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Modelling Energy Security: The Case of Dutch Urban Energy Communities

Javanshir Fouladvand, Deline Verkerk, Igor Nikolic, and Amineh Ghorbani

Abstract Energy communities are gaining momentum in the context of the energy transition. Given the distributed and collective action nature of energy communities, energy security of these local energy systems is more than just security of supply and related to issues such as affordability and acceptability of energy to members of the community. We build an agent-based model of energy communities to explore their security challenges. The security dimensions we consider are availability, affordability, accessibility and acceptability, which are referred to as the 4As. The results confirmed that there is always a trade-off between all four dimensions and that although it is difficult to achieve a high energy security performance, it is feasible. Results also showed that among factors influencing energy security, the investment of the community plays the biggest role.

Keywords Energy security · Energy community · Renewable energy technologies · Agent-based modelling and simulation (ABMS)

1 Introduction

The biggest potential to reduce greenhouse gasses emissions lies in the energy sector [1]. In this line, shifting from centralized energy systems to decentralized renewable energy technologies (RETs), is expected to fundamentally contribute to the goals of energy transition [2]. Therefore, local community initiatives namely energy communities, as one of the possible approaches to enlarge the share of local RETs, are gaining momentum [3].

Community energy systems (CES), contribute to the local generation, distribution and consumption of RETs [4]. Although there are different definitions of CES in

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the literature, a CES can be defined as, "people in a neighbourhood, who invest in RETs jointly and generate the energy they consume." [5]. This definition and other ones in literature (e.g. [6]), all emphasize on collective action of individuals in decision-making processes and actions within CES [7].

A crucial topic to consider for CES, is energy security of these energy system [8]. Energy security is a complex concept [9], and various disciplines such as public policy, economics, and engineering contribute to its definition [10]. There are more than 45 definitions of energy security in the literature [10]. For instance, Asia Pacific Energy Research Center (APERC) definition is: "The ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" [10]. All of these definitions mainly consider conventional energy systems, namely centralized, fossil-fuel-based and national energy systems [10]. However, these definitions are yet to be explored at the community level, to match the unique characteristics of CES such as being based on collective and distributed renewable energy generation.

Thus, in this study we explore energy security of CES, using Agent-Based Modelling (ABM), given the bottom-up, collective nature of these energy systems. Although there are already many existing models of CES (e.g. [4, 11–13]), none have addressed the security of these systems, and as a matter of fact energy security in general. The goal of the model is to explore the impact of various parameters on CES's energy security. The ABM is developed based on the 4As energy security concept [10].

2 4A's Energy Security Concept

Among many definitions of energy security one of the best known and frequently used definitions is the 4As concept proposed by the APERC: availability, accessibility, affordability and acceptability [14]. The 4As definition provides room to capture the collective nature and decentralized characteristic of CES and is therefore selected as the core definition of energy security for this modelling exercise.

Availability is about the physical existence of the energy resources to be used for the energy system [9]. An indicator to measure availability is the domestic energy generation per capita of an energy system (either by fossil or renewable energy) [14]. Another indicator is the shortage percentage, which occur when there is a mismatch in demand–supply and individuals are therefore disconnected from energy supplies [15].

Affordability is related to the costs of the energy system and whether it is affordable or not [14]. Among different indicators of affordability, energy price is the most common [9]. Size of investments made in order to improve energy security [9], is also another affordability indicator in the literature.

Accessibility can be defined as having sufficient access to commercial energy to promote an equal society [14]. Diversification of energy resources is a popular indicator to increase and measure accessibility [9]. Diversity indexes provide a means of quantifying the diversity in energy supply, in order to eliminate supply risks [9]. Multiple integrated diversity indicators are presented in the literature, such as Shannon index [9].

Acceptability refers to the social opinion and public support towards energy sources [9]. This is often linked to societal elements such as welfare, fairness and environmental issues [16]. Although APERC uses an economy's effort to switch away from carbon intensive fuels as an indicator for acceptability [14], carbon content and the CO_2 emission of an energy system as whole are also suggested as indicators for acceptability [9].

3 Research Methods and Data

3.1 Agent-Based Modelling (ABM)

In the limited literature of energy security of CES, optimization is the main approach (e.g. [17]). These studies do not capture the complexities and trade-offs of decision-making processes with regards to energy security. However, as systems are based on collective action of individuals who have different motivations and criteria to make decisions, it is an important aspect to be studied. ABM provides the opportunity to capture these individual behavioral choices and their collective action. ABM also provides the ability to add the time variable, which allows to examine different energy security scenarios. This is important, as individual decisions, the trade-offs related to energy security, and the ability to adopt and learn from each other towards collective energy generation, influence each four dimensions of energy security of CES. The developed ABM in this study is described in details in Sect. 4, using ODD protocol [18].

