Modeling Energy Communities in the Netherlands

- Attaining energy autonomy for Dutch energy communities by leveraging diverse demand profiles through demand response

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Executive summary

Amidst the discourse regarding the decentralization of urban energy systems, community energy has emerged as a solution for not only matching the demand locally but also facilitating collaboration amongst local prosumers. An energy community or cooperation is a collective of residential electricity consumers (or prosumers) non-energy small and medium-sized enterprises (SMEs) formulating a bottom-up social-economic network involved in decentralised energy production van der Schoor and Scholtens (2015) This study is focused on community energy projects in the Netherlands. According to energy monitor (2020), The Netherlands is proudly hosting over 487 energy communities and stands third in the number of community energy projects in the EU (Elena & Andreas, 2020). However, the gap between Germany, the leader in community energy projects and the Netherlands is more than three folds. This indicates that the full potential of community energy projects in the Netherlands is not unleashed yet. Also, existing studies on community energy projects are primarily focused on residential community projects that have little to no inclusion of small and medium enterprises as community members besides residential households. Including non-residential community members such as SMEs, offices, and schools with complementing demand profiles and flexible loads can help the energy community to leverage demand response policies. This research focuses on evaluating how time-of-use tariffs can be used in Dutch community energy projects while having non-residential members besides residential members in the community. The proposed study will use an agent-based model to facilitate virtual experimentation. For this purpose, a socio-technical model of the energy community will be created for the community electricity network. This model will be used as a virtual experiment platform for evaluating system and agent behaviour subjected to the time-of-use tariff for the energy community. The results obtained from the exploratory modelling analysis will help the energy community in evaluating the impact of demand response (time-of-day tariff) on the electricity cost of the community.

Contents

Chapter 1

Introduction

1.1 Background and problem introduction

As the world is moving towards cleaner, sustainable and smarter energy sources, urban energy systems are evolving into complex systems (Pagani & Aiello, 2013). This is attributed to an exponential growth of distributed renewable energy sources (like Solar and Wind) in the last decade. The widespread of distributed renewable generation along with the evolution of energy storage has converted many electricity consumers into "prosumers" (An electricity consumer who is also involved in the generation process) whilst transforming the unidirectional electricity grid into a bidirectional network. Amidst this, the energy community has emerged as a promising solution to facilitate collaboration among prosumers and meet the energy demand locally. An energy community or cooperation is a collective of residential electricity consumers (or prosumers) non-energy small and medium-sized enterprises (SMEs) formulating a bottom-up social-economic network involved in decentralised energy production van der Schoor and Scholtens (2015).

European Commission in its Renewable Energy Directive - II (RED-II) has acknowledged the potential of energy communities. RED-II enables households and non-energy SMEs (Small and Medium Enterprises) with local authorities to operate individually or as a part of the energy community to consume, trade and store the energy generated from renewable sources (EU, 2021). The RED-II will be adopted by EU countries, however the transposition in the Netherlands. The directive adoption process is delayed because of challenges related to integration with the Dutch legislature.

However, the complex nature of transactions and uncertainties regarding policy and business model makes decision-making regarding investments and assets ownership challenging for energy communities. In addition to this, most of the existing studies and financial models limit energy communities to residential members and have limited inclusion of non-residential members and functionalities like EV charging. This is an untapped opportunity for leveraging the complementing demand profiles through demand response. Both residential households and offices have flexible loads (i.e. heating, cooling, lighting, and ventilation for offices whereas washing machine, dishwasher, heating for households) which can coexist for maximizing the self-sufficiency of the community (Reis et al., 2020). The directive clearly mentions the inclusion of non-energy small and medium enterprises and local authorities (EU, 2021). In addition to this, current financial models for energy communities are either cost-driven or profit-driven whereas the directive mentions that purpose of the energy community is not attaining financial profit but providing environmental, social and economic benefits to the local communities European Commission (2018).

According to Elena and Andreas (2020), the Netherlands stands third in the number of community energy projects in the EU. However, the difference between the number of projects in Germany (leader in the list) and the Netherlands is over three folds. This indicates, that the full potential of community energy projects in the Netherlands is still untapped. Apart from this, none of the studies implementing demand response in community energy projects is conducted or tested in the Netherlands. Therefore, this research is focused on the Netherlands to provide relevant insights and expand the knowledge base required for making community energy projects self-sufficient.

1.2 Research objective

The objective of this research is twofold. First, this research will identify key attributes of the Dutch energy communities along with the uncertainties influencing their decision-making regarding investment in generation or storage assets and responding to demand response (time-of-use tariff in this case). This information will be used for building an agent-based model to get a better understanding of the transactive behaviour of Dutch energy communities. Choice of the agent-based model as research methodology is substantiated in the section 2.4 and section 4.1. This study will also include small and medium enterprises and local authorities as non-residential members in the energy community as per the directive release by European Commission (2018). Including non-residential members with complimenting energy demand profiles provide the opportunity for better peak management through demand response policies. Demand response and its relevance for energy communities are further discussed in the literature review section 2.3. The scope of this model will be limited to the electricity distribution network at the community level. However, this model can be extended to include heat and gas networks in future versions. This model is intended to create a model of community energy to facilitate virtual experimentation and act as a testing ground to evaluate demand-response policies (time-of-use tariff in this case). An existing or potential site for the energy community will be selected and modelled as a case study. The proposed model will aid modelled energy community to take the necessary steps required to reduce grid dependence and achieve self-sustenance.

