESULTS FOR NORMALISATION OF SUB-CRITERIA INFORMATION FOR EACH COLLECTIVE TECHNOLOGY ALTERNATIVE

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings		
					A1	A2	A3
C1	Financial	Investment costs	Min	€/HH	1,000	0,000	0,608
		Maintenance costs	Min	€/yr	1,000	0,000	0,173
		PBT tech	Min	yr	1,000	0,000	0,352
		Subsidy coverage	Max	Fraction	1,000	0,432	0,000
C2	Environmental	CO_2 emissions	Min	t/HH/yr	0,000	0,885	1,000

		Land use	Min	HA/Kwh	0,000	1,000	0,994
		Awareness	Max	number	1,000	0,556	0,000
C3	**Energy**	**energy independence**	Min	KWh/yr	0,000	0,962	1,000

CRITERIA WEIGHTING

First, the value system of the agent is normalised. Then, this normalised value is used for determining the preference weight for each criterion in the MCDM process. Then, the weight for each sub-criterion is calculated by dividing the weight for each criteria by the number of sub-criterion (see example in Table 21).

TABLE 21: EXAMPLE OF FINAL WEIGHT PER SUB-CRITERIA IN MCDM FOR TECHNOLOGY ALTERNATIVE SELECTION

Criteria	Values	Normalised value	Number of sub-criteria	Sub-criteria	Weight
Financial criterial	6	0.3	4	CAPEX	0.075
				OPEX	0.075
				Payback time	0.075
				Subsidy coverage	0.075
Environmental criteria	9	0.5	3	CO_2 emissions	0.16
				Land use	0.16
				Social acceptance	0.16
Independence criteria	4	0.2	1	Energy input to the system	0.2

ALTERNATIVE SCORING

Once the rating of each alternative on each sub-criterion has been calculated (Section 6.2.2.5) and each sub-criterion has a weight assigned (Section 6.2.2.6) the score for each alternative is calculated by multiplying all sub-criterion ratings for an alternative with their respective weights. The outcome provides a number from 0 to 1 and the alternative with the highest score is considered to be the preferred option.

$$Alternative\ 1\ (A1) = (1 + 1 + 1 + 1) \times 0.075 + (0 + 1 + 0) \times 0.16 + 0 \times 0.2 = 0.46$$

6.2.3. LAYER 3 – GOVERNANCE: TEC BOARDS

Due to the lack of real data the TEC board values were assigned randomly. Every board in the model is given a random value ranging from 1 to 10 for each value: environmental concern, financial concern and energy independence concern. Then, the prioritised and leading value is determined based on these randomly assigned values. In the case were two value types are assigned the same value, it is assumed that the priority will be given to environmental concern, followed by economic concern and finally energy independence.

6.2.4. LAYER 4 – INDIVIDUAL ANALYSIS: HOUSEHOLDS

DRIVERS TO JOIN

The four key values that influence a person's degree of participation in a community energy systems which are included in the model are environmental concern, financial concern, energy independence concern and sense of community. The survey conducted for Koirala et al., (2018) research asked the respondents to rate the environmental and socio-economic-institutional drivers in Likert-type scales of 7 points. The results for four of the drivers included in these survey were used as input for the values held by the households in the model (see Table 22).

TABLE 22: MEAN AND STANDARD DEVIATION VALUES FOR DRIVERS USED TO MODEL THE VALUES SYSTEM OF HOUSEHOLDS IN THE MODEL

	Drivers	Mean	SD	Scale
Environmental	**Good for the environment**	5.45	1.55	7-point
Socio-economic-institutional	**Economic benefits**	5.19	1.54	7-point
	Sense of community	3.80	1.72	7-point
	Independence of national grid	3.62	1.87	7-point

Since the survey was done in a scale of 7 points, the information was first calibrated for a 10 point scale to fit the data input for the model. Then, the information on the mean and standard deviation were inputted in an online tool to produce a normal distribution dataset (Socscistatistics, 2020). The tool produced a dataset of 100 values ranging from 1 to 10 which was then visualised as a histogram. The histogram presented the results by frequency of responses for each point in the scale. Finally, the information on the histogram was used to create Table 14. The information on this table was used to assign to each household a value for each value type.

TABLE 23: PERCENTAGE OF THE NEIGHBOURHOOD POPULATION THAT IS INITIALLY RELATED TO EACH POINT IN THE SCALE FOR EACH VALUE TYPE

Scale	1	2	3	4	5	6	7	8	9	10	Total
Environmental concern	-	1	2	3	10	13	11	10	13	37	100
Economic concern	1	1	4	8	10	15	20	10	16	15	100
Independence concern	9	9	10	13	13	16	14	7	5	4	100
Sense of community	6	6	10	16	17	15	14	8	4	4	100

Household SVO

Once every household in the neighbourhood has been assigned a value for each value type, the social value orientation of the household is calculated. The two-stage classification method developed by Nascimiento (2019) was used to classify the households into one of the four social value orientation groups (altruistic, cooperative, individualistic, competitive).

The overall drive to join the community is calculated using the following expression:

$$\Delta drive = S_{environment} + S_{community} - (S_{financial} + S_{independence})$$

The first stage was to identify the households that fall under the altruistic and the individualistic social value orientation. For that, it is assumed that the altruistic households are those who place a higher value in the environmental concern and sense of community ($\Delta drive > 1$). As oppose to the more individualist households that score higher in the financial and energy independence concern ($\Delta drive < -1$).

However, those individuals which final score ($\Delta drive$) gives a result close to 0 ($-1 > \Delta drive < 1$), move unto the second stage of the classification method. For these the focus is how high they score in the sense of community driver. Those with a score lower than 5 will be classified under the competitive SVO and those that score higher than 5 under the cooperative SVO.

The results shown in Table 24 indicate that most of the households have a more pro social orientation (62%) and most of the households fall under their the altruistic and individualist group (92%).

TABLE 24: EXAMPLE OF INITIAL SVO DISTRIBUTION FOR AN AVERAGE DUTCH NEIGHBOURHOOD GIVEN MODEL OUTPUT

	SVO 1 Altruistic	SVO 2 Cooperative	SVO 3 Individualistic	SVO 4 Competitive

Neighbourhood share (%)	58	4	34	4

NEIGHBOURHOOD STRUCTURE AND DYNAMICS

The structure for the small world network of the neighbourhoods and the interactions between the households has been modelled by replicating and adapting the network generated by the "small worlds" model found in Netlogo library. This model is an adaptation of a model proposed by Watts and Strogatz (1998). It begins with a network where each household (node) is connected to his or her two neighbours on either side. Then, every time step which corresponds to one month, 10% of the nodes rewire one of their edges to connect with a different node. After rewiring, the households involved in the interactions will update their value systems leaning to that of the neighbour's opinion. Since the household's SVO depends on their value systems, this might also be altered as a result of these neighbourhood interactions.

PAY-BACK TIME (PBT) & WILLINGNESS TO PAY (WTP)

Based on the SVO group each household falls into, the household is assigned a specific expected payback time period. Following the line of reasoning of Kastner and Matthies (2016) the more an individual has a pro social value orientation, the higher their willing to invest will be. Additionally, the results from Koirala et al., (2018) survey that Nascimiento (2019) prepared substantiated this assumption. Table 25 shows the range of PBT period linked to each SVO category. For instance, a household that falls under the SVO 1 will be assigned an expected PBT between 15 to 20 years.

TABLE 25: RANGE OF PBT PERIOD ASSIGNED TO EACH SOCIAL VALUE ORIENTATION CATEGORY

	SVO 1 - Altruistic	SVO 2 - Cooperative	SVO 3 - Individualistic	SVO 4 - Competitive
Expected PBT	15-20	10-15	5-10	1-5

Based on this expected PBT assigned to each household, a limit to how much the household is willing to invest (WTP) in the thermal energy community is then calculated. The following equations explain how this attribute is calculated. The willingness to invest is calculated based on the accumulated savings the household will make during the time period of their PBT. The accumulated savings are calculated by the sum of the difference between what the household would pay in the reference scenario and what they expect to pay in the new technology scenario based on the expected annual gas and heat price. In the model the household has the information on the current gas price and the expected gas price increase for the 10 year period. The heat price is assumed to not vary throughout time.

$$\text{Willigness to invest (WTP)} = \Sigma_1^{PBT}\left(\text{gas costs}_{r,i} - \text{heat costs}_i\right) \text{ (1)}$$

$$\text{gas costs}_{r,i} = heat\ demand_r \times gas\ price_i \text{ (2)}$$

$$\text{heat costs}_i = heat\ demand_i \times heat\ price_i \text{ (3)}$$

CO_2 EMISSIONS

Another important attribute of each household is the amount of CO_2 emissions related to the heat consumption emitted per year. Equation 1 shows way in which this is calculated. The calculation of the CO_2 intensity is explained in the technology section (6.2.1*)*

$$CO2\ emissions_{HH} = heat\ demand_{collect} \times CO2_{int,collect} + heat\ demand_{ind} \times CO2_{int,ind} \text{ (2)}$$

OTHER PARAMETERS

Table 26 shows other important attributes that are assigned to the households.

TABLE 26: OTHER VARIABLES ASSIGNED TO HOUSEHOLDS IN THE MODEL

Parameter	Value	Unit	Source
Heat demand	13500	KWh/yr	CBS
Insulation heat demand reduction	50	%	Nava Guerrero et al., 2019
Space heating share	0.835		Eurostat
Hot water share	0.165		Eurostat

6.3. PARAMETER SET UP & VALIDATION

In the model there are a number of parameters representing different institutional factors and attributes which values can be assigned externally. This section focuses on explaining and validating the alternatives the model provides as options to experiment with. The attributes representing the gas and CO_2 price, number of households and the range of number of neighbourhoods, were validated using literature data. However, for the minimum share of the neighbourhood, the rate of neighbours interactions and the subsidy availability per neighbourhood, a sensitivity analysis was conducted given the lack of accurate data from the literature.

6.3.1. GAS PRICE AND CO_2 PRICE

Osman (2017) explains how future gas price uncertainties are a great barrier for the success of district heating projects. If agents and investors cannot predict what these future prices will be, their financial feasibility analysis will not have enough credibility. Additionally, if agents cannot ensure residents that in the long run they will be having large savings as a result from disconnecting from the natural gas source, it will be hard to convince them to participate in the project. Therefore, the gas price and their expected future growth are important parameters to consider in the analysis of the formation of thermal energy communities since it heavily influences the feasibility and acceptability of the district heating projects.

A policy that will have a great impact on the future gas price if it finally gets implemented is the application of a CO_2 tax. Borenstein (2019) states that a CO_2 tax at 50 euros will increase the gas price by 30%. Therefore, given the fact that such CO_2 tax has already been announced as part of the climate plans, this should be taken into consideration in the model.

The current gas price in the Dutch market is 0.096 EUR /KWh and PBL (2018) in the Energy and Climate outlook of 2019 predicts that this price will growth at a rate of 0.6 EUR cents / m3 (0.003 EUR/KWh) until 2030. Moreover, the same report projects a CO_2 price in 2020 of 22 EUR/t with a growth until 2030 of 2.5 EUR /yr. With this latter information of the CO_2 price, the impact on the current reference gas price was calculated given the calculations of (Boreinstein, 2019), which is shown in Table 27.

TABLE 27: DATA INPUT FOR GAS PRICE

	Gas price	Gas price growth
	EUR/KWh	EUR/KWh/yr
Reference	0.096	0.003
CO_2 tax (22 EUR + 2.5 EUR/yr)	0.106	0.004

6.3.2. Number of neighbourhoods & number of households

When developing the parameter of how many neighbourhoods should be included in what the model is representing as one municipality in the Netherlands the focus was in estimating the average number of neighbourhoods per municipality that are expected to be disconnected from the gas grid by 2030.

The Netherlands Environment Assessment Agency (PBL) concluded that the measures proposed in the Climate Accord published on 13 March 2019 would result in some 250,000 to 1,070,000 buildings being made 'gas-free', however, the target is at 1.5 million buildings. With the information of the number of municipalities in the Netherlands (277) and assuming there is an average of 1440 inhabitants per neighbourhood (Sleutjes, de Valk & Ooijevaar, 2018), and 2.17 inhabitants per household (CBS), the number of neighborhoods per municipality that should transition off gas can be estimated. The calculation results in an average of 664 households per neighborhood and a range between 1.19 and 5.08 neighborhoods with the proposed measures and 7.11 neighborhoods as the target.

$$\frac{Number\ neighbourhoods\ off\ gas}{municipality} = \frac{households\ off\ gas}{municipality} \div \frac{households}{neighbourhood}$$

$$\frac{households\ off\ gas}{municipality} = \frac{gas\ free\ buildings}{municipality} \times share\ residential\ stock$$

$$\frac{households}{neighbourhood} = \frac{inhabitants}{neighbourhood} \div \frac{inhabitants}{household}$$

As a result, the decision was made to model one neighbourhood as 660 households and run the model for a number of neighbourhoods per municipality ranging from 1 to 7 to consider the scenarios with the current policies and the target for 2030 and to be able to analyse whether the most suitable institutional conditions and factors vary across municipality sizes. Therefore, three municipality sizes will be included in the experimentation: 1, 3 and 7 neighbourhoods.

6.3.3. Share of neighbourhood

This attributes relates to the minimum share of the neighbourhood that needs to find consensus over each decision in the model before being able to move to the next stage. The PAW subsidy website states that the feasibility studies presented as part of the subsidy application should take into consideration the participation of all the households in the neighbourhood. However, from conversations with experts it was concluded that this is improbable to be achieved and that in practise municipalities are having conversations any neighbourhood willing to start a TEC project regardless of the initial neighbourhood participation levels. Since there is not a clear understanding of where to draw the limit in this attribute, a sensitivity analysis was conducted to give this attribute a specific value.

The sensitivity analysis was conducted following the OFAT (one-factor at a time) approach (Ten Broeke et al., 2016). All the parameters were fixed at a certain value and only the value of study was altered. For each parameter the model was run 30 times. The amount of CO_2 emissions avoided per neighbourhood and the share of households connected at a municipality level were gathered as the output to determine the attribute's value. These were considered the most important KPIs out of the nine KPIs developed since they account for both the sustainability and acceptability of the thermal energy project.

A first sensitivity analysis was conducted for a range between 0 and 1 in steps of 0.2. However, it was observed that after 0.4, the average share was 0. As a result, a second sensitivity analysis for a range between 0 and 0.5 in steps of 0.1 was done. Figure 10 and Figure 11 show the outcome of the sensitivity analysis for the indicators of CO_2 emissions avoided per neighbourhood and the share of households in the municipality connected to the district heating network. On the x-axis the Figures show the parameter ranges (0-0.5) and on the x axis the two outcomes of the sensitivity analysis. Each box represents the range in the results and the black line the mean for each parameter value.

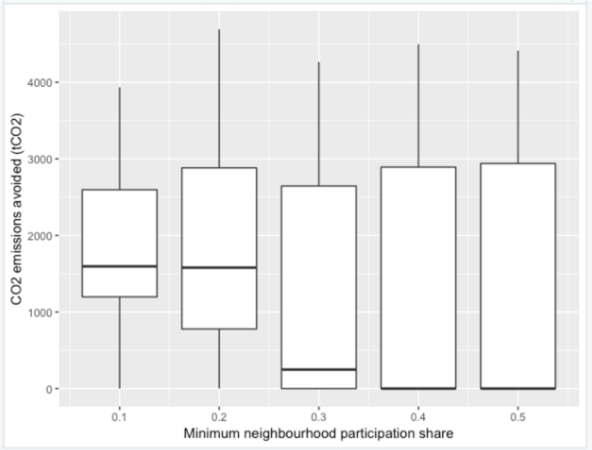


FIGURE 10: SENSITIVTY ANALYSIS OUTCOME FOR THE SHARE OF NEIGHBOURHOOD (C02 EMISSION REDUCTION)

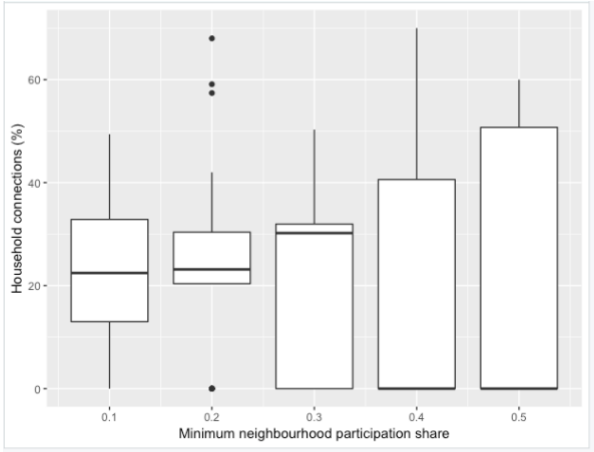


FIGURE 11: SENSITIVITY ANALYSIS OUTCOME FOR SHARE OF NEIGHBOURHOOD (HOUSEHOLD PARTICIPATION)

The results show that when the minimum neighbourhood share is set higher than 0.3 few neighbourhoods reach the set up phase. However, between the other two values 0.1 and 0.2 the conclusion is not as straight forward. On one hand, the average and maximum CO_2 emissions avoided is higher when the minimum share is set at 0.1 yet, on the other one, the average share of connections is higher when the share is set at 0.2. In the end it was decided to leave the share at the minimum possible value (10% of the neighbourhood) since it's the one closer to the reality in the Netherlands.

6.3.4. HOUSEHOLD INTERACTIONS

Research has been previously conducted which studies qualitatively the degree of involvement and participation of Dutch neighbours in their neighbourhood. However, when gathering quantitative information on the matter little information was found. A survey conducted by Kamer (2020) in the Netherlands with 2108 respondents asked participants to describe their level of household participation (see Figure 12).

The results which are presented below show that at least 4% of the neighbourhood is very active and involved in the neighbourhood and 24% are sometimes involved. Provided this information, a sensitivity analysis was conducted to fix the parameter somewhere in the range between 4% to 30%.

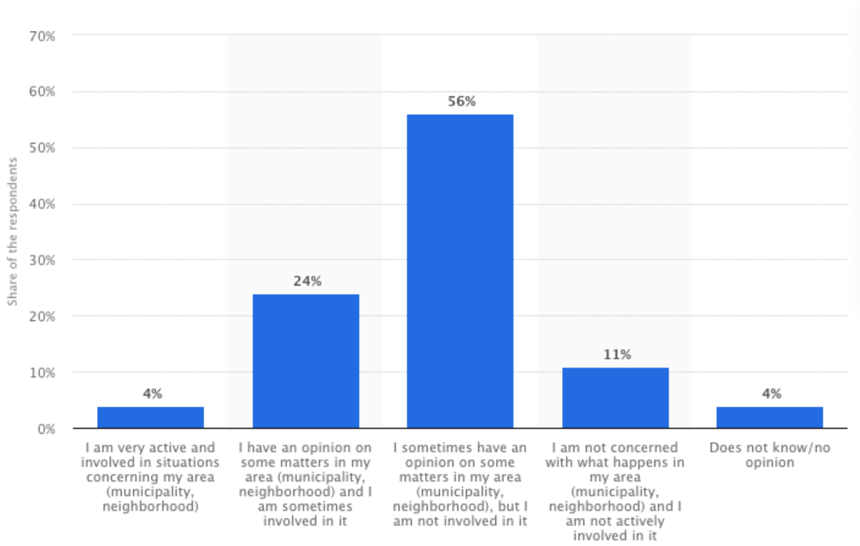


FIGURE 12: NEIGHBOURHOOD PARTICIPATION IN THE NETHERLANDS (KAMER, 2019)

Figure 13 and Figure 14 displaying the output from the sensitivity analysis show that when the projects are more successful when interaction rate is 10% or higher. However, in between 10% and 30% the change in the indicators is not significant enough. Going back to the statistics gathered in Koirala et al., (2018), 10% of the neighbourhood seemed like a reasonable assumption for the model since it would mean the 4% highly involved neighbours and 25% of the ones that sometimes get involved.