3.2 Parameterizing Using Dutch Data

Data from Netherlands Environmental Assessment Agency (PBL) and Statistics Netherlands (CBS) are used to parameterize the model. To model the decision-making processes of agents, data from the survey among 599 Dutch citizens about their motivations for joining CES [19] is used which will be further explained in Sects. 4.2. and 4.3. Furthermore, the one-factor at a time (OFAT) approach is used to analyze the sensitivity of model outcomes to various parameter inputs.

4 Model Conceptualization and Implementation

4.1 Modelling Purpose

The purpose of the model is to explore energy security of CES, as collective and distributed RETs.[1] This is done by investigating the impact of various parameters (see Sect. 4.7.) on energy security of such energy systems.

4.2 Entities and State Variables

Households are the only agents in the model. They use the national electricity grid and natural gas before joining a CES. We assume that these agents are in one neighborhood and have already decided to join a CES at the start of the simulation. The attributes of the households are energy demand, budget and internal motivations (that change during the simulation based on their network). Following [5, 19], the motivations taken into account are energy independence, trust, environmental concern and economic benefits, each having a value between 0 to 10 (0 weakest, 10 strongest).

Being a member of CES, the households have three energy choices, namely, (i) collective renewable energy (RE) system (ii) individual RE system, and (iii) national grid. The latter two are selected by individuals, in addition, if the energy provided collectively does not meet their individual demands.

4.3 Interactions, Network and Adaptation

The households are connected using a small world network commonly used in the context of CES (e.g. [11, 20]). In each tick (representing a month), a random agent interacts with one of the other agents in its social network and is influenced by it. If the agent's motivations (i.e. energy independence, trust, environmental concern and economic benefits) are between 2 and 8 (i.e., the values are not extreme and not hard to change [11, 21]), they will be updated leaning one value towards the interacting neighbour's opinion, this being for better or for worse. This form of social interactions is used at the beginning of each simulation step to update the motivations for each agent. These connections eventually lead to the whole community making a decision about their CES.

[1] The model is available in CoMSES Net: https://www.comses.net/codebase-release/53329335-a5cc-48c3-bfe6-f19dad2f8694/

4.4 Model Initialization and Narrative

Before the initiation of CES, the household agents used natural gas and national electricity grid to cover their demand. In order to make the decision on different sources of energy (i.e. collective RETs, individual RETs, national grid) for the CES, the households first go through a period of opinion exchange, which means connected individual households learn more about their neighbours' motivations and possibly grow more towards each other. This is based on social interactions that are presented in Sect. 4.3. After the period of opinion exchange, agents have three decisions to make, namely: (i) Choosing the percentage of RE that they want to generate collectively together, (ii) Choosing an additional individual option, in case the collective RE generation does not fully cover the demand, and (iii) After the technology reaches its lifetime, involving new participants and deciding on continuing participation and new CES.

First, the households make a decision on choosing how much collective RE they want to generate which may not always cover all the needed demand collectively, i.e., the households choose an amount of RE (for this study solar photovoltaic (PV) and ground-source heat pump, see Sect. 4.5.) that covers a fraction between 10% and 100% of community demand. More environmental friendly households choose higher collective RE generation. The constrain, however, is in the initial investment, as higher collective RE generation, needs higher investment. Each agent will make a decision about its preferred collective RE, and the amount which is chosen the most among agents, is the one for the whole community.

When the chosen collective energy generation doesn't fully cover all the community demand, the households depending on their individual motivations, have three options: (i) choosing individual RETs, (ii) compensate their energy demand (i.e. lowering the demand and facing discomfort), or (ii) import energy from the grid (i.e. continue to consume natural gas and national electricity grid). The money which is saved due to lowering the demand (as households consume less, they pay less), will be saved overtime and will be invested on individual RETs. This is the option that most environmental friendly agents, who do not have the required budget yet, choose.