1.3 Societal relevance and suitability as a thesis project

Energy communities are promising citizen-driven initiatives taking the bottom-up path to transcend towards accessible, sustainable, efficient and low-carbon urban energy systems (Bomberg & McEwen, 2012). Perez-DeLaMora et al. (2021) signifies the community-building aspect of the energy community and its contribution towards society building, energy security and resilience of urban energy systems. In addition to this, community energy projects also created a conducive environment for developing and propagating grassroots innovations (Martiskainen, 2017). (Stewart, 2021) suggests that community energy projects successfully propagate the benefits of low-carbon technologies to the deprived and low-income areas of society.

Therefore, this project has a significant place in the societal discourse regarding energy transition. Apart from societal relevance, this research intends to use a data-driven modelling approach for supporting decision-making under uncertainties. Hence, this project fits all the requirements for a thesis project of MSc. Engineering and Policy Analysis.

1.4 Role of Croonwolter&dros

This study is proposed in cooperation with Croonwolter&dros, a technical service provider with a growing energy branch called Energico. Energico is venturing into energy management and intends to develop community energy projects in the Netherlands. This research will provide them with insights into the transactive behaviour of community energy projects in the Netherlands.

Croonwolter&dros has offered their expertise in form of an energy expert in the thesis committee along with their extensive network and support for gathering data for this study. This topic is finalized after a series of discussions and brainstorming sessions with Croonwolter&dros. The means-end tree along and objective tree used during the brainstorming sessions are attached in the appendix A of this proposal.

1.5 Research proposal outline

The remaining of this proposal has the following structure. Chapter 2 is a literature review positioning the proposed thesis topic in the scientific discourse. The literature review highlights the knowledge gap and acts as an input for the next chapter. Chapter 3 formulates the main research question along with the research approach and sub-questions derived to answer the aforementioned. Lastly, chapter 4 sheds light upon the methodology proposed for answering the research questions along with a tentative timeline.

Chapter 2

Literature review

To further explore the academic milieu of energy communities, a literature review was conducted.

This chapter starts with explaining the methodology used to collect the literature followed by discussing the key concepts. Lastly, the chapter is concluded by highlighting the knowledge gaps identified during the literature study.

2.1 Literature search

The literature review was conducted through search engines and web tools like Scopus, PubMed, Google Scholar and ScienceDirect. Apart from this, Leiden University Library and TU Delft Library were also used to access additional journals and articles. Following keywords were used in permutation and combination to search for the relevant literature. *Keywords: "Energy Community", "Smart Local Energy Grid", "Energy community modelling", "RE Community in the Netherlands", etc.* Additionally, forward and reverse snowballing was done to find the previous and derivative research work of selected papers. This snowballing was done using a web application called Research Rabbit and figure 2.1 depicts the cluster of papers reviewed.

Lastly, over 60 articles/papers from different platforms/journals were initially selected and filtered using the following criteria:

- Language: Articles published in the English language were considered for this review. Because of the linguistic constraints of the author, limited Dutch articles are included. However, critical articles and policy papers were considered after translation using google translate.
- Relevance to research topic: Articles and research papers focused on energy communities and modelling were selected for the review.
- Date of publishing: As this is a recent and growing field, 15 papers are published after 2018. The oldest paper selected for review is from the year 2016.
- Credibility of the research journal: All the journals and sources selected are accredited in the scientific community.

As the research is focused on energy communities in the Netherlands, most of the literature is based in Europe and studies conducted in (or around) the Netherlands. However, to understand the global perspective of technology, three articles discussing the global take on Energy Communities are included in the literature review.

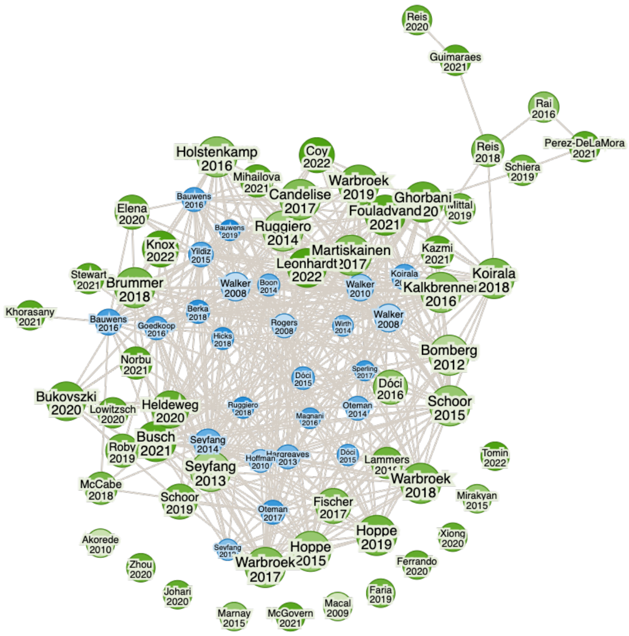


Figure 2.1: Literature Snowballing: Green bubble indicates literature included and the blue bubble indicates literature excluded from the study. The excluded papers are filtered out as per the criteria. These papers are either focused on thermal energy projects or represented through subsequent literature.