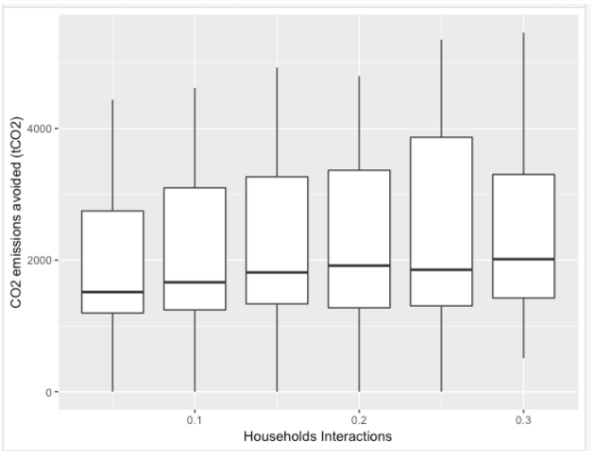


FIGURE 13: SENSITIVITY ANALYSIS OUTCOME FOR HOUSEHOLD INTERACTIONS (CO2 EMISSION REDUCTION)

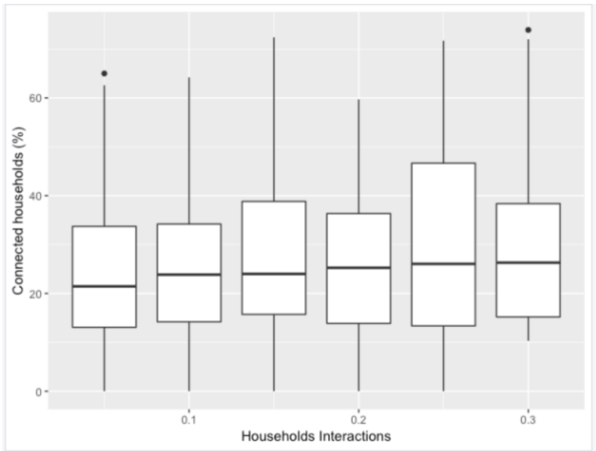


FIGURE 14: SENSITIVITY ANALYSIS OUTCOME FOR HOUSEHOLD INTERACTIONS (HOUSEHOLD PARTICIPATION)

6.3.5. INPUTS FOR BASE SCENARIO

This section presents a summary of the parameters used in the model with the reference to the section in which the value selection is validated either through literature or through the sensitivity analysis. The values for the technology characteristics have been omitted to avoid repetition but they can be found in Section 6.2.1.

TABLE 28: MODEL DATA INPUT

Parameter	Type	Value	Section	Description
Months	Numeric	120	5.1	Timespan of the simulation in months. One tick is one month.

Number of neighbourhoods	Range	1-7	6.3.2	Number of neighbourhoods modelled in one simulation.
Minimum neighbourhood participation	%	10	6.3.3	Minimum share of neighbourhood that needs to be willing to invest in order to set up the TEC.
Number of households per neighbourhood	Numeric	660	6.3.2	Average number of households per neighbourhood.
Household interactions	%	10	6.3.4	Percentage of households that interact with each other every month.
Environmental concern	Distribution	1-10	6.2.1.1	Level of environmental concern of the household based on external data input
Cost concern	Distribution	1-10	6.2.1.1	Level of financial concern of the household based on external data input
Energy independence concern	Distribution	1-10	6.2.1.1	Level of concern for becoming energy independent of the household based on external data input
Sense of community	Distribution	1-10	6.2.1.1	Level of community sense of the household based on external data input
Social Value Orientation	Range	1-4	6.2.1.2	Social value orientation assigned to each household based on their internal values
Payback time	Range	5-20	6.2.1.3	Time in years the household is willing to wait to recover the initial investment. It is assigned based on the SVO.
Annual heat demand per household	Numeric	13510	6.2.1.5	Amount of annual heat demand per household in KWh in the reference scenario.
Insulation heat demand reduction	%	50	6.2.1.5	Percentage of heat demand reduction after the household improves the house insulation.
Hot water heat demand share	%	16.5	6.2.1.5	Average share of the total heat demand that goes to heating the water.
Municipality subsidy	Numeric	4000	5.2.3	Amount in thousand euros of the subsidy the government has available per municipality for the transition to a gas-free area.
Municipality subsidy policy	Options	Environment, social, economic, trade-off	5.2.3	Policy the government follows to decide whether a subsidy project gets accepted.
Municipality subsidy dispatch frequency	Numeric	1	5.2.3	Times in a year the government decides on the subsidy dispatch.
Gas price	Numeric	0.0965	6.3.1	Initial market price of natural gas in euros per KWh. Price for the first 1_2 months of the simulation run.
CO_2 price	Numeric	22	6.3.1	Initial market price of the CO_2 tax in euros per ton of CO_2. Price for the

				first 12 months of the simulation run.
Gas price increase	Numeric	0.003	6.3.1	Amount the natural gas price increases per year. The gas price gets updated every 12 ticks in the simulation
CO_2 price increase	Numeric	2.5	6.3.1	Amount the CO_2 price increases per year.
TEC board value ranking: environment	Random	1-3	6.2.2	Ranking assigned from 1 to 3 to the environmental concern of the TEC board. It is randomly assigned.
TEC board value ranking: social	Random	1-3	6.2.2	Ranking assigned from 1 to 3 to the financial concern of the TEC board. It is randomly assigned.
TEC board value ranking: economic	Random	1-3	6.2.2	Ranking assigned from 1 to 3 to the concern for energy independence of the TEC board. It is randomly assigned.
Collective technology decision time limit	Numeric	12	5.2.4	Maximum number of months the TEC board and neighbourhood has to make a decision over the collective technology.
Individual technology decision time limit	Numeric	6	5.2.4	Maximum number of months the TEC board and neighbourhood has to make a decision over the individual technology.
Technology installation time	Numeric	6	5.2.4	Time in months it takes for the developer to construct and make the connections to the households.

6.4. Verification

Before running the experimentation it is critical to verify that the model does what is intended to do according to the conceptualization and formalization. Throughout the formalization the agent behaviour was constantly recorded and track to ensure the formalization was being done correctly. This testing requires recording the inputs, states and outputs of the agent and confirming this aligns with the flowchart. At the end of the formalization state a single agent testing was conducted. This was done for each agent type of the model

6.4.1. Households

TABLE 29: VERIFICATION OF ACTIONS AND STATES OF HOUSEHOLDS

Step	Actions
Check SVO assignment	- When the difference of the values is higher than 1 (SVO 1). **Confirmed** - When the difference of values is lower than 1 (SVO 3). **Confirmed** - When it is in between and sense of community is higher than 5 (SVO 2). **Confirmed**
Check assignment of PBT	- When SVO is 1, PBT higher than 15. **Confirmed** - When SVO is 2, PBT between 10-15. **Confirmed** - When SVO is 3, PBT between 5-10. **Confirmed** - When SVO is 4, PBT between 0-5. **Confirmed**

Check assignment of WTP	- When CO_2 tax is off, when PBT exp of household is 10 WTP of household is 7466. **Confirmed** - When CO_2 tax is on, when PBT exp of household is 10 WTP of household is 8993. **Confirmed**
Check neighbourhood formation	- Households connected to each other belong to same neighborhood. **Confirmed** - When the number of households is at 200, there are 200 households in each neighborhood. **Confirmed** - When the number of neighborhoods is set at 3 and household number at 500, there is a total number of 1500 households separated in 3 neighborhoods. **Confirmed**
TEC board participation	- If TEC board values ranking is cost, independence, environment, household with the same ranking move into participation 1. **Confirmed** - When households are in categories SVO 1 or SVO 2, and two value categories have equal value, environment prioritized over economy, prioritized over independence. **Confirmed** - When households are in categories SVO 3 or 4 and two value categories have equal value, economy prioritized over environment, over independence. **Confirmed**
Households collective tech decision	Household develop a ranking based on their values. **Confirmed** - Household gives 0.61 to the highest value - Household gives 0.28 to the second highest value - Household gives 0.11 to the lower value
Household individual tech decision	Only when the preferred individual technology of the household matches the communities preferred option, the household goes into participation 3. **Confirmed**
Household investment decision	Once the community is set up, household move to participation 4 when WTP < than the investment required per household by the TEC board. **Confirmed**
Check heat demand and CO_2 emissions	- When not connect, household demand is 13513.5. **Confirmed** - When connected, household demand decreases by half (6756.75). **Confirmed** - Initial CO_2 emissions per household is 2702.7. **Confirmed** - CO_2 emissions of households with participation lower than 5 are higher than CO_2 emissions of households with participation 6 and this higher than households with participation 5. **Confirmed**

6.4.2. TEC Boards

TABLE 30: VERIFICATION OF ACTIONS AND STATES OF TEC BOARDS

Step	Actions
Set up of TEC board ranking:	- The same ranking is not assigned to two different variables. **Confirmed** - There is always a value with 0.11, 0.28 and 0.61. **Confirmed** - Initial CO_2 emissions of NB when household number is 100 is 0. **Confirmed**
CO_2 emissions	- CO_2 emissions of neighbourhood after 1 step is 22522 and after step 2 is 45044. **Confirmed** - If TEC not set up, CO_2 emissions after one year when number of households is 100 is 270270. **Confirmed** - After set up, CO_2 emissions avoided increase every step. **Confirmed**

TEC board persuasion	- If TEC board persuasion is on, TEC boards go through training and connect with households. **Confirmed** - If TEC board persuasion is off, TEC boards do not interact with households. **Confirmed**
Changing states	- Change to built: When share of households with participation 1 is higher than 0.1. **Confirmed** - Change to formed: When share of households with participation 3 is higher than 0.1. **Confirmed** - Change to subsidy approved: When TEC subsidy is yes. **Confirmed** - Change to set up: When share of households with participation 5 is higher than 0.1. **Confirmed**
TEC board collective technology decision	- TEC boards create collective technology when they reach built state. **Confirmed** - For each TEC board, 5 different collective techs are created, identified by the neighborhood number. **Confirmed** - TEC board select their initial tech choice to be the one with the highest WTP outcome from the MCDM process. **Confirmed** - TEC board waits 6 months to check the support of this technology. If support is not higher than 0.1, the TEC board selects the second in their priority list and waits 6 months. **Confirmed** - After 1 year (12 months), the TEC board finally selects the technology with the highest support. **Confirmed**
TEC board develop individual technology	- Only when there is enough support for the collective scenario, the TEC board creates the individual technologies. **Confirmed** - TEC board creates 3 different potential individual technologies identified by the neighborhood number. **Confirmed**
Calculation of TEC investment	When individual technology part of scenario, TEC investment includes the individual tech investment. **Confirmed**
Neighbourhood set up	- Only after they have received the subsidy, they install the technology. **Confirmed** - Instalment takes 6 months. **Confirmed**

6.4.3. MUNICIPALITY

TABLE 31: VERIFICATION OF ACTIONS AND STATES OF MUNICIPALITY

Action	Steps
Ranking	When ranking is equal to trade off, weights are equally distributed across values. **Confirmed**
Subsidy dispatched	When having one neighborhood, the investment dispatched is equal to the investment received by the TEC board. **Confirmed**
CO_2 emissions	Cumulative CO_2 emissions are the sum of the cumulative CO_2 emissions of the neighborhoods. **Confirmed**

CHAPTER 7: RESULTS

The experimentation include a total number of 96 different combinations of institutional conditions and factors (3*2*2*2*4 = 96). Each combination was run 100 times hence, the experimentation resulted in a total number of 9600 runs. Table 32 summarises the range of values inputted for the institutional conditions and factors.

TABLE 32: PARAMETER INPUT FOR EXPERIMENTATION

Parameter	Value	Unit
Number of neighbourhoods	1, 4, 7	-
Participation policy	A/B	-
Persuasion training availability	No/Yes	-
Municipality subsidy amount per neighbourhood	3000, 4000	Thousand euros
Municipality subsidy policy	Environment, social, economy, trade-off	-

First, an overall analysis of the experimentation has been conducted with the complete data set for all the neighbourhoods simulated in the experimentation on the basis of the key performance indicators (KPIs) described in Section 5.4. The results are shown at the neighbourhood level and at the municipality level. Secondly, from this analysis, what a “successful and unsuccessful neighbourhood” is in the model was characterised on the basis of the key three KPIs (CO_2 emissions reduction, neighbourhood participation and formation process duration). With this, a more specific analysis has been conducted with the data set for the “successful neighbourhoods” and “unsuccessful neighbourhoods” with the aim of identifying, respectively, the most ideal and ineffective combinations of institutional conditions and factors. At last, the model simulations outcome data was analysed aiming at concluding whether the hypotheses described in Section 5.5 can be validated.

7.1. OVERVIEW AT THE NEIGHBOURHOOD LEVEL

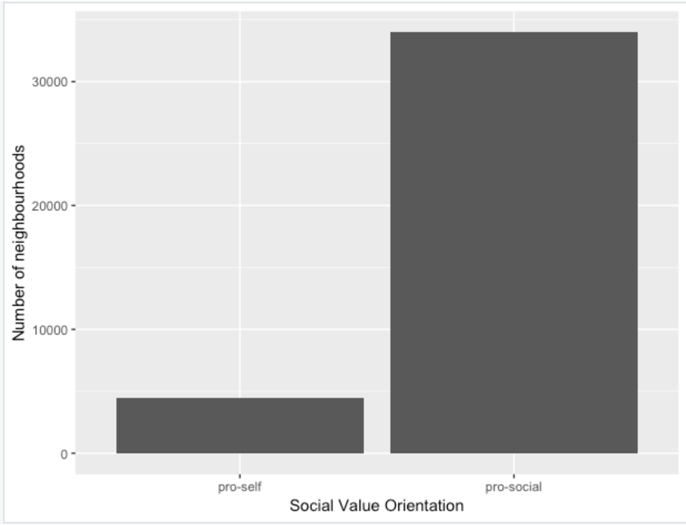
This section presents the general results from the simulation experimentation at the neighbourhood level and it is structured through the nine KPIs explained in Section 5.4.

7.1.1. KPI 1: FINAL SVO DISTRIBUTION

Table 33 shows the average distribution of households across the four SVO types included in the model. Figure 16 and Figure 15 show respectively the distribution of the TEC boards based on their value system and of neighbourhoods based on their social value orientation at the end of the model run.

TABLE 33: AVERAGE HOUSEHOLD DISTRIBUTION PER SVO TYPE

SVO 1	SVO 2	SVO 3	SVO 4
57.6	6.7	29.4	6.3



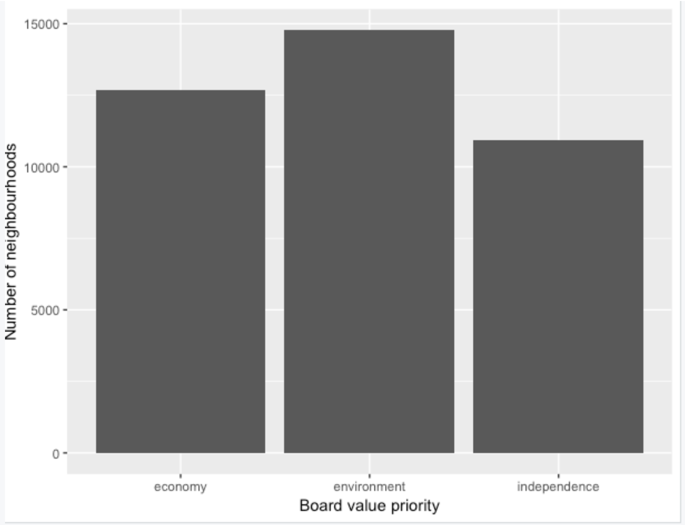


FIGURE 16: TEC BOARD DISTRIBUTION BASED ON SVO TYPE

FIGURE 15: TEC BOARD DISTRIBUTION BASED ON VALUES

Regarding the TEC board, the fact that those with environment as the leading value were more recurring, followed by economy and lastly energy independence is a consequence of the assumptions made during the model implementation (see Section 6.2.2).

With respect to the neighbourhoods SVOs, it is important to note that initially all neighbourhoods have pro-social value orientations (see Section 6.2.4). However, in some cases, the interactions between the neighbourhoods and the TEC board, lead to households modifying their SVOs. If the number of households changing their SVOs is significant enough, this ends up changing the neighbourhood's SVOs. Figure 16 shows that only around 15% of neighbourhoods have turned into pro-self oriented neighbourhoods at the end of the 10 years model run. Hence, it can be concluded that despite households interacting with each other and some boards implementing persuasion initiatives, the general overarching value system of the neighbourhood is very hard to change. This in line with Four layer model of Williamson where the first layer, cultural norms, is the one which operates at the lowest pace and require hundreds of years to change.

7.1.2. KPI 2: CO2 EMISSION REDUCTION

Figure 17 and Figure 18 show the results for the KPI CO_2 emission reduction percentage in 2030 at the neighbourhood level. Figure 17 shows the distribution of neighbourhoods based on their CO_2 emission reduction percentage in 2030 compared to the base scenario where the full neighbourhood would be covered by natural gas. Figure 18 visualises the same data but cumulatively. The blue line represents at each point in the Y-axis the share of neighbourhoods that have reduced their CO_2 emissions by the level indicated by the X-axis or less. The red line represent the average CO_2 emission reduction considering all neighbourhoods and the green line the average only those that successfully established.

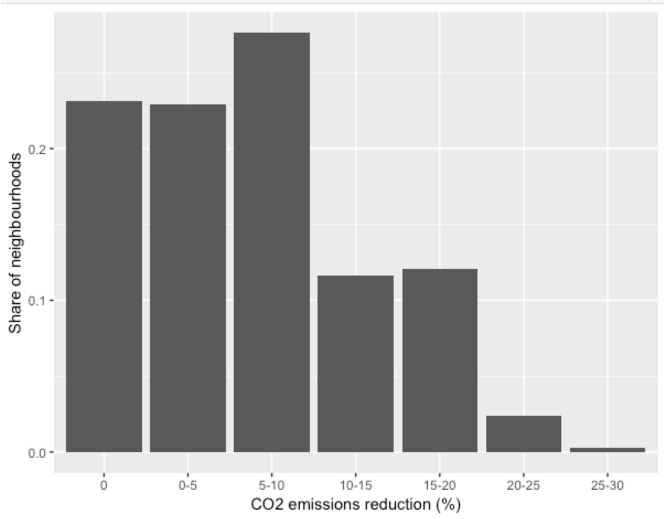


FIGURE 17: NEIGHBOURHOOD DISTRIBUTION FOR CO2 EMISSION REDUCTION LEVELS

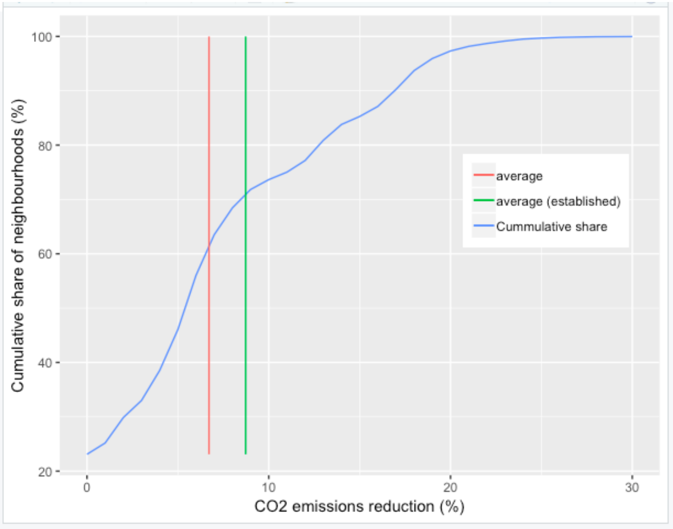


FIGURE 18: NEIGHBOURHOOD CUMULATIVE DISTRIBUTION FOR CO2 EMISSION REDUCTION LEVELS

First of all, it can be observed that around 75% of neighbourhoods get established and they reduce their emissions in average by 9% (green line) and by up to 30%. However, only 15% of established TECs reduce their emissions by 15% or more. Overall, a high formation rate can be observed yet an important barrier can be detected at 10% emission reduction. This reduction amount does not seem enough given the high level of investment required for establishing thermal energy communities and the drastic reduction of CO_2 emissions in the Dutch heating sector required to achieve the objectives set by 2030 and 2050. However, it is in line with other studies on the environment impact of district heating communities (Van den Wijngaart, 2012).