Every year (12 ticks in the simulation), the community checks (i) whether they have reached the end of their project time-horizon (i.e. 55 years), (ii) whether the technologies in place have reached their lifetime. If the technologies have reached their lifetime, the community will start another information exchange period including new members (i.e. new households who moved to the neighbourhood) and making decision on choosing a new configuration (i.e. 10% - 100% collective energy). As the new households have their own motivations, energy demand and investment, the new collective energy generation might be different. When the community chooses the new amount, the households who have a different preference over the new amount, leave the community system, which means they are disconnected from the CES (i.e. they connect fully to national grid or get their energy demand elsewhere). Figure 1 presents the model conceptual flowchart.

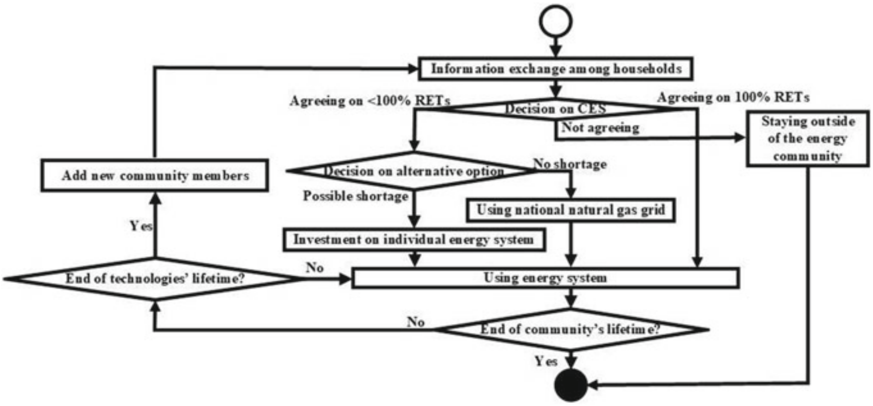

Fig. 1 Model conceptual flowchart

4.5 Technical Assumptions and Model Inputs

The technological option that households can choose for both collective and for individual energy systems, are solar photovoltaic (PV) and ground-source heat pumps. Two reasons account for this selection: solar PV is a mature technology and it is the main technology that the majority of current CES are using [22]. Heat pumps will be used for the reason that they offer a good combination with solar PV, to prepare for the transition towards an electricity based heating systems [23].

Households have three available energy options: (i) national grid, (ii) collective solar PV and heat pump, (iii) individual solar PV and heat pump. Table 1 presents the parameters related to these technologies. Overall, the efficiency of the system in this study is considered 0.85% [24], carbon emissions assumed as 0.46 (kg/kWh) [25], technologies' costs are based on [26, 27], and average available sun radiation for the Netherlands is 4.38 (hours/day).

4.6 4As as Key Performance Indicators (KPIs)

Availability: Average voluntary discomfort percentage: To assess availability, a measure is used that indicates to what extent the energy is available to meet the demand of each agent [31], which for our modelling exercise is translated as Eq. 1:

$$Availability = 100\% - average\ voluntary\ discomfort\ percentage \quad (1)$$

To calculate average voluntary discomfort, considering the current demand, the percentage of collective and individual RE generation in CES (i.e. total RE), the baseline, and the average willingness to compensate (i.e. the average percentage of

Table 1 Model's input

Input	Value (unit)	References
Number of households in a neighbourhood	500 n	[28]
Interacting connections per household	13 n	[13]
Electricity price	0.20 (€/kWh)	[29]
Duration of information exchange period[a]	7 (months)	
Project time-horizon[a]	55 (years)	[30]
Minimum investment size[a]	1 (kw)	[30]
Baseline energy (always be covered)[a], [b]	10 (%)	
% new households[a]	20 (%)	

[a]For the value of this assumption, OFAT sensitivity analysis is performed, as it is not the focus of the modelling exercise
[b]The energy demand which is crucial to be always provided and never will be compensated

the all agents are willing to avoid using national grid, see Sect. 4.7.), are subtracted (Eq. 2).

$$\begin{aligned} &Average\, voluntary\, shoratge\, percentage(\%) = (100\% - total\ RE(\%) \\ &-baseline\, energy(\%) - average\, williwgness\, to\, compensate(\%)) \end{aligned} \tag{2}$$

Affordability: Average costs: To assess affordability, a measure is used that calculates the total system costs per agent [31], which is implemented as (Eq. 3):

$$Average\ costs\ (€) = \frac{\left(\begin{array}{c} Investment\ costs\ scenario(€)+ \\ Costs\ energy\ import\ (€) + Investment\ new\ community\ members\ (€) \end{array}\right)}{Participating\ households} \tag{3}$$

Accessibility: Diversity index: Based on Shannon index [31], diversification is used to measure the accessibility of a CES as presented in Eq. 4.