2.2 Energy communities and their policy prominence

The notion of clustering the energy assets or networks is not new in energy systems. Traditionally Islands and remote energy clusters were operated as autonomous energy systems, however, the energy flow in these clusters was predominantly unidirectional. With increased penetration of distributed renewable energy, the flow of electricity became bidirectional and clusters evolved as micro-grids and mini-grids (Marnay et al., 2015). However, energy clusters were formulated by the local demand or consumption patterns of an area whereas, energy communities necessarily include the energy generation profile of the area. This theoretically positions them differently but approaching these as mirror concepts provides an opportunity to evolve urban energy clusters into energy communities. Brummer (2018) provided a literary comparison of community energy projects in the UK, Germany and the USA highlighting the benefits and barriers for these projects. These projects are citizen-driven and hugely impact the sustainability and energy transition discourse in the society (Fischer et al., 2017). The level of citizen participation and engagement in the community energy projects are driven by trust, awareness, personal gain and affinity towards sustainability (Kalkbrenner & Roosen, 2016), (Koirala et al., 2018). van der Schoor and Scholtens (2015) emphasizes the need for a shared vision for strengthening the network aligning the interests in community energy projects.

Energy communities rose to the pinnacle of prominence in the scientific literature and policy discourse recently after European Union (EU) introduced a framework for prosumers in Renewable Energy Declaration - II (RED -II) (EU, 2021) and Directive on common rules for the internal market for electricity (IEMD). The EU (2021) provides legal rights to Households and SMEs in EU states to operate individually or form a Renewable Energy Community on a non-profit basis to consume, sell and/or store the renewable energy. Hoppe et al. (2019) highlights the importance of renewable energy cooperative for simulating household energy savings. This new governance system enables energy communities to trade electricity (1) within the Energy Community, (2) among different Energy Communities, and (3) between energy communities and markets. Whereas, IEMD provides additional power to enable distribution, aggregation, efficiency along with other energy services. Busch et al. (2021) performed a detailed literature review for policies and regulations regarding energy communities in the EU whereas Renata Leonhardt et al. (2022) provided an overview of global policy discourse around community energy projects.

These community energy projects require support from local authorities and intermediaries. The role of local authorities in supporting citizen-driven initiatives is discussed by Hoppe et al. (2015). Apart from local authorities, intermediaries (or Community coordinators) also play a critical role in bridging the technology gap for the communities by providing necessary infrastructural and technical support (Warbroek et al., 2018). However, the level of involvement and motives of intermediaries and third parties in community projects widely vary based on social and political milieu (Holstenkamp & Kahla, 2016).

2.2.1 Literature-based on community energy projects in the Netherlands

The case study conducted by (Warbroek & Hoppe, 2017) for Dutch community energy projects in Overijssel and Fryslân regions provides a governance model for local authorities to support citizen-driven low carbon initiatives. The social, organisational and governance factors characterising Dutch community energy projects are highlighted by Warbroek et al. (2019). Community energy projects require to implementation of smart grid features for enabling demand response and active monitoring (Knox et al., 2022). Lammers and Hoppe (2019) conducted a study for analyzing 'rule of the game' governing the decision making regarding smart grid projects in the Netherlands and concluded that not all stakeholders actively participate in the decision making.

2.3 Demand response in energy communities

Demand response is a price or incentive-based policy instrument used to shift the demand curve and energy consumption behaviour of electricity consumers (Faria et al., 2019). Demand response is crucial for energy communities because of three reasons.

First, to manage the indeterminacy of renewable energy sources. Solar and Wind are the most accessible renewable energy sources and act as the most common generation sources for energy communities (Schiera et al., 2019). These energy sources are intermittent and energy storage is not enough to attain self-sufficiency, particularly during peak hours. Reis et al. (2018) mentions demand response as the most effective measure for attaining self-sufficiency in the energy community and refers to it as "democratization of energy".

Second, to reduce dependence on energy storage systems. Existing business models used by community energy projects do not account for battery degradation costs in the expenses and heavily depend on energy storage for meeting the peak demands (Huang et al., 2022). This is unrealistic and reduces the life of energy storage further adding to the overall energy cost. Thus, demand response can reduce the dependency on energy storage for managing peak generation and peak demand.

Lastly, to optimize the utilization of energy assets in the energy community. All the developed countries discourage the export of renewable energy back to the grid and this is evident by a reduction in feed-in-tariffs. In addition to this, the European Commission (2018) indicates the non-profit behaviour of energy communities to curb the electricity feed into the grid Xiong et al., 2020. As a result, the price of exporting electricity is getting much lower than the price of importing electricity from the grid. Therefore, it is critical for energy communities to optimize the energy assets within the community and become self-sustaining with limited grid support (Huang et al., 2022).

2.4 State-of-the-art literature and knowledge gaps

Community energy projects involve multiple stakeholders and their interaction leading to unpredictable outcomes in the long term. The actors involved in these projects learn from their previous decisions and adapt. Thus, community energy projects fit the requirements of complex adaptive systems enlisted by Nikolic and Ghorbani (2011). Agent-based modelling (ABM) effectively captures the complex adaptive behaviour of energy community members and their informed decision-making regarding energy transactions along with social activities like cooperation, coordination and negotiation capabilities (Reis et al., 2020). ABM involves multiple agents representing the actors in the system acting and reacting to each other's actions by taking informed decisions to fulfil their respective objectives (Dam et al., 2012). In addition to this, Perez-DeLaMora et al. (2021) highlights the effectiveness of ABMs in developing strategies for energy communities.

