Environmental and Climate Technologies
2022, vol. 26, no. 1, pp. 606–615
https://doi.org/10.2478/rtuect-2022-0046
https://content.sciendo.com

Energy Community Measures Evaluation via Differential Evolution Optimization

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***Abstract* – Energy communities are paving the way for new cooperation opportunities related to energy consumption and energy production. Individuals unite in energy communities to reduce the costs related to energy consumption. Although previous work has mainly focused on energy exchange inside the community. This work aims to investigate the Pareto-optimal solutions to the transformation of a historical district into an energy community. For energy efficiency and production measure calculation, a system dynamics model is developed. Multi-objective differential evolution optimization method is employed for the evaluation of energy efficiency and production measures with a focus on net present value, self-sufficiency, annual emission reduction, and specific heat consumption. The optimization target functions can be increased at a cost in net present value. Replacement of household appliances and windows enables significant energy demand reductions while maintaining positive net present value. Electricity production from photovoltaic panels offers an additional pathway to increase self-sufficiency share while maintaining positive net present value.**

***Keywords* – Clean energy; energy efficiency; multi-objective; pareto-optimal; thermal storage; renewable energy; sustainability**

1. INTRODUCTION

1.1. The Essence of Energy Communities

Energy communities are associations voluntary established by citizens with a common interest in implementing energy efficiency measures and introducing renewable energy sources to reduce their consumption, and energy costs, and increase self-sufficiency [1]. Establishing these communities can alleviate energy poverty and empower citizens to become prosumers [2].

Energy communities make it easier to attract private investments in renewable energy production, provide flexibility with demand-response and storage technologies, and increase public acceptance of such projects [3]. Mentioned possibilities follow the 'Clean Energy for all Europeans package' policy framework to move away from fossil fuels toward cleaner energy [4]. The transition contributes to the reduction of greenhouse gas emissions, as of the current situation buildings are responsible for 40 % of EU energy consumption and 36 % of the energy-related GHG emissions, and 75 % of buildings are not energy efficient [5].

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1.2. Modelling Application in Energy Communities

Various models have been developed to assess the potential of energy communities. The pool trading model considering home energy management systems within the energy community can decrease end-user costs by 16.63 % [6]. Energy communities allow prosumers to exchange the energy produced locally and reduce the need for external energy sources [7]. Shared renewable energy generation can provide greater self-consumption shares to the aggregated load of a building [8]. These are only a few examples of available studies on the energy community modelling. Mainly studies focus on electricity production and exchange in the energy community. The topics included are – rooftop photovoltaic panels (PV), battery electricity storage, demand side management, time of use tariffs, etc., [9]–[14]. The energy community studies focus on single-objective or multi-objective optimization inside the community through introduction of energy exchanges. However, it is not investigated how various combinations energy community measures go hand in hand through multiple objectives.

This study aims to determine optimal solutions from a heat and electricity demand perspective for energy communities based on self-sufficiency share, net present value, specific heat consumption, and emission reduction percentage after implementing energy efficiency, energy production, and energy storage technologies. A system dynamics model of monthly demand and supply of energy flows has been developed for this analysis. The model allows exploring energy efficiency measures, on-site renewable energy production, and thermal energy storage potential in energy communities. The multi-objective differential evolution optimization method is applied for the evaluation of Pareto-optimal solutions.

2. MATERIALS AND METHODS

Fig. 1 shows the overall research framework of this study. Scientific publications on energy communities and their current modelling trends are reviewed. The energy community system dynamics model is developed that evaluates energy efficiency, energy production, and energy storage measures. Additionally, the model uses input data such as weather, electricity consumption profile, building envelope areas, and thermal resistances. In this model energy consumption is evaluated before and after the implementation of measures. A multi-objective differential evolution optimization method is applied to the energy community model to find the optimal solutions between net present value and energy self-sufficiency, specific heat consumption, and percentage emission reduction. Following the Pareto-optimal solution curve recommendations are provided for the implementation of energy efficiency, energy production, and energy storage measures.

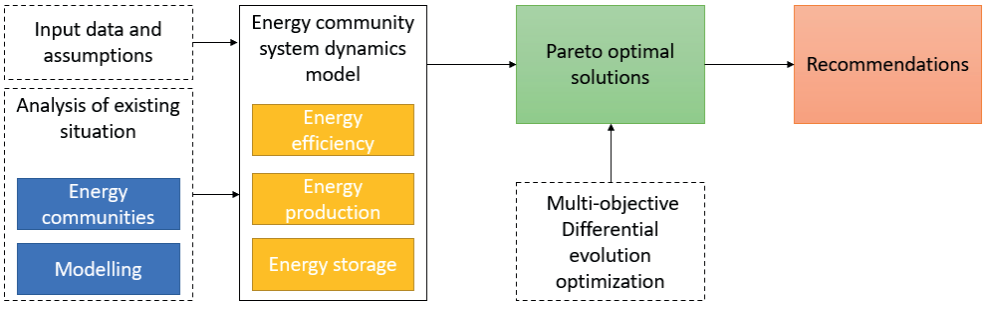


Fig. 1. Research framework.

2.1. System Dynamics

System dynamics is a powerful computational tool to model complex and dynamic processes. The system dynamics approach is based on studying the change in behaviour of a system and the underlying structure underlying the behaviour. The structural analysis of the system and the interlinkages of the system components offer a better understanding of the system [15]. Stocks and flows are building blocks of system dynamics models [16]. A modelling software Stella® Architect [17] was used for model development.