7.1.3. KPI 3 & KPI 4: Final share of neighbourhood support and participation in TEC

Neighbourhood support accounts for the share of households that agrees with the project plans yet neighbourhood participation only accounts for those households that have invested and connected to the district heating system. Figure 20 and Figure 19 show the distribution of neighbourhoods based on the level of neighbourhood support and participation respectively. Moreover, similarly to the Figure 18, Figure 21 presents the same results but in a cumulative manner.

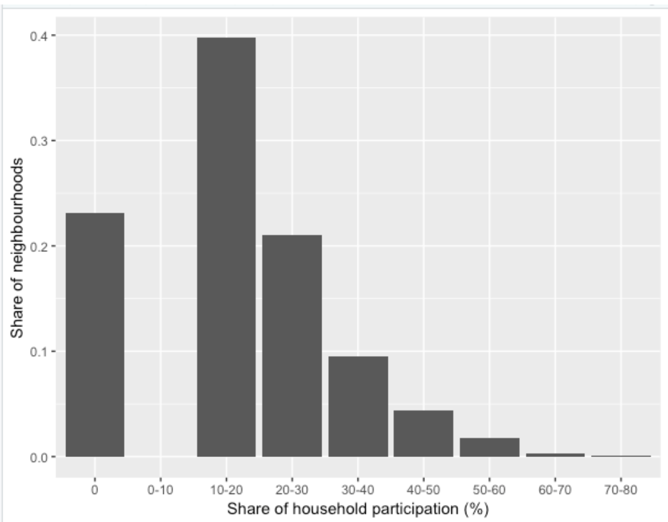


FIGURE 19: NEIGHBOURHOOD DISTRIBUTION FOR SHARE OF HOUSEHOLD PARTICIPATION

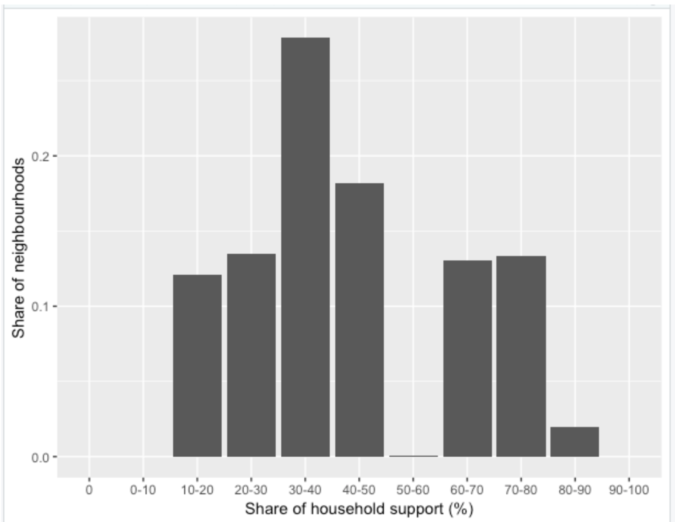


FIGURE 20: NEIGHBOURHOOD DISTRIBUTION FOR SHARE OF HOUSEHOLD SUPPORT

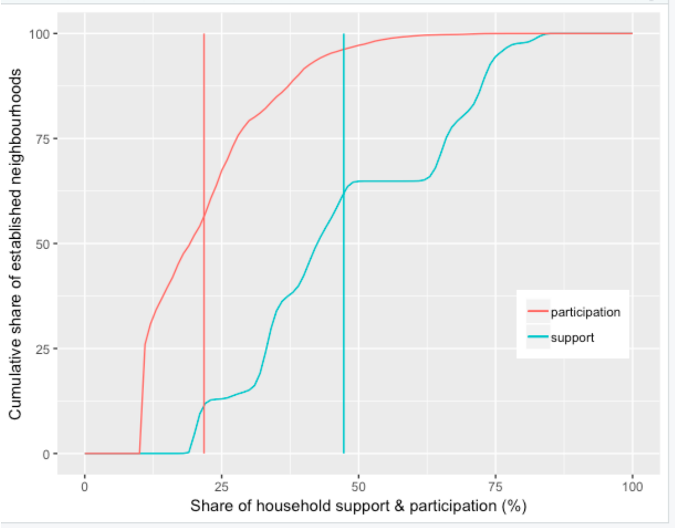


FIGURE 21: NEIGHBOURHOOD CUMULATIVE DISTRIBUTION FOR HOUSEHOLD SUPPORT (BLUE LINE) AND HOUSEHOLD PARTICIPATION (RED LINE)

The average level of neighbourhood support for established TECs is around 50% and the maximum is 85%. With respect to neighbourhood participation (i.e. connection to the thermal energy community), the average level is 22%, the maximum level is 77%. The results for neighbourhood support are quite positive yet for participation they can be considered to be low since only 30% of the neighbourhoods achieve a participation of more than 25%. In other words, the gap between the number of supporters and participants is significant. This means that there is a high share of households that are interested and supportive of the project but the project does not meet their financial expectations and they end up not participating in the TEC. Lastly, the relationship between neighbourhood participation and CO_2 emission reduction of TECs is explored in Section 7.1.7.

7.1.4. KPI 5: Duration of formation process

Figure 22 presents the results for the duration of the establishment process in a cumulative way. The red line represents the average duration and the blue line the share of neighbourhoods (Y-axis) that successfully established before the month indicated in the X-axis. The small steps observed in the graph can be explained by the assumptions made regarding the dispatch of the subsidy, which only occurs once every 12 months (see Section 5.3.3).

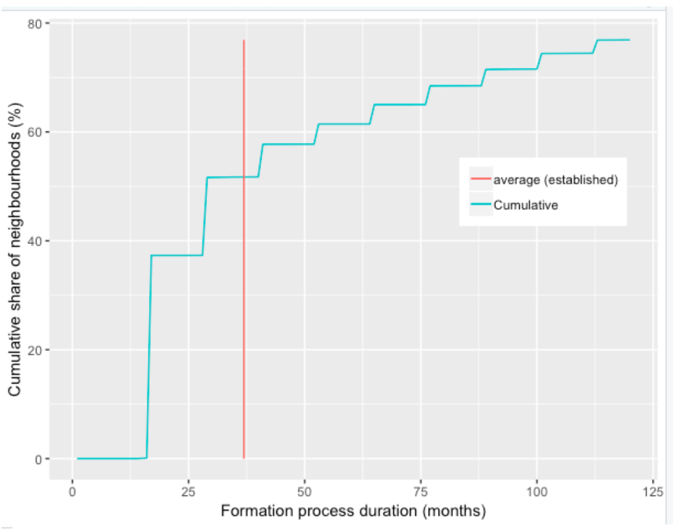


FIGURE 22: NEIGHBOURHOOD CUMULATIVE DISTRIBUTION FOR FORMATION PROCESS DURATION

The average formation time is 37 months (3 years) and around 50% of the communities get formed within 3 years. These results show that it is very possible for agents to reach consensus and establish thermal energy community projects in a short time. Lastly, the relationship between process duration and CO_2 emission reduction of TECs is explored in Section 7.1.7.

7.1.5. KPI 6 & 7: Collective & individual technology selection

This section looks into the technology scenarios selected by the TEC boards together with the neighbourhoods regardless of whether the community finally succeeded. As already explained in Section 5.3.1 technology scenarios are formed by a collective component (aquatermal (TEA), thermal energy storage (ATES) or biogas) and an individual component (heat pump (1), solar thermal (2) or none (3)) , and Figure 23 presents the frequency distribution of each selected technology scenario. The bars indicate the collective heating technology and the colour the individual heating systems.

It can be observed that the agreement over the technology scenario can be reached fairly easy since in almost every run a decision is reached. Regarding the collective generation technologies, TEA systems were certainly preferred over the others (50% TEA, 30% ATES, 20% biogas). In addition, regarding the arrangement of the scenarios, there is a clear preference over combining the ATES and TEA systems with solar thermal systems and the biogas system with heat pumps. Lastly, fully collective scenarios were not very popular, only selected around 5% of the time.

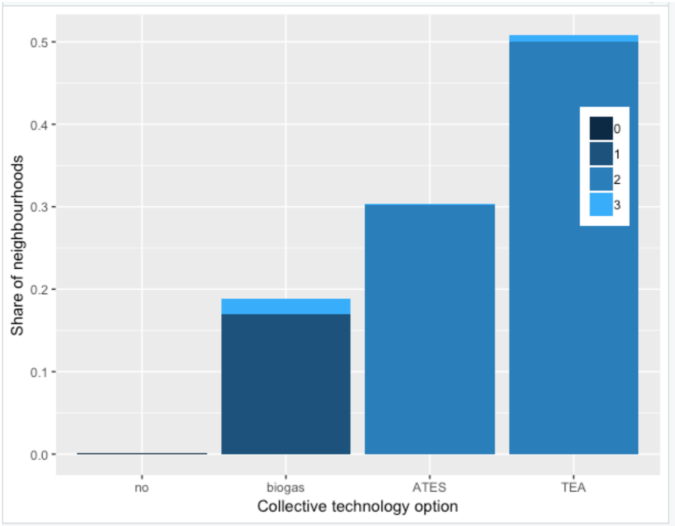


FIGURE 23: NEIGHBOURHOOD DISTRIBUTION FOR TECHNOLOGY SCENARIO

In order to have an in depth analysis and interpretation of these results it is important to look at the value systems held by the TEC boards which selected each technology scenario. Figure 24 shows the leading value of TEC boards under each technology scenario and Table 34 presents the specific data on the average level of environmental, financial and independence concerns of the TEC boards per selected technology scenario.

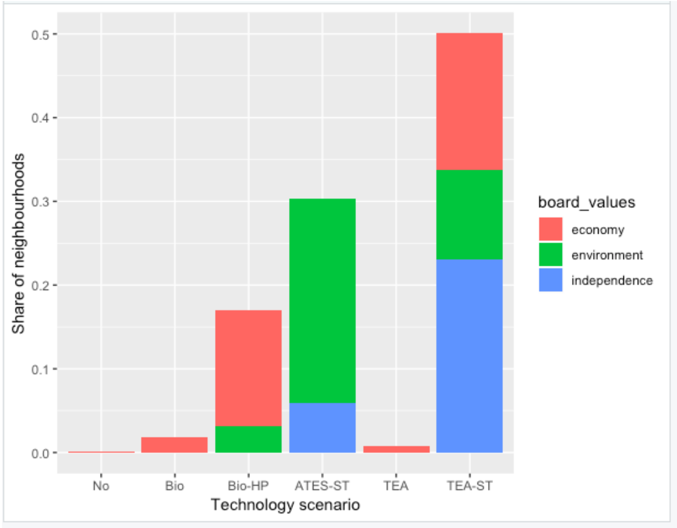


FIGURE 24: NEIGHBOURHOOD DISTRIBUTION FOR TECHNOLOGY SCENARIO BASED ON BOARD VALUES

TABLE 34: AVERAGE LEVEL FOR EACH VALUE TYPE OF TEC BOARDS PER TECHNOLOGY SCENARIO (FROM 1 TO 10)

TEC board value priority	Technology scenario	Average environmental concern	Average economic concern	Average independence concern
Economy	**No**	4.0	8.0	1.0
	Bio-HP	3.7	8.1	2.5
	Bio	3.8	8.4	2.9
	TEA-HP	4.3	7.9	6.3
	TEA	3.9	7.6	5.9
Environment	**Bio-HP**	8.0	7.2	1.5
	ATES-ST	8.0	3.1	4.4
	TEA-ST	7.7	6.7	5.5
Independence	**ATES-ST**	7.0	1.9	8.3
	TEA-ST	3.6	4.6	8.0

It can be observed that those TEC boards led by environmental concerns never select a fully collective alternative. When it is only environmentally concern that drives their decision making, TEC boards will prefer the ATES alternative. However, when, besides environment they also have high financial and independence concerns (scoring higher than 5 in all of them) they will have a preference over TEA systems. Finally, when they are only concerned about the environmental impact and the economic feasibility, they will go for the biogas systems.

For those TEC boards focusing on the project's financial feasibility, the choice is mainly divided between biogas with heat pump and TEA with solar thermal systems. The first is likely chosen when costs are the only TEC board's concern and the latter when this is also complemented by high independence concerns. However, sometimes, when the only concern of the TEC board is costs, they will choose fully collective systems (either biogas o TEA).

When exploring those TEC boards highly concerned with becoming independent from the grid, there is a clear preference over the TEA with solar thermal systems. Only when this is accompanied by high environmental concerns, the selection may switch to ATES systems.

Lastly, the relationship between technology scenario selection and CO_2 emission reduction of TECs is explored in Section 7.1.7.

7.1.6. KPI 8 & 9: AVERAGE HOUSEHOLD INVESTMENT & SHARE OF COMMUNITY INVESTMENT

Table 35 shows for those established thermal energy community how much households invested per technology scenario, and Figure 25 presents how much each household invested in the TEC as a proportion of the total required investment.

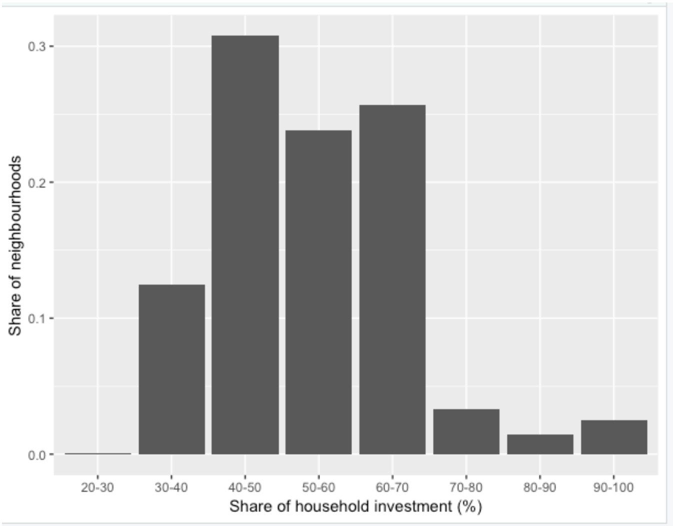


FIGURE 25: SHARE OF HOUSEHOLD CONTRIBUTION TO TOTAL INVESTMENT

TABLE 35: HOUSEHOLD INVESTMENT AMOUNT PER TECHNOLOGY SCENARIO ALTERNATIVE (IN EUROS)

Tech scenario	Bio	ATES	TEA
Fully collective	14.000	23.000	20.000
Collective + individual	18.000	26.000	22.500

Figure 25 shows that the range of neighbourhood's contribution to total investment is quite large. In average, neighbourhoods are willing to cover 55% of total investment and only few neighbourhoods were capable of fully covering the investment without external support. It can be concluded that it is unrealistic to request households to cover more than 70% of the costs which means that for projects to succeed municipalities will need to cover at least 30% of the project costs.

Moreover, from Table 30 it can be observed that, overall, households are willing to invest, in average, around 20.000 euros in a timeframe of 20 years. In other words, there are willing to invest around 1000 euros per year on the heating transition. However, it is higher for those scenarios with ATES systems, followed by TEA and then biogas. And additionally, scenarios including individual generation technologies are more costly for households.

7.1.7. KPI CORRELATIONS

This section presents the most interesting findings from exploring the correlations between the different key performance indicators presented in the sections above.

Independently, high level of neighbourhood participation and a fast formation process lead to high final levels of CO_2 emission reduction. However, achieving high household participation requires TEC boards to invest additionally time resources in developing a trusting relationship with the neighbourhood. As a result, it is important to find where the trade-off is between these two KPIs. Figure 26 visualises the impact of the duration of the formation process (x axis) and the final level of household participation (colour) on the final level of CO_2 emission reduction at a neighbourhood level (Y axis).

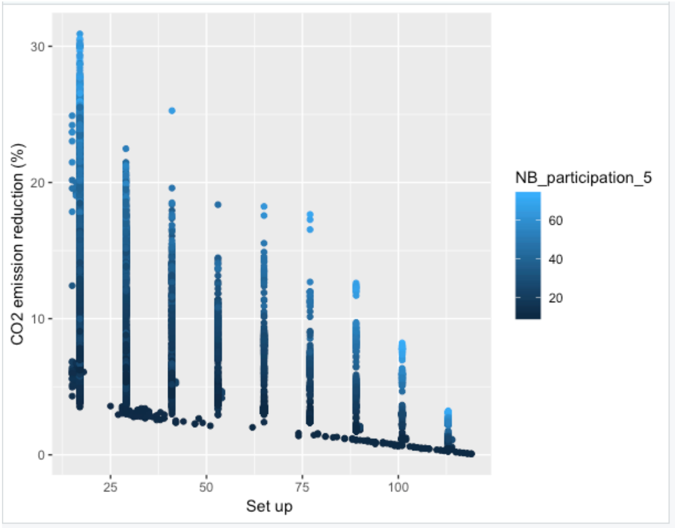


FIGURE 26: CORRELATION BETWEEN PROCESS DURATION AND HOUSEHOLD PARTICIPATION WITH LEVELS OF CO2 EMISSION REDUCTION

Given the high range of final CO2 emission reduction outcomes observed in Figure 26 for those boards that get formed early, it can be concluded that the sooner the TEC gets set up, the more important it is to focus on achieving high levels of neighbourhood support. However, it can also be observed by comparing the first and last columns in the graph that having a fast formation process is more important than waiting to achieve high neighbourhood participation levels before the community is set up.

Moving on, to understand the impact of technology selection on the level of CO2 emission reduction, Figure 27 visualises the final level of CO_2 emission reduction at a neighbourhood level (y-axis) for the different process duration (x-axis) and the collective technology selected (colour).

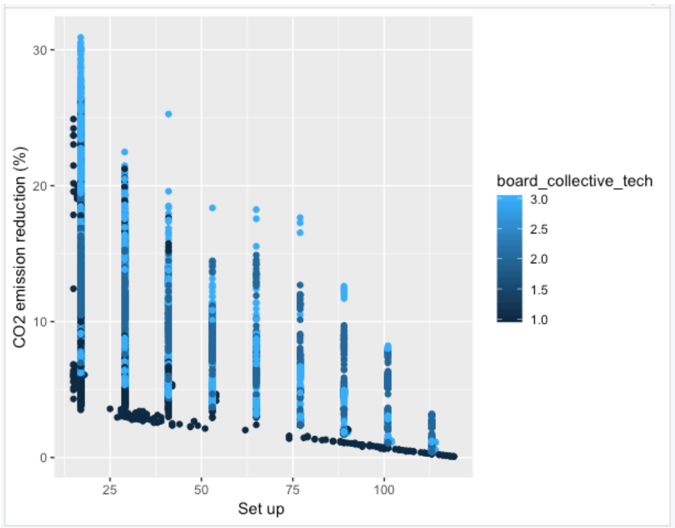


FIGURE 27: CORRELATION BETWEEN PROCESS DURATION AND TECHNOLOGY SELECTION WITH LEVELS OF CO2 EMISSION REDUCTION

It can be observed that the results are less conclusive in this case. Given that ATES and TEA systems have lower CO_2 emission intensity than biogas, they are more likely to achieve higher final level of CO2 emission reduction regardless of what the duration of the process is. However, there are some bio scenarios that were capable of achieving higher CO_2 emission reduction levels than ATES and TEA scenarios when the TEC got quickly established.

Another interesting point of analysis is exploring whether the share of neighbourhood participation is a determining factor for the level of neighbourhood's contribution to TEC investment. Figure 28 shows neighbourhood's contribution to TEC investment (y-axis) for the range of neighbourhood participation levels (x-axis). The blue line represents the general trend of the dataset.