Unfortunately, existing ABM models do not capture all the dynamics of energy communities (particularly in the Netherlands) and therefore are not suitable for testing policies and supporting decision making. Following are the three knowledge gaps identified during the literature study.

Firstly, most of the studies and models are limited to residential community members. Recent literature like Diogo V. Guimaraes et al. (2021), Mittal et al. (2019), Schiera et al. (2019) and Tomin et al. (2022) consider only residential members for energy community. Whereas, European Commission (2018) explicitly recommends the inclusion of non-residential members like SMEs for the formulation of an energy community. Additionally, most of the neighbourhoods have non-residential buildings with significant potential for generation and energy storage assets. Reis et al. (2020) highlights the need for including non-residential agents (i.e. SMEs, Office and EV charging) in the energy community and evaluating their potential for self-sufficiency of energy communities. Therefore, the aforementioned models are not capable of testing policies involving non-residential members in the community.

Secondly, as an extension of the above-mentioned gap, demand response opportunities are not sufficiently explored in the energy communities. Considering non-residential and EV charging stations (having complementing energy consumption profiles) can generate opportunities for demand response policies. Reis et al. (2020) explores demand flexibility by introducing non-residential members to the energy community but does not consider Electric Vehicle (EV) charging in the analysis. In addition to this, the economic analysis does not address the role of intermediaries and service providers required to manage and maintain the infrastructure. Another analysis by Tomin et al. (2022) explores the demand flexibility for energy communities but the load profile considered are limited to residential consumers ignoring the benefit of complementary load profiles of non-residential members.

Thirdly, misaligned objectives of existing energy community models. Most researches regarding energy communities are focused on cost reduction or profit maximization Xiong et al., 2020. Therefore, agents are programmed to make decisions inspired by the aforementioned objectives. However, the European Commission (2018) and (J. Lowitzsch et al., 2020) emphasise the non-profit aspect of these energy communities. Thus the agent's goal should be realigned to achieving self-sufficiency in the community and reducing dependence on the grid.

Chapter 3

Research question

Chapter 2 highlighted the knowledge gaps in the recent research around energy communities. In a nutshell, these gaps include exclusion of non-residential members in energy communities, limited exploration of demand response opportunities, not focusing on attaining self-sufficiency within the community. This research envisages bridging these knowledge gaps in the context of the Dutch social-political and technical milieu, by using data from the Netherlands. Thus to address these knowledge gaps, following research question is formulated:

"How does demand response by residential and non-residential community members affect the economic attractiveness of electricity and self-sufficiency in Dutch energy communities?"

Non-residential members refer to SMEs (not trading in energy for profit), Schools, Restaurants and EV charging stations as community members.

3.1 Research approach and sub-questions

The aforementioned research question can be answered by adopting an exploratory modelling approach. The suitability of using an exploratory modelling approach can be explained by the need for a better understanding of the complex transactional behaviour of the energy community. Additionally, no study focused on Dutch community energy projects evaluating the impact of the time-of-use tariff was found during the literature review. Thus, the agent-based modelling approach can facilitate virtual experimentation to compare different outcomes to fulfil the aforementioned purpose.

Following sub-questions are derived to answer the main research question:

1. What are the key social, financial, institutional (policy & regulation) and technical aspects characterizing a Dutch energy community?
2. What are the key uncertainties influencing the decision-making in the Dutch energy communities?
3. How can an ABM reproduce the current real-life behaviour of residential and non-residential community members in the chosen energy community?
4. What effect does a time-of-use tariff have on the grid dependence and energy costs in the modelled energy community? This can be assessed by evaluating the results with no demand response (i.e. base case), demand response from residential only, from non-residential only, and from both.

Chapter 4

Research plan

This chapter sheds light upon the research methodology proposed for answering the research questions mentioned in the chapter 3 followed by a research plan and tentative time schedule.

4.1 Research methodology

Section 3.1 elucidated the choice of exploratory modelling as the preferred research approach. Energy communities are complex socio-technical systems involving multiple stakeholders taking informed decisions and interacting with each other (Dam et al., 2012). Every energy community is unique in its composition and functioning and ABMs can effectively capture the unique characteristics of community members Mihailova et al., 2022. These parameters can be easily tweaked to reproduce the model for a different setting and suggested model validation and calibration tools can be used for ensuring "fit-for-the-purpose". Agent-based modelling involves encoding actors as agents making autonomous decisions based on decision drivers and their previous decisions (Nikolic & Ghorbani, 2011). Agents are assumed to make rational decisions for attaining their personal goal based on the principle of distributed artificial intelligence (Rizk et al., 2018). These agents can not only decide for themselves but also can communicate, coordinate and negotiate with each other (Wooldridge, 2009). Thus, because of this autonomous behaviour of agents in ABM, it is selected over other simulation methods for modelling the socio-technical systems of the energy community. In chapter 2, the literature review further highlights the suitability of agent-based models for studying energy communities. Thus agent-based modelling is selected as the research methodology for implementing the exploratory modelling approach.

4.2 Data requirement

The data required for this research is shown in the figure 4.1 and table 4.1. The model will be primarily built using the open-source data to keep the model open-source and accessible for energy communities across the Netherlands. Using open-source data creates a trade-off between accessibility and quality of data. To fill this gap, high-resolution feeder (neighbourhood electricity bus) level data will be used for model calibration and validation.