$$\begin{aligned} &Diversityindex = -1 * ((choosen.collectiveRE * \ln choosen.collectiveRE) \\ &+(choosen.individualRE * \ln choosen.individualRE)+ \\ &(choosen.nationalgrid * \ln choosen.nationalgrid)) \end{aligned} \tag{4}$$

Acceptability: **CO_2 reduction per household**: As acceptability is linked to environmental issues and reducing CO_2 emissions of the energy sector [9], to assess acceptability, CO_2 reduction is measured in the model as presented in Eq. 5:

$$Carbon\ reduction(kg\ CO2) = \frac{\begin{pmatrix} Carbon\ emission\ of\ the\ traditional\ energy\ sysytem\ (kg\ CO2) - \\ Carbon\ emission\ of\ the\ community\ energy\ system\ (kg\ CO2) \end{pmatrix}}{Participating\ households} \quad (5)$$

4.7 Model Parameters and Experimental Setup

To explore the energy security of CES, four parameters are selected from the literature that are potentially influential for energy security:

- **Demand of the households:** Since one of the primary motivations of CES is to generate energy to meet the local demand [7], energy demand is important for a CES. Following [16, 32], we hypothesize that lowering the energy demand helps to enhance energy availability and therefore energy security.
- **Budget of households:** Investment-size plays a large role in CES [5]. At the same time higher investments can play a major role in increasing availability and affordability and therefore security of an energy system [9].
- **Energy prices:** Rising energy prices is argued as an effective strategy to lower energy consumption and an opportunity for deployment of CES in the literature [22]. In the energy security literature, it is argued that higher energy costs, result in lower affordability and therefore lower energy security [16, 32].
- **Willingness to compensate over use of energy grid:** According to the participatory value evaluation theory, people are willing to accept changes in the provision of public goods [33]. Willingness to compensate has also been explored in the energy security literature as important for the 4As' dimensions [33].

We use these four parameters, as input to our modelling exercise. Using data from PBL, the average households demand and natural gas price were extracted. The experimentation include a total number of 108 different combinations of settings for the four parameters (4*3*3*3 = 108), as shown in Table 2. Each combination was repeated 100 times hence, the experimentation resulted in a total number of 10,800 runs.

Table 2 Experimental settings

Model parameter	Value
Each household demand (kWh/year)	8185, 15,161, 22,622, 30,084
Natural gas price (€/kWh)	0.09, 0.12, 0.15
Willingness to compensate (%)	10, 20, 30
Budgets/ Investment-size (€)	2500, 5000, 7500

5 Results

5.1 *Overview of Each KPI Individually*

In this stage results for the final end-state of each run (i.e. in 55 years) for each KPI are presented separately. In Fig. 2 the results are categorized into the three categories:

- Best results: the best 10% of runs for each specific KPI (green colour);
- Worst results: the worst 10% of all runs for each specific KPI (red colour);
- Others: remaining 80% of the runs (grey colour)

KPI 1: Average voluntary discomfort percentage: The simulation results for average voluntary discomfort (shortage) percentage are always less than 20%. Only 10% of the runs have a discomfort percentage higher than 9%. These runs include communities with the most environmental friendly behavior but not financially strong enough to have 100% CES. Therefore, for the demand that they do not meet with