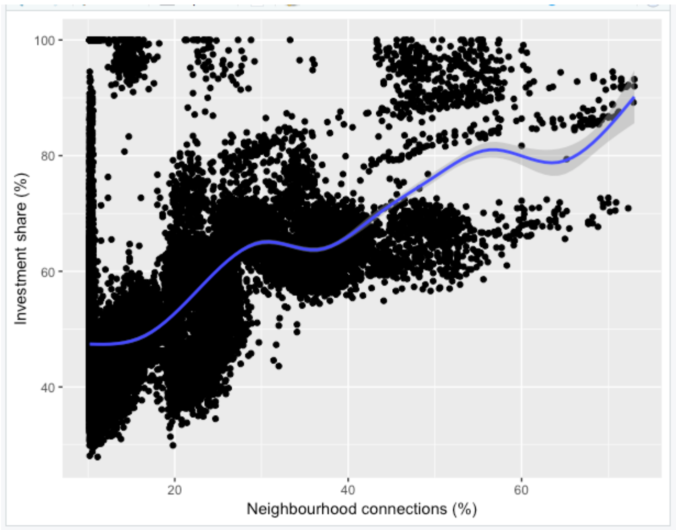


FIGURE 28: CORRELATION BETWEEN HOUSEHOLD PARTICIPATION AND NEIGHBOURHOOD INVESTMENT CONTRIBUTION

In general lines, it can be observed that the higher the participation the more the neighbourhood will be able to cover the required investment. The implications of this insights rely on the fact that if the municipality has a small budget for implementing thermal energy projects, they will need to focus on gathering as much neighbourhood support as possible for the project to be feasible.

7.2. OVERVIEW AT THE MUNICIPALITY LEVEL

After analysing the KPIs at the neighbourhood level, this section focuses on disclosing the most important outcomes at the municipality level. This distinction between municipality sizes to analyse if this has an impact on the key performance indicators. The results are presented for each municipality size ranging from smallest to largest (left to right).

7.2.2. KPI CO_2 EMISSION REDUCTION

Figure 29 shows the frequency distribution (histogram) of final CO_2 emission reduction share levels in 2030 for each municipality size (small, medium, large). Additionally, Figure 31 present the same results but cumulatively. The blue line represent the share of neighbourhoods that have reduced their CO_2 emission up until the level specified by the x-axis. The red line shows the average CO_2 emission reduction considering all neighbourhoods and the green line that for only the neighbourhoods that succeeded in the formation process. Lastly, Table 36 shows the data on the average share (green line) and its transformation into absolute terms for each municipality size.

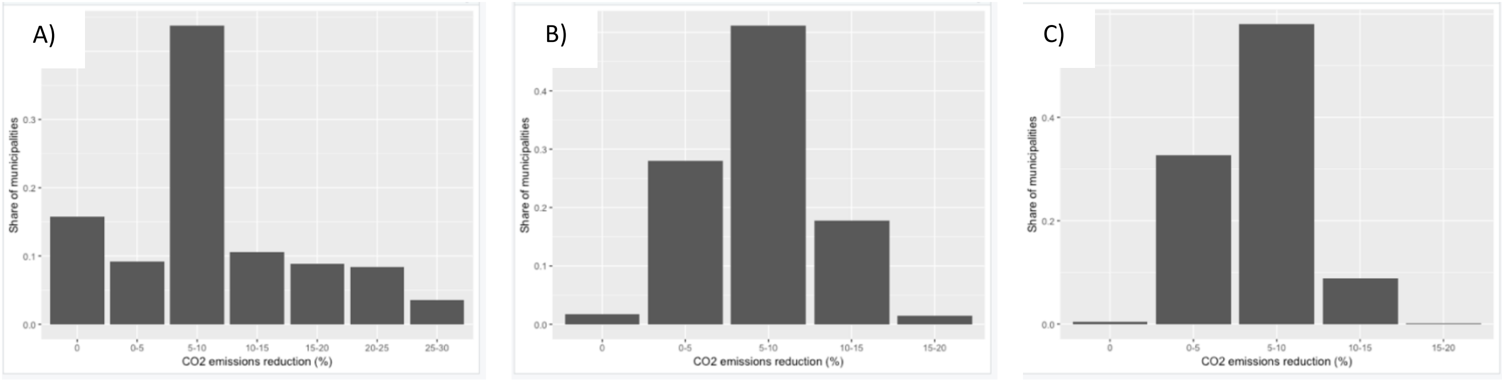


FIGURE 29: MUNICIPALITY DISTRIBUTION FOR CO2 EMISSION REDUCTION. A) SMALL MUNICIPALITY, B) MEDIUM MUNICIPALITY, C) LARGE MUNICIPALITY

TABLE 36: DATA ON CO2 EMISSION REDUCTION PER MUNICIPALITY SIZE

	Small	Medium	Large
Average reduction (%)	10.6	7.1	6.2
Average reduction (tCO_2)	1900	5000	7700

The first thing to notice from Figure 29 is that most commonly municipalities reduce their emissions by 5 to 10% regardless of the size. From Table 36 it can be observed that the larger the municipality the harder it is to achieve high emission reduction shares. Moreover, the results for medium and large municipalities are very similar in percentage terms. Overall, larger municipalities are able to reduce more CO_2 emissions in absolute terms while the percentage is higher in smaller municipalities.

7.2.3. KPI HOUSEHOLD PARTICIPATION IN TEC

Figure 30 presents the distribution of neighbourhood participation shares at the municipality level for each municipality size. Additionally, Table 37 presents the results for the average number of successful neighbourhoods per municipality size, and similarly to the results presented in the section above, the average share of household participation and its translation into absolute terms given the total number of households for each municipality size.

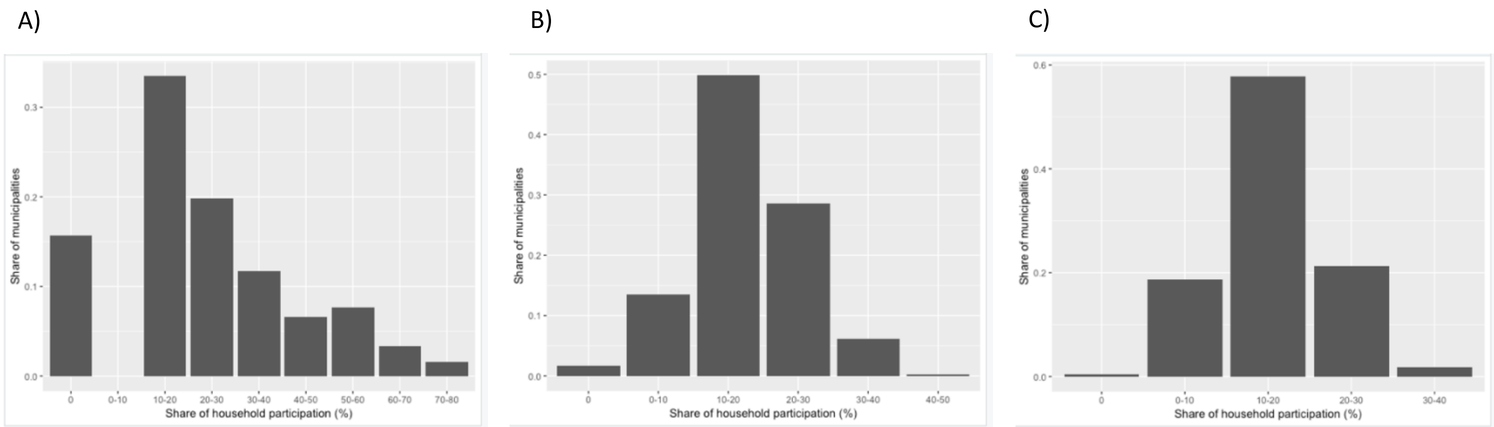


FIGURE 30: MUNICIPALITY DISTRIBUTION FOR HOUSEHOLD PARTICIPATION. A) SMALL MUNICIPALITY, B) MEDIUM MUNICIPALITY, C) LARGE MUNICIPALITY

TABLE 37: DATA ON HOUSEHOLD PARTICIPATION PER MUNICIPALITY SIZE

	Small	Medium	Large
Municipalities with TECs (%)	85	97	99
Average participation share (%)	28	18	15

Average number of connections	185	475	693

It can be observed that overall municipalities manage to get 10% to 20% of the municipality's population to participate in the TEC regardless of their size. However, similarly to what occurs with the share of CO_2 emission reduction, the larger the municipality the harder it gets to achieve a high participation share, yet the difference between the outcome of medium and large municipalities is very small. And again, in absolute terms, larger municipalities are able to get more households connected to the district heating network in place.

7.3. OVERVIEW OF INSTITUTIONAL CONDITIONS RESULTS

Once the general analysis of the key performance indicators has been conducted, this section focuses on showing the general impact of the different institutional conditions alternatives included in the experimentation. These are the participation policy, persuasion policy and municipality subsidy strategy. The results for the impact of the change in subsidy amount have not been included because the simulation outcome showed that this parameter had no influence on the key performance indicators of the model. Since the participation policy is implemented at the TEC board level, its impact on the KPIs is therefore shown at the neighbourhood level. For the other two, persuasion policy and subsidy strategy, since these policies would be implemented at the municipality level, the results are presented at this level of detail.

7.3.2. PARTICIPATION POLICY

The first parameter analysed here is the participation policy alternatives. The individual policy (policy A) gives the option to the households to connect to the district heating system whenever they are ready to make the investment. However, when the collective participation policy (policy B) is in place, households can only connect when the investment for the collective technology that will cover their heat demand is fully covered. Figure 31 and Figure 32 present respectively the results for the final level of CO_2 emission reduction frequency of neighbourhoods at each level of CO_2 emission reduction.

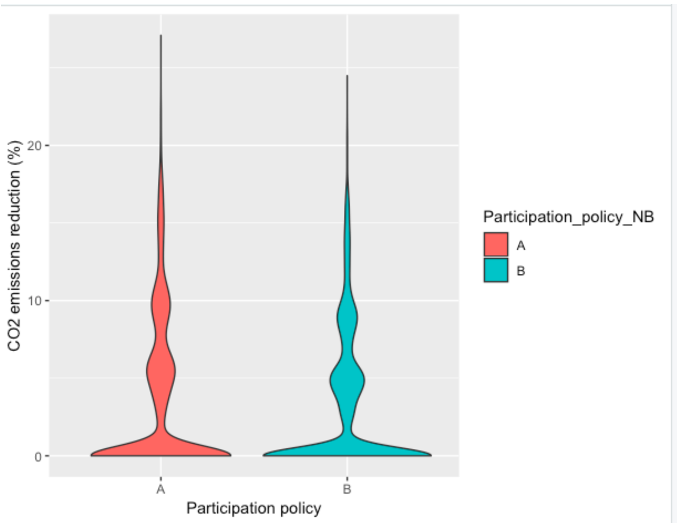


FIGURE 31: CO2 EMISSION REDUCTION LEVELS PER PARTICIPATION POLICY ALTERNATIVES AT NEIGHBOURHOOD LEVEL

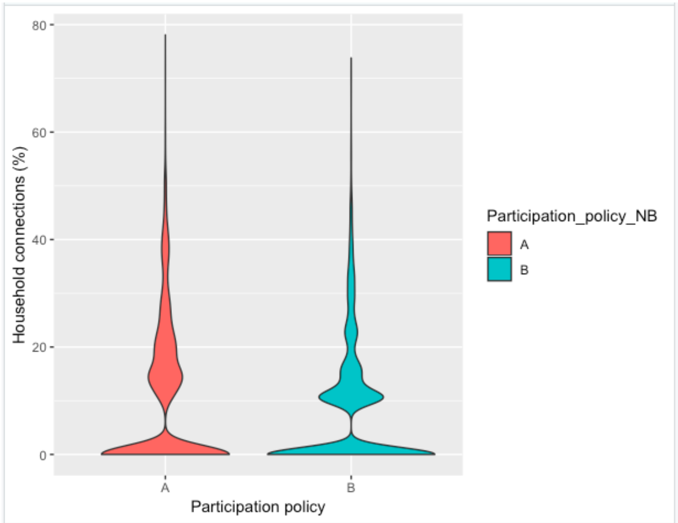


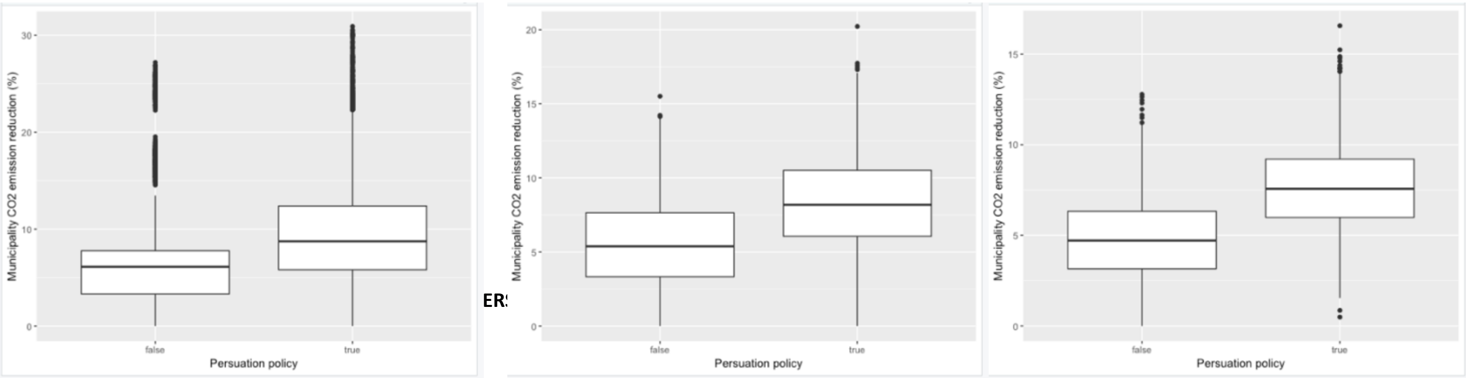
FIGURE 32: HOUSEHOLD PARTICIPATION LEVELS PER PARTICIPATION POLICY AT NEIGHBOURHOOD LEVEL

The figures show how the individual policy (policy A) has a more positive impact on the CO_2 emission reduction and on the level of household participation of the neighbourhoods compared to the collective policy. This makes sense since the sooner they are able to connect the sooner they will insulate their houses to achieve the required connection standards of having energy label B. The same trend occurs when looking at the share of household connections. Lastly, it is important to state by looking at the length of base of the shapes in the graphs that the individual participation policy also leads to more neighbourhoods setting up a thermal energy community

7.3.3. PERSUASION POLICY

Moving unto the availability of persuation skill trainings, Figure 33 presents respectively the results of the impact of this policy on the KPIs of CO_2 emission reduction and household participation for each of the municipality sizes.

A) B) C)



A) B) C)

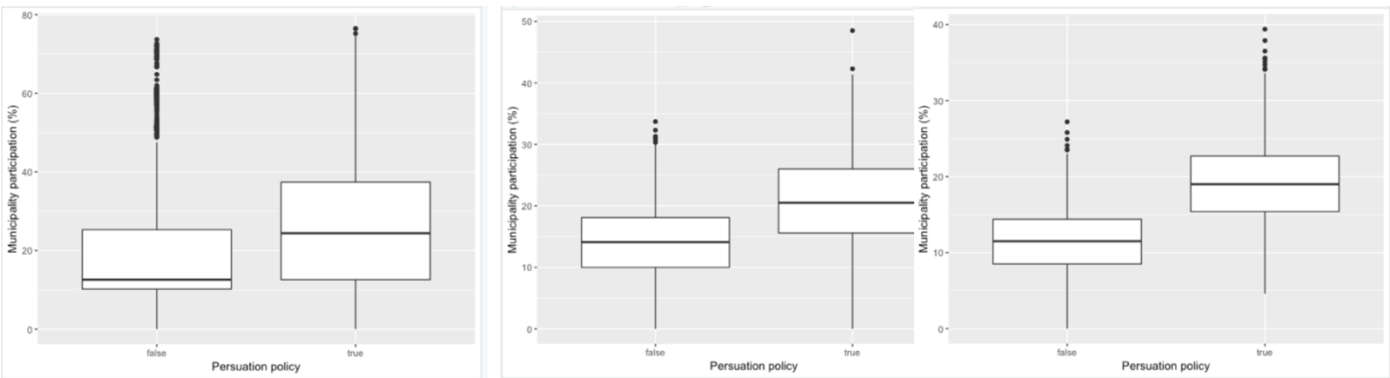


FIGURE 33: HOUSEHOLD PARTICIPATION PER PERSUASION POLICY ALTERNATIVE AT MUNICIPALITY LEVEL. A) SMALL MUNICIPALITY, B) MEDIUM MUNICIPALITY, C) LARGE MUNICIPALITY

It can be observed that providing persuasion trainings to the TEC boards for them to improve their cooperation and communication with the neighbourhoods has a positive impact on the success of thermal energy communities regardless of the municipality size. In particular, the availability of the trainings increases both the level of CO_2 emission reduction and of household participation by 5% in average.

7.3.4. Subsidy policy

The last institution to be analysed is the strategy the municipality uses to decide on the dispatch of the subsidy for gas-free neighbourhoods. The experimentation included four different alternatives: minimising costs, maximising environmental impact, maximising participation and acceptance, and lastly, a trade-off between these three options. Figure 34 and Figure 35 present the results for the level of CO_2 emission reduction and of household participation for the municipalities under each municipality strategy alternative.

A) B) C)

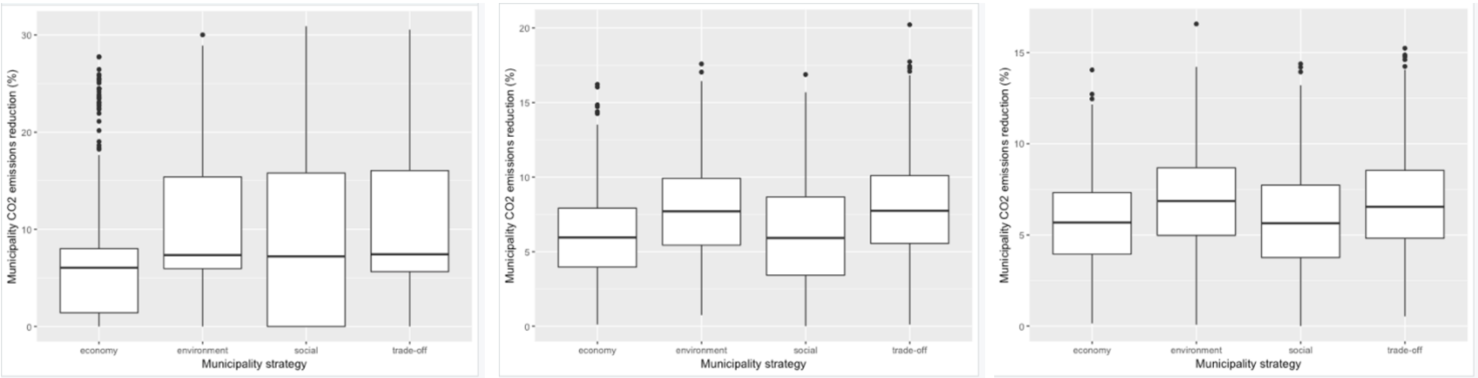


FIGURE 34: CO2 EMISSION REDUCTION LEVELS PER MUNICIPALITY STRATEGY ALTERNATIVE AT MUNICIPALITY LEVEL A) SMALL MUNICIPALITY, B) MEDIUM MUNICIPALITY, C) LARGE MUNICIPALITY

A) B) C)

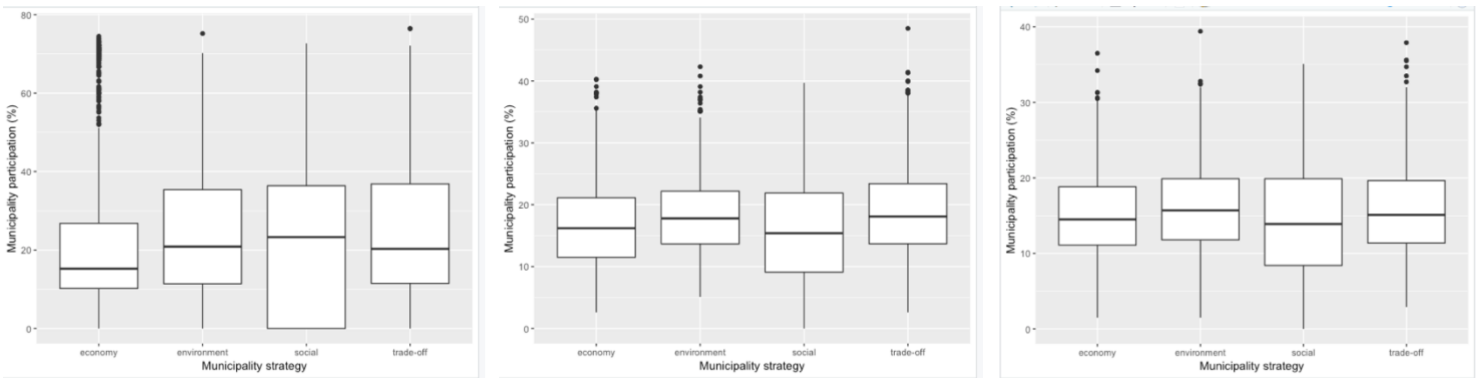


FIGURE 35: HOUSEHOLD PARTICIPATION LEVELS PER MUNICIPALITY STRATEGY ALTERNATIVE AT MUNICIPALITY LEVEL. A) SMALL MUNICIPALITY, B) MEDIUM MUNICIPALITY, C) LARGE MUNICIPALITY

The results show that for medium and large municipalities, the strategies that lead to a better outcome in terms of both CO_2 emission reduction and participation level is the environmental and the trade-off strategy. For small municipalities the results are less conclusive. A social strategy leads in average to slighly higher levels of CO_2 emission reduction than the environmental and trade-off alternavies but it is also the one that shows the highest range in the outcome. The economic strategy in is clearly the least effective one in smaller municipalities.