Table 4.1: Data requirements

1.	Average household size in the neighbourhood	CBS
2.	Electric car owners by neighbourhood	CBS
3.	Per capita energy consumption in the NL	CBS?
4.	Hourly energy consumption data for residential consumers	DRED
5.	Hourly energy consumption data for Offices	To be determined
6.	Hourly energy consumption data for Restaurants	To be determined
7.	Hourly energy consumption data for School	To be determined
8.	Existing solar, wind and energy storage capacity installed in the energy community	CBS?
9.	Weather data (hourly solar irradiation and wind speed)	KNMI
10.	Hourly electricity pricing data	To be determined
11.	Social, technical, institutional and financial characteristics of community	Expert interviews and survey results of (Koirala et al., 2018)
12.	Existing energy assets (both generation and storage) along with respective generation profiles	Expert interviews
13.	Organizational structure of energy community	Expert interviews

4.3 Research method

The essence of the proposed research methods is captured in the figure 4.1. The entire research can be broken down into four phases as follows:

4.3.1 Phase 1: Information gathering

The information-gathering addresses research sub-questions 1 and 2. To answer these research questions, a combination of literature review and structured interviews with Dutch energy community operators will be performed. Interviews with community grid experts in the Netherlands will be conducted to get information about community energy projects. The outcomes of this exercise will provide deep insights into the functioning of Dutch energy communities and uncertainties influencing their decision-making. During this phase, all the tentative energy community sites and data banks of Croonwolter&dros will be explored. Based on this, a list of community energy projects will be prepared and ranked based on data availability. The site with the most data available will be selected for the project. This will lay the foundation for the next steps in the project.

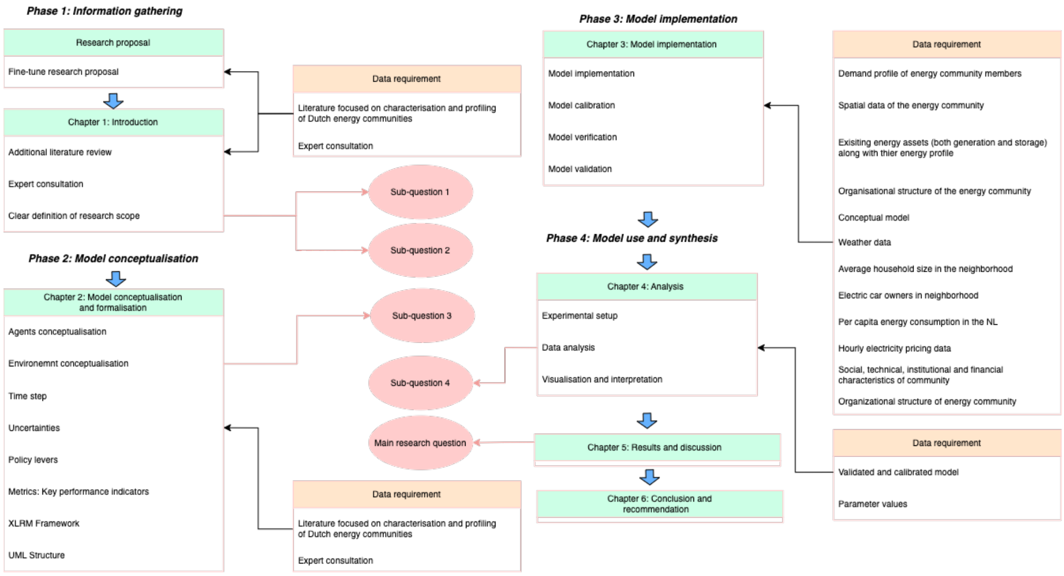


Figure 4.1: Research Plan

4.3.2 Phase 2: Model conceptualisation and formalisation

Based on the inputs of Phase 1, the model environment and agents will be conceptualized. This will be followed by model formalization which involves documentation of the conceptualized model. Modelling frameworks like XLRM and UML structures will be used to capture the conceptualized agent behaviour and model structure (Kwakkel, 2017 and Ambler, 2005). The preliminary vision of the model can be explained through a system story explained below.

System's story: Preliminary model conceptualization

The model will have two agent breeds, community member and community coordinator. The community coordinator is a service provider who provides infrastructure, manages the community and trades energy on the behalf of the energy community. Based on the initial demand data, generation data and solar potential, the community coordinator assess the requirements for the community for attaining self-sufficiency. These requirements could be either Solar PV, Storage or EV charging. The community coordinator will share these requirements with the community members. When the community will become self-reliant, the coordinator will indicate to members that no more capacity addition is required. It is assumed that all the members are already convinced about the potential of the energy community. Every agent can make a choice of investing in renewable assets based on decision drivers suggested by Ghorbani et al. (2020) for energy community members in the Netherlands. These drivers are Environmental concern, Trust, Social Norms, and Personal gain. However, the allocation of these drivers to households is difficult. Therefore, existing consumer surveys will be used to determine the conviction of community members. Figure 4.3 showcases the proposed conceptual agents along with their tentative roles and figure 4.4 depicts the community configuration adapted from the Reis et al. (2020).