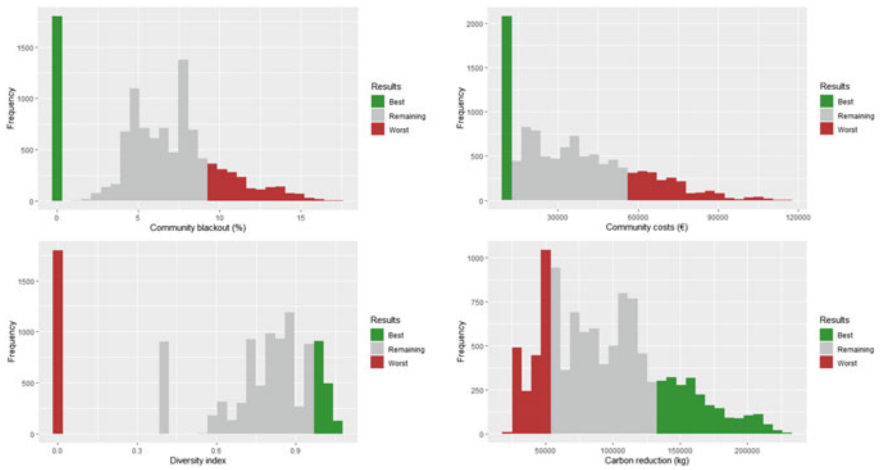

Fig. 2 Overview of KPIs

the collective energy, they voluntarily chose discomfort, instead of the national grid. There is a large peak in the 0% discomfort, which is mostly for runs that chose 100% CES. These communities are also the most environmental friendly communities, but with strong financial resources. The majority of the simulation runs, however, are in the middle range of the discomfort percentage, between 4 and 9%. Lower demand, higher energy generation and higher energy import lead to best performance of this KPI. While higher budget showed positive influence, natural gas price and compensation were not impactful.

KPI 2: Average costs: Average costs are calculated for each household, based on the cost of community in its life time (i.e. 55 years) divided by number of households. As Fig. 2 illustrates, the majority of runs have low costs. Considering the assumptions related to current and future energy prices, 75% of all runs have better economic performance than using only grid. This means individual households who participate in a CES, spend less money over 55 years on their energy bills. All the communities with the lowest costs, are communities with lowest demand. However, this does not necessarily mean that they have higher investment as they have various investment sizes. Higher import dependence (higher energy import form outside of system boundaries) usually is more likely to lead to lower cost. Natural gas price, willingness to compensate and energy generation did not show a meaningful influence on KPI 2. Also, environmental friendly agents are distributed within all of the communities, however, their population is more condense within communities on average and lower costs.

KPI 3: Diversity index: This is an indicator to measure the diversity of energy sources in a CES. There is a peak at 0 which shows the dominance of a specific energy source, e.g. collective Solar PV. These communities are communities which choose 100% collective energy and they also have low energy demand. The majority of the runs, however, have a diversity index between 0.6 and 0.9, which means they have both RE (with different generation capacity 10–100%) and natural gas as their energy source. The runs with diversity index higher than 0.9 have various parameters settings (see Sect. 4.5.), but the high willingness to compensate is high among them.

KPI 4: Carbon reduction index: The carbon reduction index measures the average CO_2 reduction of each CES participant through its life time (i.e. 55 years). As the communities at least have to choose 10% RE generation, the carbon reduction is always more than 0, see Fig. 2. The best performance for this indicator is for communities with CO_2 reduction higher than 130.000 kg, which mostly have high budgets and environmental friendly motivation. However, they have various demands, difference in natural gas prices and different “willingness to compensate” values. The communities with lowest CO_2 reduction have the lowest budget.

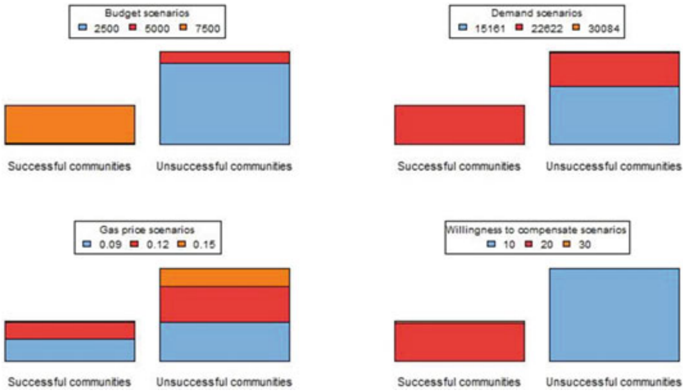

Fig. 3 Parameters for most and least successful energy security performances

5.2 Most and Least Successful Energy Security Performances Based on All 4 KPIs

In this part, the communities with the best and worst overall performances are analyzed. The procedure to define these energy security performances is as follow:

- **Most successful performances**: From the 10,800 model runs, for each KPI the 50% best performances are extracted separately. This gives us for each KPI, 5400 runs that have performed the best. Within these four sets of 5400 runs, the overlapping runs are selected, which are only 197 model runs in total. These 197 runs are the runs that have the best performances for all the KPIs.
- **Unsuccessful performances**: Through the same process, 50% of worst performances are selected separately for each KPI and then the overlaps are extracted leading to 458 runs.

Consequently, the values of the four parameters for the most successful and least successful were more closely studied. For the budget and willingness to compensate, a clear division was identified between the successful and unsuccessful communities. The 197 successful runs are dominated by highest budget and average willingness to compensate. On the other hand, unsuccessful performances have the lowest budgets and lowest willingness to compensate. Natural gas price varies for both successful and unsuccessful energy security performances. However, successful performances do not have the highest natural gas price. Figure 3, illustrates these findings.