7.4. Techno-institutional conditions for most successful neighbourhoods

In this section we dive deeper into understanding what techno-institutional conditions are likely to lead to very successful outcomes. For that, it is important to first identify what a “successful neighbourhood” mean for this simulation. Based on the results, we have identified the thresholds for the three critical key performance indicators. These thresholds indicate the bottom line for the highest 10% of the neighbourhood for each KPI. Regarding the CO_2 emission reduction percentage, the highest 10% of neighbourhoods arrive to a reduction percentage of 17% or higher, a share of neighbourhood connections of 39%, and a duration process of 17 months or less. When combining these three criteria, the data set of the neighbourhoods that comply with it account for 5% of the total number of neighbourhoods.

The results in this section present the distribution of the successful neighbourhoods data set for each institutional and technological alternative at the TEC board level (values and participation policy) and at the municipality level (persuasion and subsidy policy).

7.4.2. TEC BOARD LEVEL: VALUES

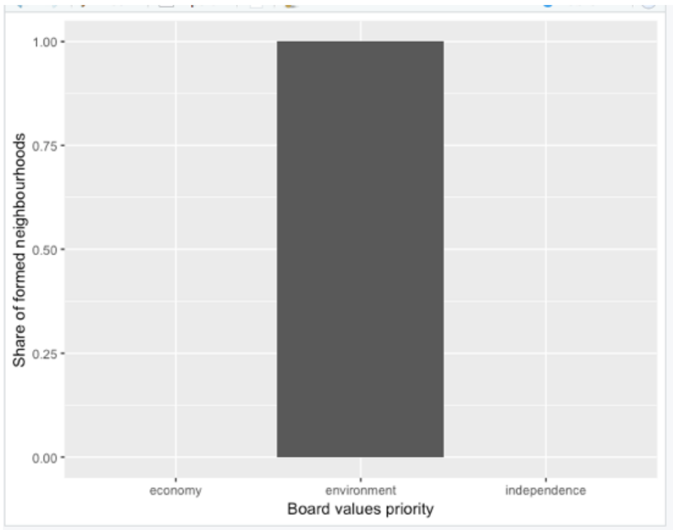


FIGURE 36: SUCCESSFUL TEC BOARD DISTRIBUTION PER VALUE TYPE

Regarding the values held by the successful neighbourhoods the results are very conclusive: all successful neighbourhoods have a TEC board with environmental concern as their priority; no successful TEC board has independence or economy as the main concern. This is in line with the results presented in Figure 16 on the social value distribution of neighbourhoods which showed that most neighbourhoods have a pro-social value orientation. Hence, these neighbourhoods are more likely to support pro-environmental boards.

7.4.3. TEC BOARD LEVEL: PARTICIPATION POLICY

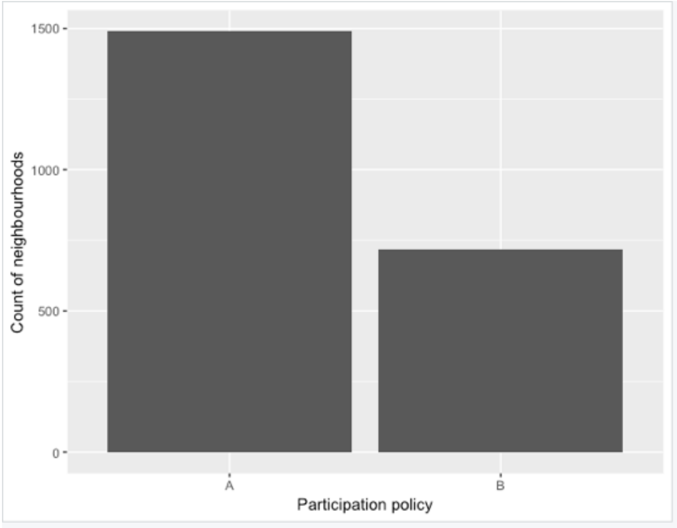


FIGURE 37: SUCCESSFUL NEIGHBOURHOOD DISTRIBUTION PER PARTICIPATION POLICY.

With respect to the participation policy for TEC expansion, neighbourhoods are more likely to arrive to successful outcomes when TEC boards implement an individual participation policy (A) instead of a collective one (B). In other words, giving more freedom for households to individual choose when to connect to the district heating system once this is in place results in a better outcome.

7.4.4. MUNICIPALITY LEVEL: PERSUASION POLICY

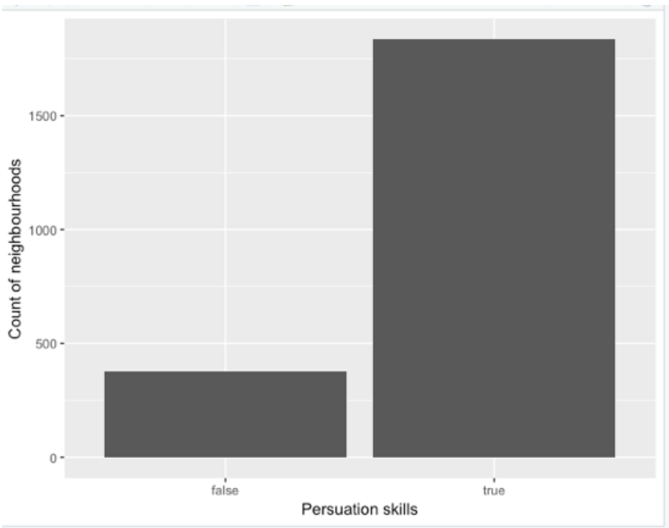


FIGURE 38: DISTRIBUTION OF SUCCESSFUL NEIGHBOURHOODS PER PERSUASION POLICY ALTERNATIVE

Providing persuasion skills to the TEC boards is one of the factors that has the highest influence on the success of establishing thermal energy communities. However, Figure 38 shows that some neighbourhoods that do not attend persuasion trainings are still able to reach similar levels of CO_2 emission reduction and household participation.

7.4.5. MUNICIPALITY LEVEL: SUBSIDY STRATEGY

Figure 42 show which municipality strategy is more likely to enhance the establishment of successful thermal energy communities.

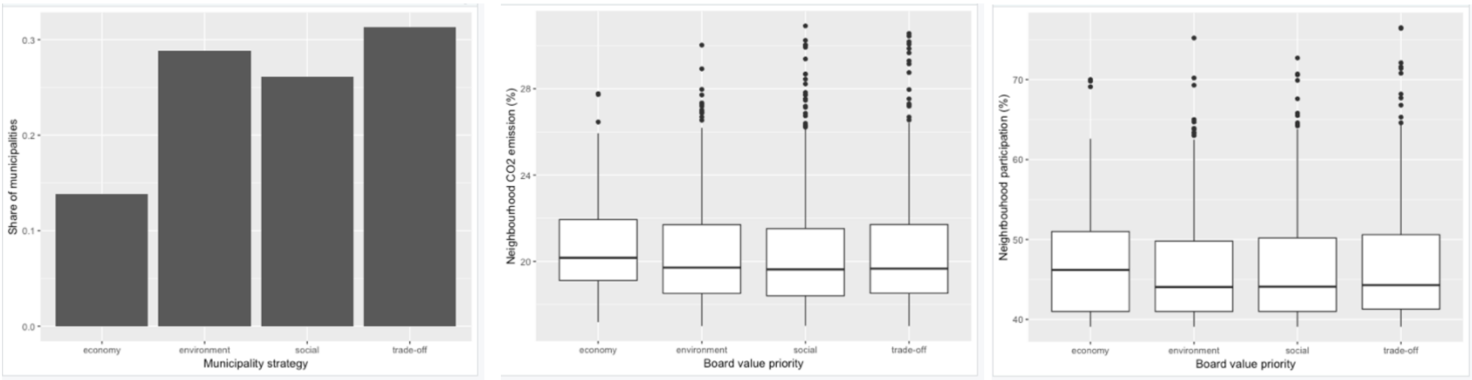


FIGURE 39: SUBSIDY POLICY IMPACT ON SUCCESS OF TEC. A) NEIGHBOURHOOD DISTRIBUTION, B) CO2 EMISSION REDUCTION LEVELS, C) HOUSEHOLD PARTICIPATION LEVEL

At first sight it could be concluded that the economic strategy has in average the best outcome yet it is important to consider that it is the alternative with the smallest dataset and this has an impact in the calculation of the mean value (dark black line). The trade-off and environmental strategy are the alternatives most commonly implemented in the successful cases followed by the social strategy. Regarding the KPI on CO_2 emission reduction Figure 39 shows that the social strategy is the one that has outliers reaching the highest levels and that the trade-of strategy has outliers reaching the highest levels for household participation.

7.4.6. TECHNOLOGY SCENARIOS

This section presents the analysis of the technological scenarios selected by the most successful thermal energy communities.

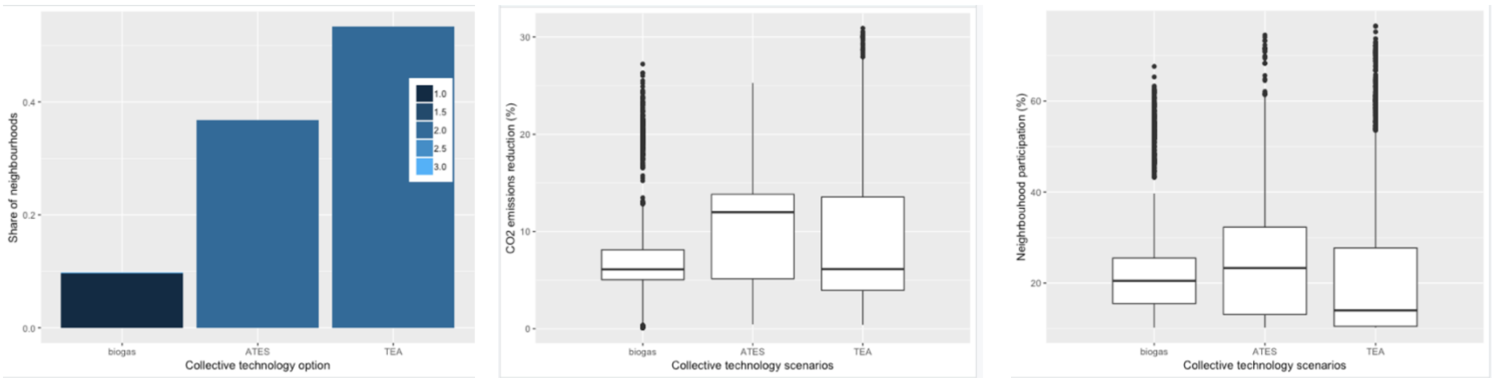


FIGURE 40: TECHNOLOGY SCENARIO IMPACT ON SUCCESS OF TEC. A) NEIGHBOURHOOD DISTRIBUTION, B) CO2 EMISSION REDUCTION LEVELS, C) HOUSEHOLD PARTICIPATION LEVEL

It is important to note that no TEC implementing fully collective scenarios reaches the success threshold . Moreover, the largest share of successful communities select TEA systems in combination with solar thermal systems, yet it is the ATES scenario the one that leads to higher CO_2 emission and neighbourhood participation levels.

Table 38 and Figure 41 attempt to provide more in depth insights on how the technology selection aligns with TEC board values and municipality strategy.

Scenario	Environment	Economy	Independence
Bio-HP	8.9	8.3	2.3
ATES-ST	8.5	3.3	6.1

Scenario	Environment	Economy	Independence
Bio-HP	8.9	8.3	2.3
ATES-ST	8.5	3.3	6.1
TEA-ST	7.5	6.3	6.2

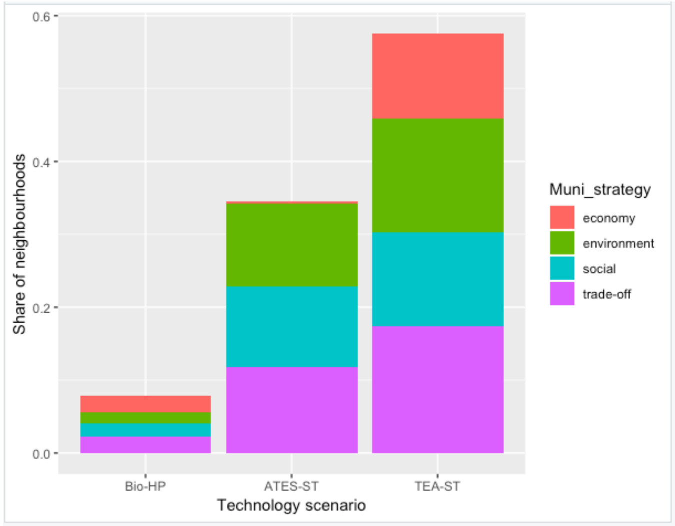


Table 38 shows the average levels of environment, financial and independence concerns of the successful TEC boards per technology alternative. In addition, Figure 41 presents the distribution of successful neighbourhoods by technology alternative (x-axis) and municipality strategy (colour).

TABLE 38: AVERAGE CONCERNS LEVELS OF THE SUCCESSFUL TEC BOARDS

Scenario	Environment	Economy	Independence
Bio-HP	8.9	8.3	2.3
ATES-ST	8.5	3.3	6.1
TEA-ST	7.5	6.3	6.2

FIGURE 41: SUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER TECHNOLOGY SCENARIO

Table 38 reveals that although the leading value is always environmental concerns only having high environmental concerns is not enough. Around 55% of the successful neighbourhoods (those choosing the TEA scenario) apart from having high environmental concerns also have high financial and independence concerns. Moreover, 35% of the successful neighbourhoods had a TEC board with high independence concern and the rest, 10%, high economic concerns. Additionally, Figure 44 reveals that all successful technology scenarios are compatible with the different municipality subsidy strategies except from the ATES scenarios which since it is the most costly one, it is not compatible with the economic strategy.

Scenario	Environment	Economy	Independence
Bio-HP	8.9	8.3	2.3
ATES-ST	8.5	3.3	6.1
TEA-ST	7.5	6.3	6.2

7.4.7. Most successful scenarios

Overall, twelve scenarios encapsulate the combination of institutional and technological conditions that lead to the establishment of successful thermal energy communities in the Netherlands. **In all of them TEC boards are characterised primarily by their high environmental concerns, for implementing an individual participation policy for TEC expansion, and for having high persuasive capabilities.** The key differences between the scenarios are on the specific values held by the board, the technology scenario selection and the municipality policy strategy.

Once these scenarios had been identified, the probability of a thermal energy community getting established under these twelve successful scenarios was calculated. Table 39 shows the institutional and technological conditions under each scenario sorted by the establishment probability from highest to lowest.

TABLE 39: SUCCESSFUL TECHNO-INSTITUTIONAL SCENARIOS

	TEC board value priority	Tech scenario	Municipality policy strategy	Establishment probability
Scenario 1.1	Environment	TEA-ST	Environment	100
Scenario 1.2	Environment	TEA-ST	T-O	99
Scenario 1.3	Environment	TEA-ST	Social	96
Scenario 1.4	Environment	TEA-ST	Economy	95
Scenario 2.1	Environment	ATES-ST	Environment	88
Scenario 2.2	Environment	ATES-ST	T-O	87
Scenario 2.3	Environment	ATES-ST	Social	83
Scenario 2.4	Environment	ATES-ST	Economy	68
Scenario 3.1	Environment	Biogas-HP	Environment	49
Scenario 3.2	Environment	Biogas-HP	T-O	52
Scenario 3.3	Environment	Biogas-HP	Social	44
Scenario 3.4	Environment	Biogas-HP	Economy	48

Overall, the scenario that leads to the best outcome is the one where environmentally friendly TEC boards select the TEA and solar thermal scenario under a municipality strategy that has an environmental or a trade-off outcome. These combination leads to very high chances of setting up a thermal energy community and that these achieve very high CO_2 emission reduction and household participation levels.

7.5. TECHNO-INSTITUTIONAL CONDITIONS FOR UNSUCCESSFUL NEIGHBOURHOODS

In this section we dive deeper into understanding what institutional and technological conditions lead to TEC boards not being able to successfully formed. In other words, this section shows the conditions linked to the neighbourhoods that did not manage to establish a TEC by 2030. This section follows a similar structure to Section 7.4: The results present the distribution of the data set for unsuccessful neighbourhoods for each institutional and technological alternative at the TEC board level (values and participation policy) and at the municipality level (persuasion and subsidy policy).

7.5.1. TEC BOARD LEVEL: VALUES & PARTICIPATION POLICY

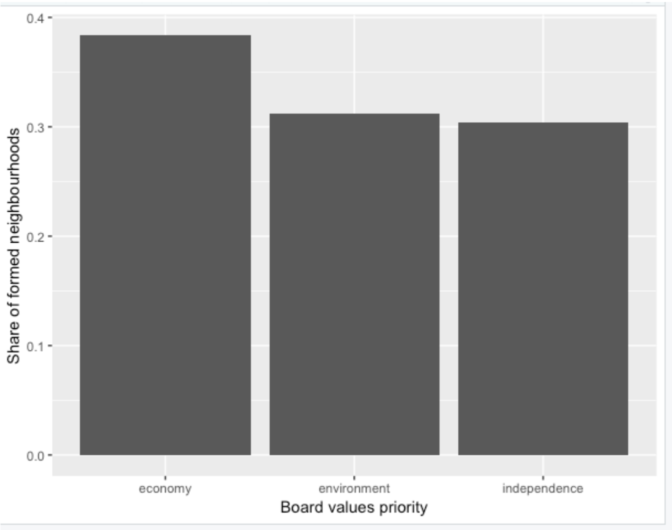


FIGURE 43: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER TEC BOARD VALUE TYPE

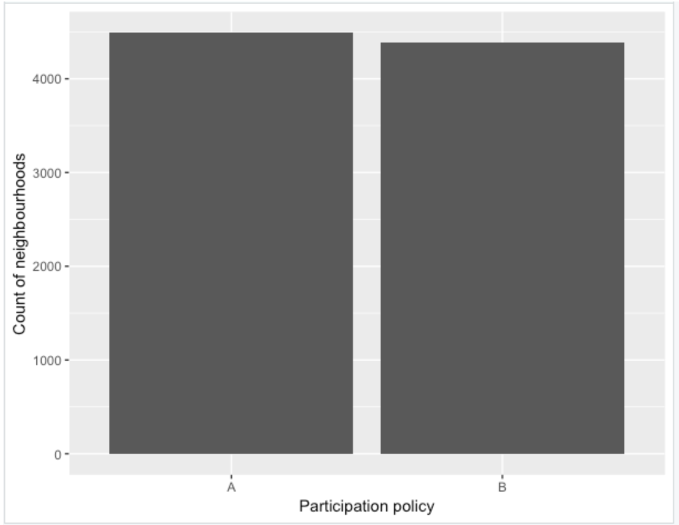


FIGURE 42: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER PARTICIPATION POLICY ALTERNATIVE

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concerns. Moreover, from Figure 42 it can be concluded that the type of participation policy is not an critical factor determining whether a neighbourhood is unsuccessful since the distribution of unsuccessful neighbourhood implementing individual and collective participation policy is almost even.