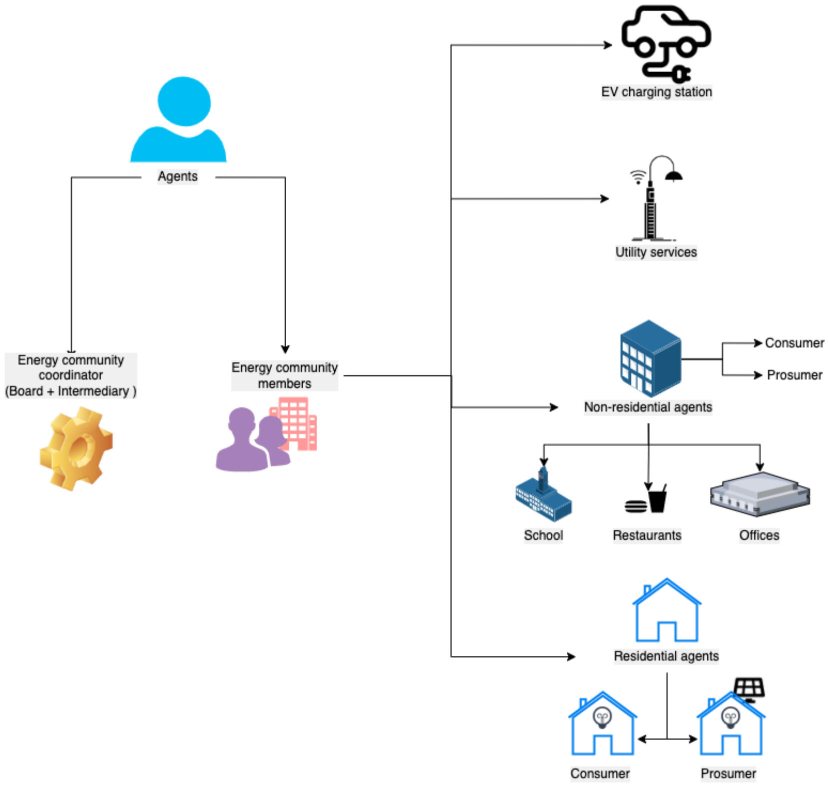


Figure 4.2: Proposed agent types adapted from Reis et al. (2020)

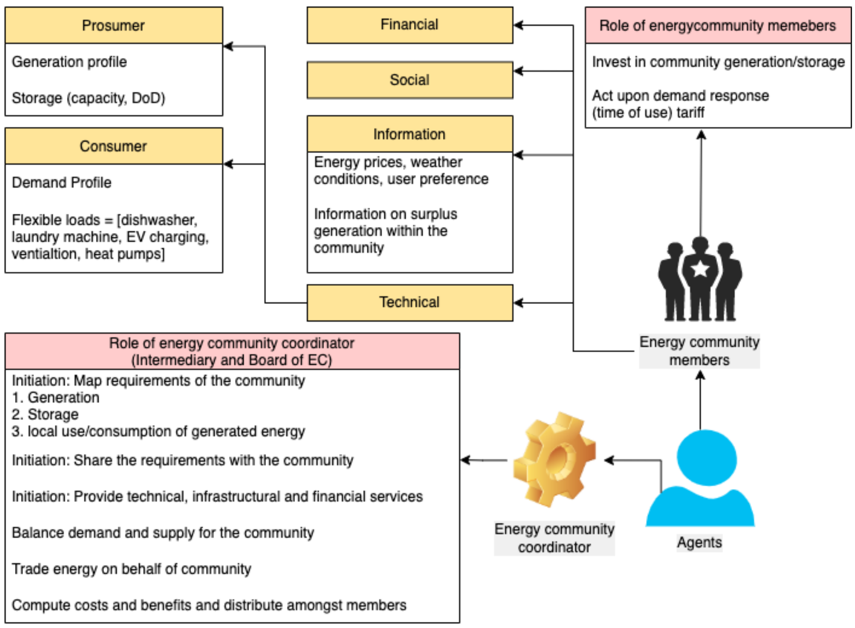


Figure 4.3: Proposed conceptual design of agents adapted from Reis et al. (2020)

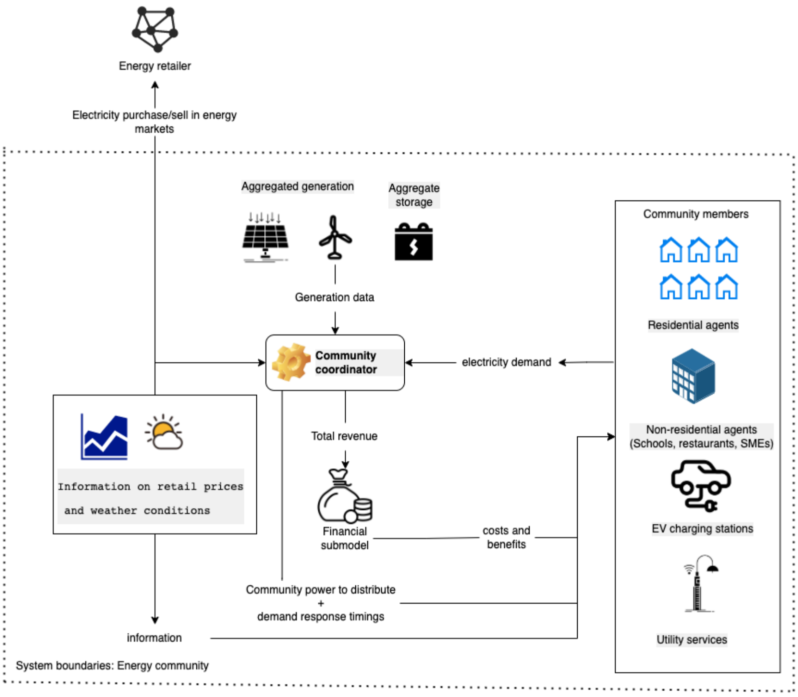


Figure 4.4: Proposed energy community framework adapted from Reis et al. (2020)