6 Discussion

We used the 4A's energy security concept [14] to conceptualize energy security of community energy systems (CES). Considering one KPI at a time, CES are able to perform well for each one. Specifically, 10% of CES had 0% discomfort (as an indicator for availability), and on average all CES reduced their CO_2 emission by 35% (as an indicator for acceptability). For the average cost of households (as an indicator for affordability) CES also performed considerably well. On average the costs per household is around €45,000 over 55 years, which is less in comparison with current energy prices. Considering the initial investment-size (see Table 2), this shows in overall that CES are economically feasible under the suggested parameter settings of this research. There are still communities with average cost of €70,000 per household, which highlights the economic challenges as studies such as [34] also mentioned.

Diversity (as an indicator for accessibility) showed various values between 0 and 1. The runs with 0 value in diversity, are the communities with 100% collective RE generation (and not 100% individual or 100% national grid). The runs that used all three possible energy resources (i.e. collective RE, individual RE and the national grid), are the ones with relatively high performance in diversity index, which shows these communities have agents with different motivations (see Sects. 4.2. and 4.3.).

However, energy security is a multi-dimensional concept, which means that all the dimensions should be considered and analyzed simultaneously. In order to draw the whole picture and provide an analysis of four dimensions together, we analyzed the communities with successful and unsuccessful energy security performances. Our analysis delineated that there are always trade-offs between the four dimensions, as among 10,800 runs only 197 (less than 2% of all runs) have a performance that is considered successful in all four KPIs (i.e., > 50%). On the other hand, the portion of unsuccessful performances (i.e. < 50% in all four KPIs) are two times higher (458 runs out of 10800, 4.2% of total runs). Although it is rare to have high performance for all four dimensions at the same time, these successful performances showed that it is feasible to reduce CO_2 emission while not facing any discomfort and financial consequences.

In order to analyze the four input parameters (i.e. demand, investment-size, willingness to compensate and prices), comparison between successful and unsuccessful energy security performances (i.e. four KPIs together) was performed. This comparison indicates which parameter leads to a better performance. The only parameter which explicitly indicated an impact on successful vs. unsuccessful performances is the budget. The successful performances have the highest budget (€7500) and unsuccessful ones are dominated by the lowest budget (€2500). Willingness to compensate and demand, however, do not indicate a strong impact on success performance. For instance, the lowest demand (i.e. 15,161 kWh) is the dominating demand parameter value among the unsuccessful performances. This is in contrast to the current body of literature which argues less demand leads to a better performance in energy security [16, 32]. Lastly, natural gas prices did not show considerable influence on energy security of CES as the unsuccessful performances have the full range of natural gas prices and the successful ones have 0.09 and 0.12 €/kWh.

7 Conclusion and Further Work

As key elements of energy transition at the local level, the CES's body of literature is growing rapidly. Yet, little attention is given to energy security of CES and the need to understand what energy security actually implies for them is becoming more vivid. Therefore, this research aimed to study energy security of CES through an agent-based modelling approach, using the 4A's energy security concept [14].

The results showed that each KPI can be individually high in performance in a CES, specifically shortage percentage and CO_2 emissions reduction. However, it is hard to reach a community state in which all four dimensions are satisfied. This highlights the difficulty, but still the feasibility to achieve a high energy security performance for CES. Among the four parameters, only the budget seemed influential. Willingness to compensate, demand ranges and energy prices did not show considerable influence. These can be translated to policy recommendations for Dutch policy-makers as:

- The budget is the most important consideration for establishing secured CES, as it can be a constrain for environmental friendly households and a concern for economically driven households. Therefore, providing more support (e.g. subsidies and loans) is effective and essential.
- Energy demand is not the most influential consideration for energy security of collective energy systems. Therefore, other policies and strategies such as RE subsidies could potentially have more impact on collective energy security, than energy demand reduction policies. Nevertheless, the households with relatively high energy demand need to reduce their demand, in order to contribute in long-term security and environmental targets [35].
- The current PBL energy price scenario (0.12 €/kWh) is a successful scenario, as higher energy prices do not lead to successful performances and no significant influence of energy prices were identified.

Although the current study sheds lights on the energy security of CES, it is still more of a conceptual model. There are certain limitations, such as the chosen energy security concept, indicators and technologies within the model. Also, using theories such as social value orientation theory and planned behavior could have led to insights regarding the influence of households' motivations on energy security.

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