7.5.2. MUNICIPALITY LEVEL: PERSUASION POLICY & SUBSIDY STRATEGY

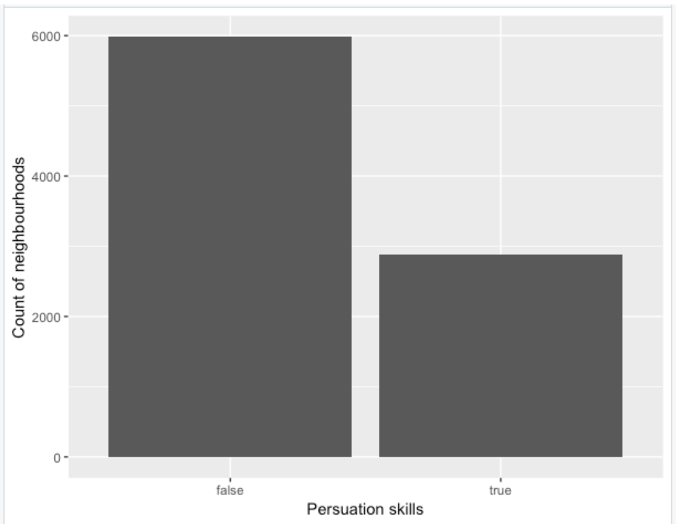

FIGURE 45: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER PERSUASION POLICY ALTERNATIVE

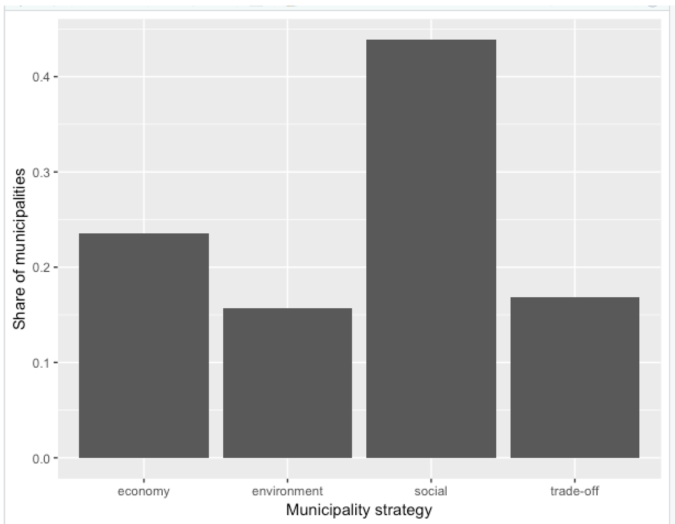

FIGURE 44: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER MUNICIPALITY STRATEGY ALTERNATIVE

At the municipality level, from Figure 45 it can be concluded that municipalities not providing persuasion trainings leads to higher chances of thermal energy projects not reaching a completion state. Regarding the municipality's subsidy strategy, Figure 44 shows that thermal energy communities are most likely not forming when municipalities focus solely on maximizing neighbourhood participation (social outcome).

7.5.3. TECHNOLOGY SCENARIO

On a technological level, Figure 47 shows the technology scenarios selected by those TEC boards that did not complete the formation process. The technology scenarios are presented in combination with the TEC board values (Figure 48) and the municipality subsidy strategy (Figure 46).

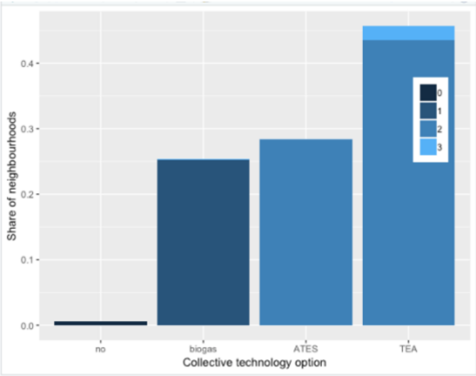

FIGURE 47: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER TECHNOLOGY SCENARIO

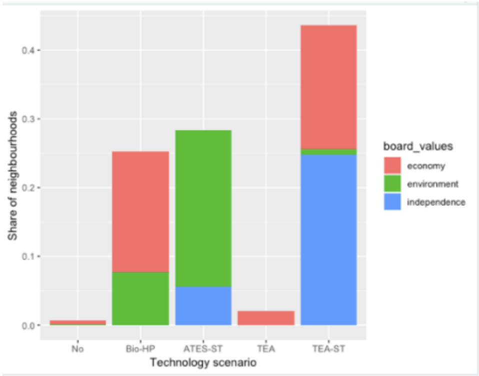

FIGURE 48: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER TECHNOLOGY SCENARIO AND TEC BOARD VALUES

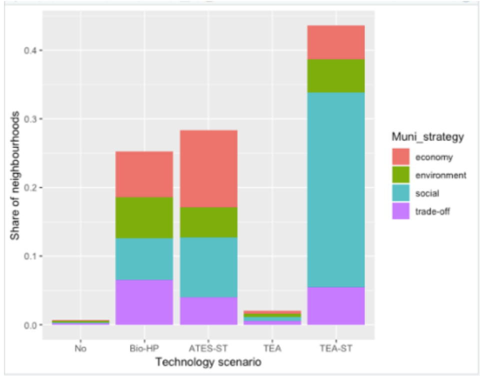

FIGURE 46: UNSUCCESSFUL NEIGHBOURHOODS DISTRIBUTION PER TECHNOLOGY SCENARIO AND MUNICIPALITY STRATEGY

concerns which selected the TEA

social strategy. In this case, either the TEC board or the technology scenario did not achieve the level of household support requested by the municipality under its subsidy strategy and hence did not receive the external financial support to cover the full investment required.

Around 20% had TEC boards with environmental concerns selecting ATES and solar thermal as the technology scenario and where there was a municipality looking at either minimizing costs or maximizing social outcomes. Similarly to the case for the TEA scenario, these neighbourhoods either did not meet the household participation standards of the social municipality strategy or the investment cost standards of the economic strategy.

7.5.4. Unsuccessful scenarios

Overall, Table 40 presents the scenarios (i.e. combination of technological and institutional factors and conditions) that have the highest probability of leading to neighbourhoods not establishing TEC.

TABLE 40: UNSUCCESSFUL TECHNO-INSTITUTIONAL SCENARIOS

	Persuasion	Participation policy	TEC board value ranking	Tech scenario	Municipality policy strategy	Establishment probability
Scenario 1.1	No	B	Economy	TEA-ST	Social	**5**
Scenario 1.2	No	B	Independence	TEA-ST	Social	**0**
Scenario 2.1	No	A/B	Economy	TEA-collect	S/Env/T-O/Econ	**2**
Scenario 3.1	No	B	Environment	ATES-ST	Social	**75**
Scenario 3.2	No	B	Environment	ATES-ST	Economy	**62**
Scenario 4	No	B	Economy	Bio-HP	S/Env/T-O/Econ	**71**

It can be observed that the combination of TEC boards with either high economy or independence concerns with municipalities not providing persuasion trainings is a recipe for failure of establishing thermal energy communities. This is especially relevant for when municipalities follow a strategy to maximise neighbourhood participation and TEC boards select TEA as the preferred collective heating generation technology. However, for scenarios 3.1, 3.2 and 4, the story gets more complex. For these scenarios, despite sometimes leading to unsuccessful outcomes, their establishment probability is higher than 50%.

Particularly, the institutional conditions in scenarios 3.1 and 3.2 can either lead to very successful outcomes or to complete failure. The combination of municipalities following a social or economic policy respectively together with TEC boards being environmentally friendly and selecting ATES + ST alternative is present in unsuccessful scenarios 3.1, 3.2 and successful scenarios 2.3, 2.4. To better understand this model behaviour, Table 41 presents for each of these scenarios the average TEC board value system, the average level of neighbourhood support and of household investment.

TABLE 41: VARIABLES INFLUENCING THE SUCCESS OF TECHNO-INSTITUTIONAL SCENARIOS WITH ATES SYSTEMS AND ENVIRONMENTALLY FRIENDLY BOARDS

Scenario number	Scenario description	Environment	Economy	Independence	TEC board support	Average exp
2.3	**Env-ATES-Social successful**	8.5	3.4	6.1	75	25127
3.1	**Env-ATES-Social unsuccessful**	7.2	1.7	2.7	26	14936
2.4	**Env-ATES-Econ successful**	8.2	3.1	5	73	25127
3.2	**Env-ATES-Econ unsuccessful**	7.9	2.7	4.4	55	16460

Table 41 shows that for these scenarios a determining factor for success is the average investment amount per household. Due to model implementation reasons, this variable is linked to the SVOs of the households (see Section 6.2.4). As a result, the difference in average household investment amount can then be explained by the lack of persuasion skills of TEC boards in the unsuccessful scenarios. In both cases, TEC boards have very high environmental concerns. Thus, a better connection between the board and neighbourhood would lead to households increasing their level of environmental concern and thus, potentially changing their SVOs to either cooperative or altruistic types. This would then have a positive effect on the household's willing to invest in the establishment of TEC.

Additionally, in particular for the cases in which the municipality follows a social (scenarios 2.3 and 3.1), the success disparity could be related to the levels of energy independence concerns of TEC boards. Successful neighbourhoods seem to have in average higher independence concerns (6.1) than unsuccessful ones (2.7).

When conducting a similar analysis for bio technology scenarios (see Table 42) it can be concluded that the value systems of TEC boards are a big influential factor. When TEC boards have high environmental and financial concerns they gather high levels of support, yet when TEC boards base their decisions solely on minimising costs, they do not even manage to gather enough support for the heat plan itself.

TABLE 42: VARIABLES INFLUENCING THE SUCCESS OF TECHNO-INSTITUTIONAL SCENARIOS WITH BIO SYSTEMS

Scenario number	Scenario description	Environment	Economy	Independence	TEC board support	Average exp
	Bio-successful	8.87	8.33	2.31	70	18106
4	**Econ-Bio unsuccessful**	3.69	7.41	1	20	**0**

7.6. HYPOTHESES TESTING

This section presents the results from testing the hypotheses presented in Section 5.5. These hypotheses have been tested by analysing the model outcomes presented in sections 7.1, 7.2 and 7.3.

7.6.1. Biophysical conditions (technology)

H1.1.: Fully collective scenarios are more popular than individual/collective scenarios. **Falsified**

Initially, since the scenarios that include individual system usually require the investment of more time and financial resources, it was expected for fully collective scenarios to be more popular than collective/individual ones. However, the complete opposite conclusion can be derived from the model outcomes. In particular, those scenarios with individual solar thermal systems are the most popular across neighbourhoods (see Figure 23).

H2.2: Neighbourhoods with fully collective scenarios are more successful than collective/individual scenarios. **Falsified**

Similarly to hypothesis 3.1, the results totally oppose this statement. Figure 41 shows that no successful neighbourhood implements fully collective scenarios and that the combination of TEA and individual solar thermal systems prove to be the technology scenario that achieves the highest level of CO_2 emissions reduction and household participation.

H3.3: Neighbourhoods installing the most environmentally friendly technology are not necessary the most successful ones. **Confirmed**

Lastly, Figure 41 verifies this hypothesis. It can be observed that although TEA is the most environmentally friendly technology (i.e. the lowest CO_2 emission intensity), ATES gives in average a better outcome for the average levels of CO_2 emission reduction and household participation. This leads to the conclusion that there are other conditions apart from technological factors, such as the institutional environment, that influence on the level of success of TEC projects.

7.6.2. Attributes of community (values)

H2.1: Neighbourhoods with households with pro-social value orientations are more successful than those with pro-self-orientation. **Undetermined**

It is not possible to arrive to a conclusion on whether this hypothesis can be proven with the results outcome due to the initial bias of the data input in the model. The derivation of the initial SVO orientation of the households based on the data input from Koirala et al., (2018) survey, results in all of the neighbourhoods initially being considered pro-social. Although due to interactions 12% become pro-self oriented, the data set itself is bias towards pro-social neighbourhoods. However, from the results shown in Table 43 a similar distribution between pro-self and pro-social neighbourhoods can be observed across the data sets for all neighbourhoods, for those who get formed and for those who are considered to be successful. This finding leads to the conclusion that both, pro-social and pro-self neighbourhoods have the same establishment and successful rate. However, this should be studied more in detail with an initial data set with a balanced distribution between these two types of neighbourhood social value orientations.

TABLE 43: NEIGHBOURHOODS DISTRIBUTION PER SVO TYPE (OVERALL, ESTABLISHED AND SUCCESSFUL CASES)

	General	Established	Successful
Pro-self	12	14.6	16
Pro-social	88	85.4	84

H2.2: Neighbourhoods with pro-self-orientations prefer those technology scenarios that mix individual and collective technologies. **Confirmed**

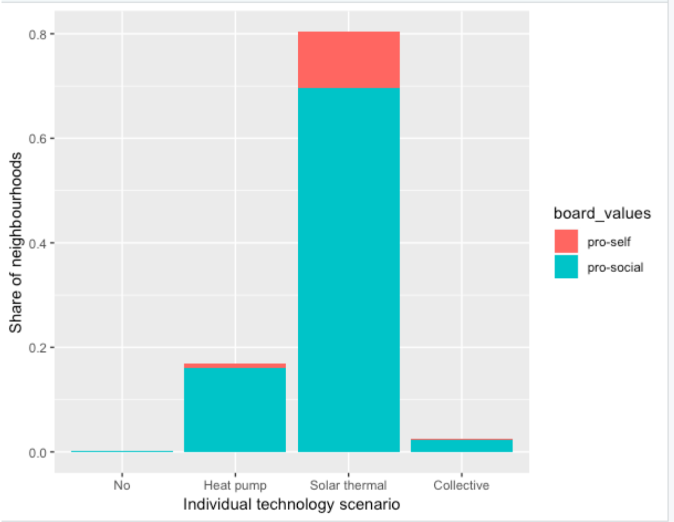

FIGURE 49: NEIGHBOURHOOD DISTRIBUTION PER INDIVIDUAL TECHNOLOGY ALTERNATIVE AND SVO TYPE

Figure 49 proves this hypothesis since the majority of neighbourhoods with a final pro-self orientation includes either solar thermal systems or individual heat pumps in the technology scenario implemented. Interestingly, Section 6.2.4 explain that pro-self oriented households are generally willing to invest less in TEC yet Table 35 shows that scenarios with individual technologies require higher household investment efforts. The underlying factors affecting this results is something that requires further research, however, a potential factor could be the differences in the level of sense of community in the two neighbourhood types.

H2.3: TEC boards with environmental concern as the higher ranking are more successful than the rest. **Confirmed**

Results shown in Figure 36 are very conclusive in this matter. Only pro-environmental TEC boards arrive to very successful outcomes. However, it is important to note as already discussed in Section 7.4.7, that only being environmentally concern is not enough for being successful and that TEC boards should consider also financial concerns and energy independence concerns when drawing up TEC projects.

H2.4: The most successful municipalities are the once that prioritises environment in their decision making process. **Confirmed**

The results in Figure 39 provide the support to approve this hypothesis. However, the trade-off strategy, which balances the three value types included in the model leads to similar results. Furthermore, it is important to consider the influence in the results of the initial input for households values, which sore high the consideration of environmental concerns. In order to test this hypothesis in other context it is necessary to adapt the initial value input to fit the local context.

7.6.3. Rules-in-use (policies)

H3.1: Individual participation policy leads to higher neighbourhood participation and CO_2 emissions avoided. **Confirmed**

Although the results presented in Figure 37 verify this hypothesis since most of the successful neighbourhoods did implement individual participation policy, the results are not conclusive enough. Figure 31 and Figure 32 show that the overall results for both the individual and collective participation policy are too similar for deriving conclusive insights or recommendations on this matter.

H3.2: Persuasion training leads to higher neighbourhood participation and hence CO_2 emissions avoided. **Confirmed**

Figure 33 supports the evident validation of this hypothesis. The results show that this policy leads to an increase of 5% in the CO_2 emission reduction levels and of 5 to 10% in the levels of neighbourhood participation.

H3.3: The municipality needs to support the TEC boards by covering at least 30% of the transition costs. **Falsified**

In average household are willing to contribute by covering 55% of the total investment required for the establishment of TECs (see Section 7.1.6). As a result, municipalities are expected to cover the 45% left assuming that no other party is involved in the TEC investment plan. However, Figure 25 does show that when the household participation levels are higher than 40% there are high probabilities that the expected contribution from the municipality stays around 30%.

7.6.4. RELATED TO TECHNOLOGICAL FACTORS

H3.1.: Fully collective scenarios are more popular than individual/collective scenarios. **Falsified**

Initially it was expected for fully collective scenarios to be more popular than the ones integrated individual systems since the latter require more time and financial resources for the households. However, the results show results that are completely contrary to the initial hypothesis. In particular, those scenarios with individual solar thermal systems are the most popular across neighbourhoods.

H3.2: neighbourhoods with fully collective scenarios are more successful than collective/individual scenarios. **Falsified**

Similarly to hypothesis 3.1, the results totally oppose this statement. Figure 41 shows that no successful neighbourhood implements fully collective scenarios and that the combination of TEA and individual solar thermal systems prove to be the technology scenario that achieves the highest level of CO_2 emissions reduction and household participation.

H3.3: Neighbourhoods installing the most environmentally friendly technology are not necessary the most successful ones. **Confirmed**

Lastly, Figure 41 verifies this hypothesis. It can be observed that although TEA is the most environmentally friendly technology (i.e. the lowest CO_2 emission intensity), ATES gives in average a better outcome for the average levels of CO_2 emission reduction and household participation. This leads to the conclusion that there are other conditions apart from technological factors, such as the institutional environment, that influence on the level of success of TEC projects.

CHAPTER 8: DISCUSSION AND CONCLUSIONS

8.1. DISCUSSION AND REFLECTION OVER RESULTS BASED ON THEORETICAL BACKGROUND

Busch et al., (2017) explain that barriers for the adoption and scaling up of district heating networks are not in the availability of the technology but are mostly found in governance and institutional arrangements. However, most of the research previously conducted on future heating scenarios has focused on analysing the techno-economic characteristics of such scenarios and have neglected the implications and impacts at a agent level or institutional landscape (Sijm et al., 2020). As a result, this research aimed at better understanding the techno-institutional conditions and factors that hinder and enable the success of thermal energy communities with a particular focus in the Dutch heating sector. This section discusses how the results presented in Section 7 can contribute to enlarging the knowledge in this topic.

These findings are discussed by linking the insights from the model back to the theoretical framework developed for this thesis.

8.1.1. INSTITUTIONAL ANALYSIS AND DEVELOPMENT (IAD) FRAMEWORK

The IAD framework is applied to the model outcome to identify (i) the most suitable criteria for the evaluation of the success of thermal energy communities, and (ii) the critical external and internal conditions that hinder or enable their success. Following the IAD framework, this section first describes the key takeaways from Chapter 7 (*outcomes*), then describes the most suitable *evaluative criteria*, and then discusses the *key external variables* that are linked to both the failed and most successful thermal energy communities in the model.