4.3.3 Phase 3: Model implementation

After the model conceptualization and formalization, the model will be implemented in python. Mesa, a python based library for agent-based modelling will be used to code the agent interaction and model space. The model will be verified for its structure and behaviour using the verification techniques suggested by Dam et al. (2012). The verification will be carried out by (1) verifying single-agent behaviour, (2) multiple agent interaction in a minimalist model and (3) agent interaction and model mechanisms in the full-fledged model. Post verification, the model will be calibrated and validated. The validation will be done at two levels, macro validation and micro validation. The former will ensure that model behaviour represent the actual system behaviour whereas the latter will validate the agent level behaviour of the model. This step will ensure that the model is fit-for-the-purpose and will help in answering the third research sub-question.

Model metrics

Following metrics (or KPIs) are based on preliminary conceptualization and will be revised based on the expert interviews in phase 1 of this research.

1. Total revenue generation
2. Total generation from renewable assets
3. Total grid imports and exports
4. Number of agents acting upon the time-of-day tariff
5. Battery depreciation

6. electricity cost for the community
7. average electricity costs for residential and non-residential members

Base case

After the above-mentioned set-up of the energy community, a base run will be performed. This base run will represent the standard functioning of the energy community without a time-of-use tariff.

4.3.4 Phase 4: Model use and synthesis

Phase 4 will involve performing experiments to answer sub-question 4.

Experimentation: Enabling demand response

For this experiment, the aforementioned model will be further extended to implement demand response. The community coordinator will assess the energy requirement of different agents and collective generation based on weather data. Based on this, the community coordinator will announce the time of use (ToU) tariff. The agents can choose to act upon ToU based on their decision drivers mentioned above. In addition to this, the robustness of demand response (ToU in this case) can be evaluated by testing the model under different weather and demand scenarios. Thus, the impact of implementing demand response on metrics mentioned in the section 4.3.3 will be evaluated. The results of this experiment will help in answering sub-question 4.

The results of the experiment will be compared with the base case to compare overall energy savings and earnings by each agent group. The outcomes of this study will help in answering the main research question.

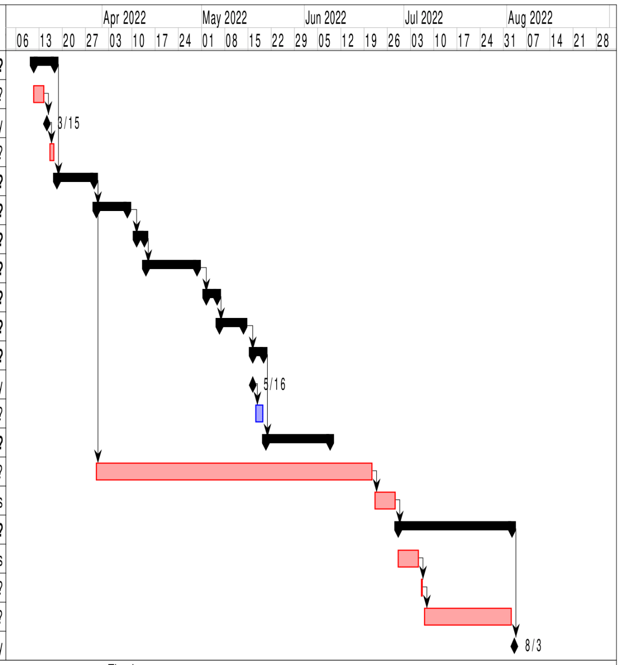
Agent-based models based on complex adaptive systems are path-dependent and highly sensitive to the initial value. Therefore each experiment mentioned above will be performed for multiple runs and aggregated outcomes will be used for the analysis and drawing conclusions.

All the key findings will be assessed and compiled to answer the main research question. the entire process will be summarised in the last chapter and all the key findings and highlights of the research will be elucidated. In addition to this, limitations along with future research recommendations will be discussed.

4.4 Time schedule

The Gantt chart shown in the figure 4.5 showcases the time schedule of activities planned in accordance with the research activities mentioned in the section 4.3. Thesis committee meetings are treated as milestones and therefore are highlighted in the chart. A midterm course correction meeting is proposed after model implementation in addition to the kick-off and green-light meetings.