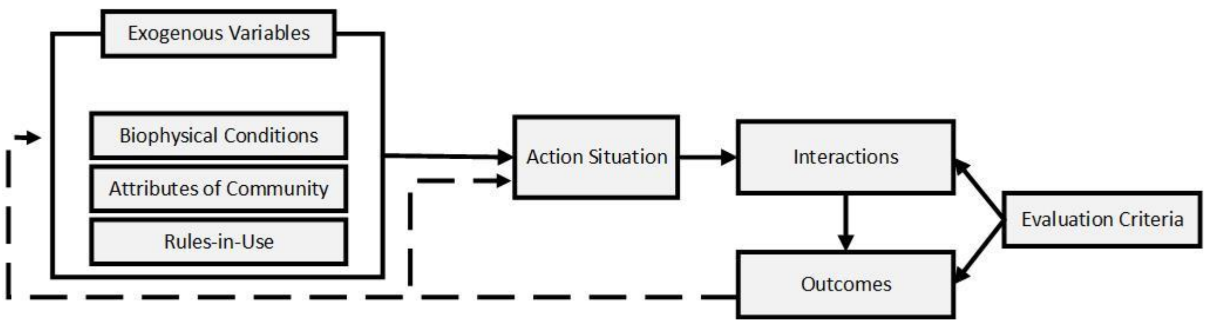

FIGURE 50: INSTITUTIONAL ANALYSIS AND DEVELOPMENT FRAMEWORK (OSTROM, 2005)

OUTCOMES

Regarding the model outcome, it was found that most of neighbourhoods will reduce their CO_2 emissions in average by 10% by 2030 and up to 30%. This is in line with the findings of study conducted by Van den Wijngaart (2012) on how much carbon reduction is achievable by measures such as building insulation and thermal energy storage in the Dutch urban heating sector. He concludes that "*cost-effective construction and local measures together can save 15 to 30 percent of the carbon emissions from the built environment by 2050*".

In addition, the model shows that achieving a reduction of more than 10% requires securing a very high household participation degree in a very short amount of time and the establishment process to be fast.

With respect to neighbourhood participation, when this is left to the voluntary choice of the household, it can be expected to gather, in average, the support of half of the neighbourhood and the final participation of 25%. Given the fact that the Dutch government aims at disconnecting 90% of households from the gas grid, the model outcome are far from reaching the target (Jansma et al., 2020). However, the results are in lined with the findings from the recent study conducted by Rooijen (2019) which found that current homeowner involvement in the natural gas-free neighbourhoods pilot plans is insufficient leading to residents not accepting and participating in the project.

Moreover, there is a positive correlation between the level of neighbourhood involvement and the community's contribution to the total investment. The lower the neighbourhood participation the more the government will need to contribute from their own pockets for the projects to be feasible. In average, with current CO_2 and gas price growth expectations, communities are willing to contribute by covering around 55% of the total investment leaving the rest (45%) to be covered by subsidy and loan schemes provided by the government. If, for instance, the government is just willing to financially support the communities by covering around 30% of the total capital investment they must ensure that around 50% of the neighbourhood will participate in the project.

With regards to the technology scenarios, given the inputs and assumptions of the model, the two most environmentally friendly options (TEA and ATES) were also the most popular ones among the neighbourhoods. These technologies were also preferred in combination with individual solar thermal systems. This result clashes with what we know about the solar thermal systems market in the Netherlands which is very small compared to that of heat pumps.

When analysing the relationship between the different outcomes it was found that although both fast process duration and high neighbourhood participation have a positive correlation with CO_2 emission reduction, having a fast formation process was the most crucial factor out of the two. Lastly, even though ATES and TEA systems have lower CO_2 emission intensity than biogas, there are some bio scenarios that were capable of achieving higher CO_2 emission reduction levels than ATES and TEA scenarios when the TEC got quickly established.

EVALUATION CRITERIA

The model outcomes reveals, on one hand, **the importance of speeding up the process of establishing these thermal energy communities in order to achieve high CO_2 emission reduction**. Nevertheless**, targeting high participation should not be neglected given the positive correlation with the level of neighbourhood investment contribution.** As a result, formation process duration and level of household participation are considered to be the two most suitable criteria for the evaluation of the success of thermal energy communities.

Moving on, the key techno-institutional conditions that enable or hinder the establishment of thermal energy communities will be discussed. For this, the conditions have been divided into three categories following the categorisation of external variables in the IAD framework: bio-physical conditions (technology), attributes of community (values) and rules in use (formal rules).

BIO-PHYSICAL CONDITIONS (TECHNOLOGY)

Within the bio-physical conditions, the focus of this study has been on the technology. In particular, three key technology alternatives have been studied: bioenergy, aquathermal systems and aquifer thermal energy storage (see Section 4.1.1).

With respect to the technology, the model reveals the **important role of installing a very environmental friendly technology for attaining high CO_2 emission reduction**. However, these technologies are also more expensive and hence require a larger financial effort from the household's point of view. In particular, the scenario which combines TEA collective heating systems with solar thermal has proven to be the one that delivers the best outcome in terms of CO_2 emission reduction, levels of neighbourhood participation and probability of succeeding in the establishment of TECs.

Although it is true that the most environmentally friendly technologies usually lead to the best outcomes, the results also prove that the **technology selection itself is not a determining factor of the success of thermal energy communities since all scenarios can either fail or succeed.** For instance, TEC boards which select TEA systems can end with either a failed outcome or a very successful outcome. In the same line of reasoning, TEC boards installing a biogas system although normally leads to an average performance, in some occasions it achieves very high KPIs.

ATTRIBUTES OF COMMUNITY

This research has particularly focused on the cultural norms (i.e. on the influence of the levels of environmental concern, financial concerns and energy independence concerns). It has applied the behavioural reasoning theory and the social value orientation theory to denote the influence of the cultural norms on the decisions made by the agents in the model (see Section 2.2).

When looking at Section 7.4 on the analysis of the most successful outcomes, Figure 36 reveal that it is a must for the leading thermal energy community TEC board to have very high environmental concerns for the project to be successful. Nevertheless, those TEC boards that arrived to having very high CO_2 emission reduction and participation levels, complemented their environmental concerns with either high financial and independence concerns or both of them. In particular, **successful TEC boards were found to frequently select TEA + ST scenarios while holding a balanced value system that highly and equally valued becoming independent, having an affordable project and being environmentally friendly**. This combination is the one that better aligns with the Dutch neighbourhood's value system, hence, leading to achieving a fast formation process with enough neighbourhood participation for the project to be feasible.

The model results are also very conclusive with respect to the community attributes that hinder the establishment of thermal energy communities. The model reveals that **TEC boards emphasising one specific value, regardless of whether that is environment, economy or independence, leads to having low TEC board support levels**. This is especially true for when the focus is on minimising costs.

RULES IN USE

This category defines all those formal rules and regulations that constrain and guide the interactions between the technology and the actors. This research has focused on the study of the influence of policies at both the municipality level and TEC board level. Regarding the latter, two alternatives for household participation policy (individual/collective) have been analysed. At the municipality level the focus has been on (i) four alternatives for the subsidy distribution strategy (environmental, economic, social and trade-off), and the provision of persuasion trainings for the TEC boards.

Linking the findings on the bio-physical conditions and attributes of community to the formal rules, it is not to a surprise that **the municipality policy that led to the best outcome is then the trade-off strategy** which equally weights the three values followed by the environmental strategy, which solely looks into the expected environmental performance of the projects. Moreover, the model clearly reveals the importance of municipalities not only supporting thermal energy communities financially but also **with providing the platform to gather the skills they might be lacking**. In the model this was represented by the persuasion trainings. Most of the successful projects were designed and implemented by TEC boards that had previously been trained on communication, persuasion and mediation skills.

On the other side, the municipality policy that most likely leads to the failure of the establishment process is that which **maximising household participation (social strategy) when in combination with** TEC boards that focus solely on **one specific concern since this latter receive low support.** Apart from the high chances of failure of the social strategy, the strategy of minimising costs is also ineffective. This strategy gives preference to the projects with bio heating systems since they are less expensive than the environmentally friendly technologies TEA and ATES. And since these latter technologies are more popular, some of these projects do not go through the screening of the economic strategy of the municipality and end up failing due to lack of external financial support.

8.1.2. FOUR LAYER MODEL OF WILLIAMSON

Overall, it can be concluded that **technology selection itself is not the most crucial and determining factor of the success of thermal energy communities but the institutional conditions surrounding it are.** Values alignment across agents, the TEC board's capacity to communicate with households and persuade them, and the municipality's fiscal strategy are key conditions that influence the success of TECs establishment process. These overarching insights from the model can be located at the different layers of the 4-layer Williamson framework which correspond with different agent groups.

- *Layer 1 – Cultures*: Relevant institutions at this level are the value and belief systems. From the discussion it is concluded that the alignment of the values held by the municipality and TEC board with those of the neighbourhood is a key condition for success. In the Netherlands in particular, the visions of thermal energy communities should represent a balanced value system that highly and equally values becoming independent, having an affordable project and being environmentally friendly.
- *Layer 2 – Institutional conditions:* The discussion shows that for thermal energy communities to succeed, it is very important to have fiscal strategies such as national subsidy and loan schemes that support the initial investment requirements of these communities. Without public financial support that covers on average 40% of the total costs, communities will unlikely be able to cover the capital costs.
- *Layer 3 - Governance*: Regarding the division of roles and responsibilities across agents the model has proven that sharing responsibilities with the citizens themselves by ensuring active household participation is another key factor. In the Netherlands this is translated into an effective design and implementation of municipal heat plans in which the neighbourhood is actively involved.
- *Layer 4 – Individual layer:* From the analysis of the results it can be concluded that the most critical actions that influence the formation of thermal energy communities in the Netherland are:
    - *Action 1- gathering of neighbourhood support*: The model outcome shows that those TEC boards that actively engage with the neighbourhoods and integrate them in the design process by taking into account their preferences gather more support and hence are more likely to succeed in the establishment of a thermal energy community.
    - *Action 2 - subsidy agreement between the TEC board and the municipality*: The model outcome shows that TEC boards cannot be successfully established without support from the municipality. For a subsidy agreement between the TEC board and the municipality to occur, their vision and strategies need to be aligned.

8.1.3. THEORIES

Moreover, the model outcome can also be discussed in terms of the theories selected for the explanation of the behaviour in the model.

- *SVOs*: In Section 2.2.2 it was stated that in the context of environmental behaviour, SVO theory is used to assess whether more pro-social value orientation is an indicator of pro-environmental behaviour (Kastner and Matthies, 2016; Sutterlin et al.,, 2013; Hoppe et al., 2019). The model simulation outcome supports this claim since the simulated pro-social neighbourhoods have a preference over the most environmentally friendly technologies and only those TEC boards with pro-social value orientation (environment) reach an excellent performance. Nevertheless pro-self-orientation is not necessarily an indicator for failure since within the failed projects there are both pro-self and pro-social TEC boards and neighbourhoods.
- *Multi-criteria decision making*: MCDM techniques started to get used in energy planning in order to incorporate social aspects to the traditional techno-economic energy system analysis (Pohekar and Ramachandran, 2004; McKenna et al., 2018). The results of the model support the claim of having to considering the internal values and belief systems of actors in such energy planning processes since the

most successful municipality subsidy strategies were the ones that reflected the concerns of Dutch households (environmental and trade-off strategies).

- *Behavioural reasoning theory*: The key contribution of the behavioural reasoning theory to the literature of behavioural intention theory is that it includes the relevance of context specific reasons for and against a decision as a key predictor of the attitudes as well as of the final decision (Westaby, 2005). When examining how the values held by the TEC board are able to explain the success of the TECs, the results show that understanding the general attitude of the TEC board (i.e. whether they prioritise environmental concerns, costs minimisation or becoming energy independence) did not provide valuable insights. It was required to dive deeper into understanding how the TEC boards valued the different concerns specifically (i.e the context specific reasons) what shed light into what value systems were likely to lead to successful outcomes.

8.1.4. KEY TAKEAWAYS AND VALIDATION

After discussing the key results from the model experimentation outcome through the lenses of the research theoretical background, the following points summarise the key takeaways from the model simulation outcome and validates them through similar claims made in other literature studies:

- Most neighbourhoods implementing sustainable district heating systems will manage to reduce their CO_2 emissions in average by 10% by 2030 and up to 30%. This is in line with the findings of study conducted by Van den Wijngaart (2012) on how the amount of carbon reduction achievable by increasing building insulation and thermal energy storage in the Dutch urban heating sector. He concludes that "*cost-effective construction and local measures together can save 15 to 30 percent of the carbon emissions from the built environment by 2050*".
- Regarding the technology, given the high popularity of TEA systems in the model outcome across all TEC board groups, TEC boards should put the priority in studying whether aquathermal systems are suitable and feasible technologies for their neighbourhoods and municipalities should focus on expanding supporting schemes for this technology in particular. The potential of aquathermal is started to get recognised by the Dutch government. This is observed in the creation of the Aquathermal Green Deal in 2019 which aims at mapping out the value and application of aquathermy as a source of heat and cold in the heat transition (GreenDeals, 2020).
- The most critical actions in the formation process of thermal energy communities are (i) gathering neighbourhood support and (ii) finding agreement between the municipality and the TEC board over their financial support. Fouladvand et al (2020) and Busch et al., (2017) arrived to similar conclusions. Fouladvand et al (2020) claim that "*the focus may need to be on incentivizing households at the beginning to join and participate in the TEC initiatives*". Moreover Busch et al., (2017) conclude that increasing access to finance and having the local authority taking up an strategy role increases the success of TEC establishment process.
- Process duration and level of neighbourhood support are suitable indicators of the success of thermal energy communities. When looking at the literature Mittal et al. (2019) also considered high neighbourhood participation a critical condition for success and included number of participants as the key metric to evaluate the outcome of an ABM which models zero energy communities. Regarding the process duration, Beggio and Kusch (2015) which analyses the success factors of European energy cooperatives did identify speed in the process as a crucial factor for collectively implementing energy renewable energy cooperatives.
- To achieve a fast formation process with high levels of neighbourhood participation, the key condition is that the TEC board actively involves the neighbourhood in the project and adapts its vision and technology preferences to fit that of the neighbourhood. This is validated by the study conducted by Rooijen (2019) which found that current homeowner involvement in the natural gas-free

neighbourhoods pilot plans is insufficient which leads to residents not accepting and participating in the project.

- Municipalities (or other relevant agents) should focus on understanding where the TEC boards are failing regarding the communication and growth strategy and support them. A way could be through the provision of trainings as suggested in the model. This insight was also provided by the model developed by Busch et al., (2017). They arrived to the conclusion that policies should focus on creating social value and be designed to support the lacking capabilities of the initiators. Moreover, van Doornbos (2020) which conducted research on citizen participation in the Dutch heating transition concluded that increased support from municipalities is needed to improve the competencies of the organisation of citizen participation in thermal energy community projects.
- In the case of the Netherlands, TEC boards and municipalities should focus on designing projects and strategies that involve environmentally friendly technologies but that, in addition, find the equilibrium with being affordable for the different agents. Developing a vision at the municipality and neighbourhood level which finds the balance between the three value explored in the model (environment, economy and energy independence) is key for projects to be successful. Nava Guerrero (2019) model outcomes also arrive to the conclusion that the most successful heating transitions transition occurred in simulation runs where all agents were environmentally oriented. However, no ABM study was found to focus on an in-depth analysis of the value systems agents have.

8.2. CONCLUSIONS

The number community energy projects Europe is rapidly growing and are expected to have major impacts within the energy sector in this continent. The concept of energy communities comprises both electricity and thermal energy systems, yet, the academic literature is dominated by studies that focus on renewable electricity (Persson et al., 2014; Denis and Parker, 2009). However, the heavy reliance on fossil fuels of the European thermal sector makes the study and development of renewable thermal energy communities vital for the success of the European energy transition (Eurostat, 2018).

One of the key features of thermal energy communities is the importance and influence of the local context. As a result, this thesis has focused on the study of thermal energy communities in the Netherlands to account for the local nature of thermal energy communities. The Netherlands was chosen mainly due to the required radical transformation of their energy sector to achieve their CO_2 emissions reduction targets of 2030 and 2050 and its current changing institutional landscape within the heating sector.

Through the literature review of thermal energy communities it was found that there was little understanding on the formation of these communities, the barriers that hinder the process and the institutional factors and conditions that help overcome these barriers. As a result, the following research question emerged:

What institutional conditions and factors hinder and enable the success of establishing thermal energy communities in the Netherlands?

To guide the answer to this main research question, several sub-research questions were designed. The first sub-research question focused on the definition and understanding of thermal energy communities by applying the framework of Fouladvand et al (2020) to the case of the Netherlands.

1. *What is the definition of thermal energy communities?*
    a. *What is the local technology implemented?*
    b. *Who are the main actors engaged?*

c. Which are the key institutions involved?

Fouladvand et al. (2020) classify CE into three main components: (i) as a technology for the generation, distribution and consumption of renewable energy, (ii) involved actors and their roles, and (iii) related institutions, formal and informal rules that govern an energy community.

Regarding the technology it was found that there are three alternatives to natural gas in the heating sector: green gas, electrical solutions, and district heating. Out of them, sustainable district heating has the highest growth potential in the Netherlands (expected to represent 15 % and 45 % of the total heat supply by 2030). Moreover, it was concluded that out of the eight key sustainable heat sources for the Netherland (aquathermal, thermal energy storage, geothermal, green gas, bioenergy, residual heat, hydrogen and solar heat) aquathermal, thermal energy storage and bioenergy are the most feasible heat sources for collective networks currently.

With respect to the actors, the research found that the key actors involved in thermal energy communities fall under one of the following categories: (i) public actors, (ii) private heat actors, (iii) civic actors, (iv) intermediaries. In the Netherlands, local public actors (municipalities) are given the responsibility to make decisions over the urban heating transition pathway and natural public institutions such as the ACM have more of a supervision and overarching regulatory role. Private companies so far have been leading on taking up the ownership of heat networks yet community ownership is now emerging as an important alternative to private ownership. Lastly, due to the multi-stakeholder nature of the urban heating system, intermediaries are key to facilitate relationships between key actors and enable sharing and pooling of knowledge. Knowledge institutions such as PBL and CE Delft are the ones taking up this role in the Dutch case study. The agent-based model focused on the actors at the local level (municipality, households and TEC boards). The results demonstrated the importance of vision alignment and good communication between these actors for the success of TEC projects.

Regarding the institutions, the agent based model proved that the challenge of overcoming the lock-in of the current infrastructure and institutional setting and of complex agent interactions are the most important barriers for the development of thermal energy communities. Moreover, it is concluded that a crucial factor for the achievement of the heat transition in urban areas is the activation and capacitation of local actors to take action and reach consensus on the re-design of the system.

2. What is the process of establishment of thermal energy communities?

Answering the second research question, based on the literature the process of TEC establishment is composed into four phases: idea, feasibility, procurement and building, and expansion. The agent based model has focused on the first two phases and has concluded that the key decisions that need to be made over these two phases are: initial mobilization of the TEC initiators and building support, (ii) building consensus over the project technical, investment and organisational characteristics, (iii) securing finance, and (iv) building the heat infrastructure.

3. What are the main factors that lead to the successful formation of thermal energy communities?

Following the meta categorisation derived by Warbroek et al., (2019) of the social, organisational and governance factors that positively impact local energy initiatives, these factors can be divided in three different groups related to (i) the leadership TEC board in charge of the project, (ii) the local community, (iii) external agents. Regarding the factors related to the energy leadership TEC board, the key factors are having the required knowledge and expertise and access to funds. With respect to the interactions between the TEC board and the local community, it is important that there is a high level of local community involvement which is translated into a high willingness to participate and to invest in the project. For this, the project must be aligned to the values of the local community. Lastly, regarding the actors external to the communities, developing strong partnerships with intermediaries and the local government is key to secure external support and complete all the skill set and resources required for the formation and operation of an energy community. It Is also crucial to have supportive policy frameworks that are responsive to the needs of the energy communities.