		Name	Start	Duration
1		**Kickoff**	**3/11/22 8:00 AM**	**5 days?**
2		Preparation for kickoff	3/11/22 8:00 AM	2 days?
3		Kick-off meeting	3/15/22 8:00 AM	1 day
4		Incorporating feedb...	3/16/22 8:00 AM	2 days?
5		**Data gathering and ...**	**3/18/22 8:00 AM**	**8 days?**
9		**Model conceptualisa...**	**3/30/22 8:00 AM**	**8 days?**
14		**Model formalisation**	**4/11/22 8:00 AM**	**3 days?**
17		**Model implementati...**	**4/14/22 8:00 AM**	**12 days?**
20		**Model verification**	**5/2/22 8:00 AM**	**4 days?**
25		**Model validation**	**5/6/22 8:00 AM**	**6 days?**
30		**Mid term**	**5/16/22 8:00 AM**	**4 days?**
31		Mid term meeting	5/16/22 8:00 AM	1 day
32		Incorporate feedback	5/17/22 8:00 AM	3 days?
33		**Experimentation**	**5/20/22 8:00 AM**	**14 days?**
38		Report writing	3/30/22 8:00 AM	60 days?
39		Break	6/22/22 8:00 AM	5 days
40		**Green light**	**6/29/22 8:00 AM**	**25 days?**
41		Green light preparat...	6/29/22 8:00 AM	5 days
42		Green light meeting	7/6/22 8:00 AM	1 day?
43		Incorporate feedback	7/7/22 8:00 AM	19 days?
44		Thesis defence	8/3/22 8:00 AM	1 day



Thesis

Figure 4.5: Gantt Chart - Time schedule for thesis activities
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Appendix A

Appendix: Problem Demarcation

This chapter focuses on the problem demarcation exercise done with Croonwolter&dros to identify the problem for this thesis project. The outcomes of this exercise are further narrowed down to formulate the current research question.

A.1 Means-end Analysis

Following is the means-end tree drawn for demarcation of the problem. This method helps in identifying the end goal and exploring means to achieve it. The proposed intervention with subsequent steps is highlighted in green colour. The inception point of the tree is highlighted with a bold border. In order to reduce bi-directional flow in the distribution network, Holarchical architecture of the grid along with the augmentation of DRE and storage capacity is proposed. The end goal of the proposed intervention is to transition towards a green and sustainable grid. The salient features of the tree are provided in the table beside the tree in figure A.1 and figure A.2.

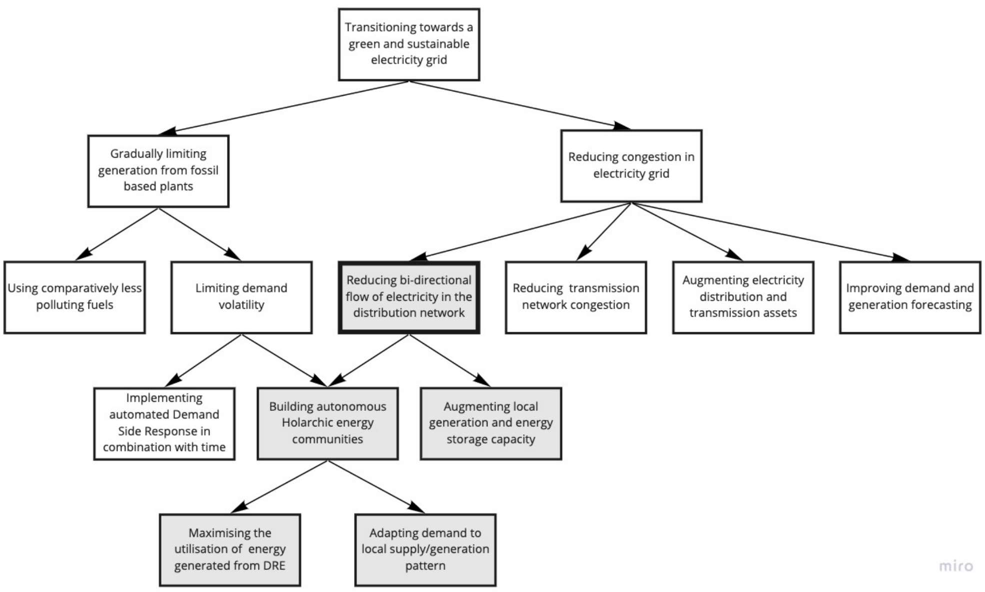

Figure A.1: Means-ends tree

Salient features of means-end analysis

Problem owner	Distribution System Operators (DSOs)
End Goal	Transitioning towards a green and sustainable electricity grid
Selected measure	Reducing bi-directional flow of electricity in the distribution network
Means	**Limitations / Side-effects**
Augmenting local generation and energy storage capacity	• CAPEX costs • Shared ownership of assets • Technical/Legal/Social limitations
Maximising the utilisation of energy generated from DRE	• Getting energy mix from unreliable historical data and weather forecasting • Recovering OPEX costs for prosumers
Adapting demand to local supply/generation pattern	• Managing addition or removal of DRE assets

Figure A.2: Means-ends analysis

A.2 Objectives

Based on the selected means, the following objective tree is drawn. The objectives shown below are derived from the pros and cons of individual means highlighted in the figure A.1. All these objectives are quantified through KPIs (Key Performance Indicators) shown in ovals.

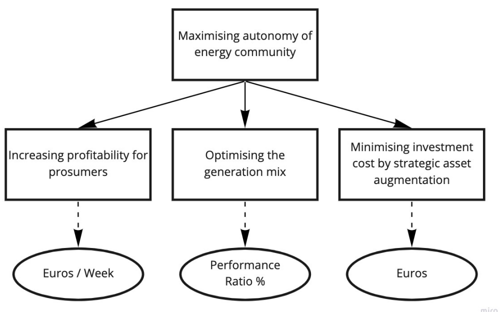

Figure A.3: Objective Tree