The answer of these three sub-research questions guided the answer to the main research question:

What techno-institutional conditions enable the formation of thermal energy communities in the Netherlands?

Regarding the technological conditions, it was found that scenarios combining collective and individual technologies are the preferred ones among Dutch neighbourhoods and that aqua thermal and thermal energy storage options are the most popular collective technological solutions, and the ones that lead to higher level of household participation and CO_2 emissions avoided by 2030. However, the model also showed that technology selection itself is not the most crucial and determining factor of the success of thermal energy communities but the institutional conditions surrounding it are.

Regarding the institutional context, the model demonstrates that projects are likely to be successful when agents share a common vision that highly and equally values (i) developing energy independent communities, (ii) using environmental friendly heating generation technologies, and (iii) providing heat at an affordable price for the consumers. Lastly, the results demonstrate that it is crucial to have supportive institutional conditions that are responsive to the local context and needs. In order to develop such an enabling institutional environment in the Dutch context, this research recommends (i) sharing decision making and financial responsibilities among all actors involved in the design and implementation of municipal heat plans, (ii) the design of fiscal structures that focus on supporting those TEC projects that are able to balance out project costs with its potential environmental impact, and (iii) the development of programs that improve the marketing capabilities of TEC boards to increase resident's knowledge about the heating transition and their participation in TECs.

8.3. Research limitations and further work

Although the research sheds light on understanding the process of establishing thermal energy communities and, in particular, what techno-institutional conditions enhance and hinder the process, several limitations exist when looking at the thesis research design. In general, the selection of the theoretical background, the case study and the model conceptualisation have limited and narrowed down the scope of the research.

8.3.1. Research methods

The decision of using Ostrom's IAD framework (2005) together with the four layer model of Williamson (1998) (see Section 2.1) has provided the lenses through which the thermal energy communities have been researched. As a result, the model insights have focused on the variables (informal and formal rules, technology) and levels (operational, governance and institutional) defined by these frameworks. It is important to keep in mind that there are other theoretical frameworks such as the socio-ecological system framework (Ostrom, 2007) that when applied to the same system and process could provide different insights to the study. In addition, the decision of using the BRT (Westaby, 2005), SVO theory (Griesinger and Livingston, 1973; Forsyth, 2006) and the MCDM technique (Wang et al., 2009) to guide the decision making processes of the actors involved in thermal energy also limits the research. There are other theories such as Ostrom's collective action theory (1990) that if implemented could have derived better insights on for instance the role of building trust in the success of thermal energy communities.

Moreover, another important limitation was the selection of the case study. The Netherlands was chosen mainly for the current challenging, uncertain and changing state of the institutional environment of the heating sector (see Section 3.1. for further explanation. However, due to the local natural of the heating sector, the choice of the Netherlands limits the application of the insights derived by the model to the Netherlands and at most, to European thermal energy communities. It would be very interesting to adapt the inputs of the model to fit the context of another country and compare the differences in the model outcomes of the model and its relation with the differences in the initial conditions of the various countries.

8.3.2. DEVELOPED AGENT-BASED MODEL

Since the focus of the thesis has been the conceptualisation, implementation and experimentation with the agent-based model, an in depth reflective look into the limitations of the model is necessary.

Models are representations of a selected aspect of the world (O'Sullivan and Haklay., 2000). Therefore, by definition they cannot include all the details of the objects that they represent and have limitations. When looking at the conclusions derived from a model, it is important to take into consideration the limitations of such model and understand its blind spots. It is only by knowing the limitations that further work can derive from this research. This section presents the limitations of the agent based model developed in this thesis and the suggested further work by dividing them in three sections (i) the data gathering process, (ii) the model conceptualisation, and (iii) model validation.

The data gathering process of this agent based modelling was conducted through desk research. The values for the variables and attributes in the model (e.g. number of households in a neighbourhood, household heat demand, level of household insulation, subsidy amount per project) were obtained by finding average figures and statistics. Although this provides general insights for the case of the Netherlands, further work could focus on developing a more concrete and realistic model by modifying the model input to include more disaggregated data on these attributes such as data distributions instead of averages. Moreover, regarding the attributes of the community at the household level, to keep the model comprehensible and obtain valuable insights regarding the techno-institutional conditions, no socio-demographic information was included. Nevertheless, information such as income distribution could provide more accurate derivations and insights on the willingness to invest of the households in TECs. In addition, only current growth expectations of the CO_2 price and gas price were included in the model. It would be interesting to study what the impact of changing future price growth will be on the feasibility of thermal energy communities. Lastly, the value system of the TEC board was randomised within the model due to the lack of data on the value preferences of the TEC boards leading thermal energy projects in the Netherlands. However, the model proves TEC board values systems to be a determining factor on the level of success of the projects. As a result, further work could look into conducting surveys to provide more realistic inputs to the model on what TEC boards in the Netherlands consider important when deciding on what heating technology to include in their projects.

Moving on, the limitations of the conceptualisation and implementation of the model are structured through the elements of the TEC framework developed by Fouladvand et al. (2020) (technology, actors, institutions) and the steps of the formation process.

Regarding the technology, three of the most feasible and accepted collective heating technologies were included in the analysis (bioenergy, ATES and TEA) and it was assumed that they could all be technically feasible in all neighbourhoods. Moreover, it was decided to do not distinguish between medium and low heating district networks to keep the focus on the decision making of the heating generation technology. Further work could focus on one hand on expanding the model to include other heating generation technology that may be less developed (i.e hydrogen or green gas) or focus on the distinction between high and medium heating networks instead of on the heating generation technologies. Moreover, the model could be coupled with a technical optimisation model for the technical outcome to be more complete and conclusive.

When looking at the actors included in the model, it was decided to include those three that were found to play a major role. Now that the model structure has been developed, further work could focus on incorporating other relevant actors such as social housing associations, energy companies or DSOs. Alternatively, it could focus on better representing the actors already included. With respect to the households, the model has focused on the role of value systems has concluded it is indeed a determining factor. However, Koirala et al., (2018) argues that another very influencing attribute is the level of trust within the neighbourhood and across agents. Further work could look into how to expand the model to incorporate this attribute in the model. Regarding the TEC boards, the model has found that policies that focus on completing the capability skills of the TEC boards are very effective an impactful. Hence, further work could look into what other skills apart from persuasion are crucial in the establishment of thermal energy communities. Lastly, the model has extensively studied the role of the government as resource supporter (finance and trainings). In reality, their function is much complex than this. The following section on formal institutions suggests different ways in which the modelling of the government's role could be expanded in future research projects.

Moving into the formal institutions linked to thermal energy communities in the Netherlands, the model has conceptualised the governmental subsidy schemes to represented the gas-free area (PAW) program of the government. These fiscal structures could be disaggregated into the three key subsidy schemes: PAW, SDE++ and ISDE to derive insights on the impact of these subsidy schemes on the scale up of Dutch urban heat networks. Moreover, an important element of the Dutch heating transition which is the Heat Act is solely represented through the calculation of the heat price following the "no more than otherwise" ("NMDA" in Dutch) principle regulated by the Heat Act. It would be very interesting to include a variable on the pricing mechanisms to explore other mechanisms apart from the NMDA one.

When looking at the establishment process explained in Chapter 4, the model has focused on the idea and feasibility phase since these were the most understudied phases. An important point of research would be to model in more detail the two actions found to be crucial in the idea and feasibility phase of the establishment process: gathering of neighbourhood support and the design and agreement over the investment plan.

Lastly, since the model of the model has proven that the results are in line with the literature on energy communities, further research could focus on conducting interviews with experts and practitioners to further validate the results and find ways for the insights to be included in the design of policies related to thermal energy communities in the Netherlands.

8.4. SCIENTIFIC RELEVANCE

The scientific relevance of this research revolves around three key points: (i) the provision of insights on the techno-institutional conditions influencing TECs, (ii) the selection of the theoretical background, and (iii) the methodology used.

8.4.1. INSIGHTS ON THE TECHNO-INSTITUTIONAL CONDITIONS INFLUENCES TECS

Regarding the literature, although several studies have addressed the topic of district heating cooperatives (Moshkin and Sauhats, 2016; Perez-Mora et al., 2018), up until now there has been limited research on thermal energy communities (TECs) in general and more in particularly on the techno-institutional factors and conditions that influence the development of TECs. As a result, this study contributes to the body of literature on community energy by increasing the understanding on the internal dynamics of TEC initiatives, and how they can be conceptualised and analysed. Moreover, with respect to the techno-institutional factors influencing TECs, this research provides an in depth understanding of the influence of values and belief systems (informal institutions) on the individual and collective decisions made by the agents involved in these communities. In particular, it explores how value systems impact agents preferences over different sustainable heating scenario. On the other hand, the research provides insights on what an enabling institutional environment looks like for the successful establishment of TECs in the Netherlands and sheds light on the importance of having a local government that is responsive to the needs of the residents.

8.4.2. Theoretical background

The two institutional analysis frameworks used in this research, the Institutional Analysis and Development (IAD) framework (Ostrom, 2005) and the four layer model of Williamson (1998), have previously been used in combination only by van Es (2017) for the study of the urban water cycle in Delft. The ABM developed in this research is one of the first to use the four layer model of Williamson as the basis for its conceptualisation. Nevertheless, this research does provides the first example of an ABM developed through the combination of these two frameworks. In particular, the IAD-Williamson framework has been used at three key stages: model conceptualisation, model implementation and the interpretation of simulation results.

- Regarding the *model conceptualisation stage* (Chapter 5), Williamson's framework has proven to be a suitable framework for the initial formulation of the problem to be addressed by the agent based model. The meta categorisation of institutions in layers in Williamson's framework allows the initial identification and description of the problem and key actors involved in to be done in a structured and hierarchical manner. Subsequently, the IAD framework has proven to be very valuable for the further decomposition of each later into more simple and understandable elements.
- Moving on to the *model implementation stage* (Chapter 6), the data gathering process was conducted by following the different layers of Williamson's framework. These eased the process of selecting and structuring the data that was relevant for the model.
- When looking at the *interpretation of the agent based simulation results* (Chapter 8), applying the IAD framework to the model outcome first enabled a detailed discussion over the critical external and internal variables that hinder or enable the success of thermal energy communities. Then Williamson's framework enabled a generalisation of the key insights from the model outcome for each actor represented in the model.

Overall, it can be concluded that the combination of the Institutional Analysis and Development (IAD) framework and four layer model of Williamson allows (i) to progress from a general to a detailed description of the model concept, and (ii) to move from a detailed interpretation of the model simulation results to a generalisation of such.

8.4.3. Research methods

Although there are several agent-based models that study energy communities (Rosales-Carreón and García-Díaz, 2015; Mittal et al., 2019; Xiong et al., 2020), only Busch et al., (2017) and Nava Guerrero et al., (2019) have focused on thermal energy communities. Similarly to this research Busch et al., (2017), explores the impact of several policy strategies on the process of developing heat networks, yet, the context is that of the United Kingdom. Nava Guerrero et al., (2019), on the other hand, does looks at the Dutch heating transition but places the focus on socioeconomic conditions instead. Therefore, this research expands the knowledge of the use of an agent based modelling approach for providing insights on the institutional factors and conditions that influence the urban heating transition and it is the first one to do so for the context of the Netherlands.

8.5. Societal relevance

8.5.1. Final recommendations

This thesis proposes several recommendations for the different agent groups the research has focused on:

General recommendations

The following insights can be generalised for all agents involved in the establishment of Dutch thermal energy communities:

- It is vital to adopt a collaborative attitude and reach rapid consensus over municipal heat plans across agents in order to reach the emission reduction objectives set for 2030 and 2050.
- It is essential that values and vision across all agents are aligned. In the case of the Netherlands, developing a vision at the municipality, board and neighbourhood level which finds the balance between environmental sustainability and financial feasibility is key for projects to be successful.

Municipalities

Given that Dutch institutional environment related to the heating sector is now going through a re-structuring process, this research can be used by the regional and local governments to guide the design and adaptation of policies to speed up the urban heating transition. In general, the key insights for local decision makers and policy makers are:

- Having the municipality taking up an strategic and intermediary role increases the success of the TEC establishment process.
- Municipalities must ensure TEC projects have access to funds. For thermal energy communities to succeed, it is very important to have fiscal strategies such as national subsidy and loan schemes that support the initial investment requirements of these communities. Without public financial support that covers in average 40% of the total costs, communities will unlikely be able to cover the capital costs.
- Regarding the heating technology, municipalities should focus on expanding supporting schemes for aquathermal technology based district heating systems in particular. These have not yet been very explored but seem to have high implementation potential.
- Municipalities should focus on understanding where TEC boards are failing regarding their communication with the neighbourhood and their citizen's engagement strategy and develop programs to support them.
- Suitable indicators for monitoring the progress of thermal energy community projects: process duration and share of neighbourhood support.

TEC boards

For the members of the group initiating thermal energy community projects in the Netherlands, the research concludes that the most important focus points during the initial stages of the projects may need to be:

- Gathering neighbourhood support: for TEC to establish fast and have high participation levels boards must develop strong links with the neighbourhood residents by actively involving them throughout the whole process and adapt their heating vision and technology selection to fit that of the neighbourhood.
- Finding an agreement with the municipality for financial support.
- With respect to heating technology feasibility analysis, given the high popularity of TEA systems in the model outcome across all TEC board groups, TEC boards should put the priority in studying whether aquathermal systems are suitable and feasible technologies for their neighbourhoods.

Households

Lastly, the research also provides useful insights at the household level:

- Sharing responsibilities with the citizens themselves is a key factor.
- Dutch households have a preference over environmentally friendly collective technologies (ATES and TEA).
- Dutch households prefer technology scenarios that include individual heating systems such as heat pumps and solar thermal systems over fully collective scenarios.
- It is expected that Dutch households will have to financially contribute around 1000 euros per year on the heating transition in a timeframe of 20 years.

8.5.2. Thermal Energy Communities in North Western Europe

Even though this research focuses on the case study of the Netherlands, it is important to state that the characterisation of thermal energy communities described in Chapter 4, the model results of Chapter 7, the insights discussed in Section 8.1 and the recommendations proposed in Section 8.5.1 can be generalised for the countries in the whole north-western region of Europe given the similarity of their institutional, governance and social context surrounding the heating transition.

Several studies on the heating transition on these countries arrive to conclusions similar to those of this research. For instance, Rocher (2014) analysed the renewal of interest in district heating in France. Similarly to the case in the Netherlands he concluded that two of the key conditions are (i) the consideration of district heating as a key instrument for the energy transition and the increased penetration of renewable energy in the country, and (ii) the recent regulatory reforms towards energy decentralisation giving new competences for local authorities to manage the energy transition at the local level. For the case of the UK, Rogers et al., (2012) study the factors enabling community leadership of thermal renewable energy projects and arrived to conclusions similar to those of this research: shared discourses of a perceived need for the transition and a long-term vision as well as external financial and capabilities support are fundamental.

The similarities across the countries of the north-western region of Europe on their approach to the heating transition are not only visible on the academic literature but also on a practical level. For instance, the Interreg North-West Europe (NWE) Programme, which is a platform which fosters transnational cooperation across the countries in this region, has developed a heat project named HeatNet NEW. This projects aims at "*creating an integrated transnational NWE approach to the supply of renewable and low carbon heat*" (NWEurope, 2020). The goal is to developing technical, institutional and organizational frameworks to foster district heating in the NEW, with a focus on the UK, Ireland, Belgium, France, and the Netherlands.

As a result, given the proven similarities of the Netherlands with the rest of the countries on the whole north-western region of Europe on an academic and practical level, the insights revealed in this research could support the work currently being conducted by the HeatNet NEW.

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APPENDIX A: MULTI-CRITERIA DECISION MAKING FOR HOUSEHOLDS ON INDIVIDUAL TECHNOLOGY

This appendix includes an example of the multi-criteria decision making process an individual households goes through to evaluate the different individual technology alternatives to complement the collective heating technology. The process follows the same steps as explained in Section 6.2.2. In this case, as seen in Step 3, the collective heating alternative is biogas and the households value system is the following: environmental concern 3, financial concerns 9 and independence concern 3 (see Step 4). Lastly in Step 6 it can be observed that for this household their preferred individual technology alternative is A1 (collective – no individual heating alternative). More information on the multi-criteria decision making processes used in the model can be could in this data file.

Step 1: what are the alternatives?

Table 1: Alternatives

Alternative	Energy scenario
A1	Collective
A2	Heatpump
A3	Solar Thermal

FIGURE 54: MCDM STEP 1

Step 2: what are the criteria?

Table 2: Criteria

Criteria		Sub-criteria
C1	Financial	Investment costs
		Maintenance costs
		Subsidy coverage
		PBT
C2	Environmental	CO2 emissions
		Awareness
C3	Energy	energy independence

FIGURE 53: MCDM STEP 2

Step 3: Calcuate performance of alternatives on each of the criteria (numbers from paper)

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings (biogas)		
					A1	A2	A3
C1	Financial	Investment costs	Min	€/HH	231,3342281	3540	3332
		Maintenance costs	Min	€/yr	12,6351225	35,4	44,982
		Subsidy coverage	Max	Fraction	0,829174664	0,282485876	0,219759904
		PBT	Min	yr	4	21,87960325	21,36510379
C2	Environmental	CO2 emissions	Min	t/HH/yr	289,864575	160,9911552	95,65530975
		Awareness	Max	number	7	8,00	3
C3	Energy	energy independence	Min	KWh/yr	1311,604412	372	223
		Tech capacity	Min	kw/HH	0,37162125	0,7432425	1,5926625

FIGURE 52: MCDM STEP 3

Step 4: Normalize the performance

When criteria objective is minimization, Ui(Xij,min) = 1 and Ui(Xij,max) = 0

When criteria objective is maximization, Ui(Xij,max0 = 1 and Ui(Xij,min) = 0

Nr Criteria	Criteria	Sub-criteria	Goal	Unit	Alternative rankings (biogas)		
					A1	A2	A3
C1	Financial	Investment costs	Min	€/HH	1,00	0,00	0,06
		Maintenance costs	Min	€/yr	1,00	0,30	0,00
		Subsidy coverage	Max	Fraction	1,00	0,10	0,00
		PBT	Min	yr	1,00	0,00	0,03
C2	Environmental	CO2 emissions	Min	t/HH/yr	0,00	0,66	1,00
		Awareness	Max	number	0,8	1,00	0
C3	Energy	energy independence	Min	KWh/yr	0,00	0,86	1,00

FIGURE 51: MCDM STEP 4

Step 5: Determine criteria weights based on SMARTER method

Environment	Economy	Energy	
3	9	3	15,0

Environment		Weight per criteria	Nr of subcriteria	Subcrit.	Weight per sub crit.
Wi = 3	Energy	0,20	1	Independence	0,20
Wi = 1	Environment	0,20	2	Awareness	0,10
				CO2	0,10
Wi = 2	Economy	0,60	4	Investment	0,15
				O&M	0,15
				Subsidy	0,15
				PBT	0,15
		1,00			

FIGURE 56: MCDM STEP 5

Step 6: final calculation for decision making

Table 5: Final decision H1 (based on weighthed sum of the utility values of all the alternatives for the various criteria)

Criteria nr	Criteria	Weight	A1	A2	A3
C1	Investment	0,15	1,000	0,000	0,075
C2	O&M	0,15	0,717	1,000	0,000
C3	Subsidy	0,15	1,000	0,130	0,000
C4	PBT	0,15	1,000	0,000	0,055
C5	CO2	0,10	0,000	0,119	1,000
C6	Awareness	0,10	0,400	1,000	0,000
C7	Independence	0,20	0,000	0,140	1,000
Weighted sum per alternative			0,598	0,309	0,320

FIGURE 55: MCDM STEP 6