2.2. Energy Community System Dynamics Model

The generic model framework consists of 3 interrelated sectors – energy demand, renewable energy production, and thermal storage. The developed model structure is applied to all buildings in the energy community. These sectors are interrelated by weather data, heating demand, and electricity demand. Measures can be applied to develop well-being and sustainability in the energy community. In what follows we will discuss these sectors in some detail. The community [18] is composed of 17 buildings. The general characteristic of the community is given in Table 1. The building parameters include building envelope areas (A), thermal resistance (R), heat loss coefficient (H_c), and the number of floors in the building (F).

TABLE 1. BUILDING PARAMETERS USED IN THE MODEL

Building envelope	Variable	Minimum	Maximum	Mean
Walls	A, m^2	373	2874	1179
	R, m^2·K/W	1	1	1
	H_c, W/K	373	2874	1179
Windows	A, m^2	33	1300	314
	R, m^2·K/W	0.36	0.59	0.42
	H_c, W/K	16.5	3510	320
Basement	A, m^2	185	1700	563
	R, m^2·K/W	0.70	1.67	1.32
	H_c, W/K	110.63	2431	425
Roof	A, m^2	185	1700	563
	R, m^2·K/W	2.13	4.78	3.30
	H_c, W/K	38.	799	171
Living space	A, m^2	558	7276	2125
Floors	F, unitless	1	5	3.41

2.2.1. Energy Efficiency Module

Initially, the energy efficiency module calculates building thermal losses based on heat loss coefficients and the difference between the set point of desired building inner temperature of 20 °C, and the outside temperature, the calculations also include inner heat gains and solar heat gains. The heat loss coefficient can be reduced by applying insulation measures resulting in reduced heating energy consumption and reduced annual heating expenses.

The energy efficiency of electrical appliances and user behaviour mainly affect the electricity consumption of a building. Cooling appliances can significantly increase electricity requirement during summer months, similarly, electrical individual heating appliances increase electricity consumption during the heating season to reach desired room temperature. Initially, the historical electricity consumption of the buildings is taken and re-calculated after applying energy efficiency measures. The area used in this study contains a

large data centre resulting in an increased annual electricity consumption share of 48 % compared to other residential areas [19].

2.2.2. Renewable Energy Production Module

As solar photovoltaics (PV) become a more popular renewable energy production option in the residential sector, energy communities can provide a substantial share of clean and renewable energy production [6]. Following renewable electricity, production options are considered in this study PV, and a photovoltaic-thermal hybrid system (PVT) [20]. Wind energy was not considered in this work due to technical and regulatory challenges related to the use of wind turbines in an urban/suburban setting.

Building rooftops, especially in cities, offer an opportunity for energy communities for decentralized energy production via solar technologies. The total available rooftop in the community is 9569 m^2. It is assumed that 450 W monocrystalline solar panels are used [21]. The panel efficiency is 22.2 %. A fully covered rooftop area would allow a total of 2120 kW installed capacity. Additionally, inverters are used [22]. During the low electricity consumption times and high solar production, the voltage on the inverter outlets increases. Eventually, when it reaches the maximum permissible value, the inverter switches off. Interaction between the solar energy produced and the inverter must result in the least possible switch-off periods. As every invertor switch off decreases the electricity production financial benefits [23].

It is assumed that the community uses the NET settlement system. NET settlement system allows prosumers to reduce their electricity bills and deliver electricity to the grid. In moments when electricity production exceeds electricity demand, surplus electricity is delivered to the grid. Electricity delivered to the grid acts as stock and is accumulated. Electricity is taken from the stock when the renewable electricity production is below the electricity demand [24]. Each interaction with the network results in different end-user electricity costs shown in Table 2.

TABLE 2. INTERACTION WITH THE NETWORK AND RESULTING COMPONENT INCLUDED IN THE FINAL ELECTRICITY PRICE

Electricity source	**Electricity tariff**	**Mandatory procurement component**		**Distribution and transmission operator services**	
		Variable cost	Fixed cost	Variable cost	Fixed cost
Demand is covered by renewables			x		x
Demand is covered within savings			x	x	x
Demand is covered from grid	x	x	x	x	x

2.2.3. The Thermal Energy Storage Module

Photovoltaic-thermal hybrid solar systems produce most of the heat in summer periods when heat demand is required for water heating, and the lowest production occurs during winter months when buildings require heat to maintain the indoor temperature of the building. Therefore, seasonal thermal energy storage is added to increase the use of renewable energy and increase self-consumption share in the community. It is assumed that thermal storage is located underground.

The thermal energy system depends on the available incoming heat supply from PVT and heat pump capacity. Incoming heat from PVT is consumed instantaneously and excess

production is stored in buffer tank storage. Based on heat pump capacity and available thermal storage volume the excess incoming heat is transferred to seasonal thermal storage. Heat is delivered from thermal storage to buildings in periods when PVT cannot supply the current heat demand. The produced energy is stored during summer and used for heating during the winter period.

2.3. Multi-Objective Different Evolution Optimization

Optimization means to find the single (and global) minimal or maximal value of an objective function defined over some search space [25]. The differential evolution (DE) optimization method was used, which is a population-based evolutionary method for real-valued global optimization that creates new solutions using rapidly computed differences in existing solutions, i.e., mutation [26]. The mutation operation 'DE/rand/1' has been selected for this study [27]. DE operates by combining existing solutions with weighted difference vectors from other solutions, i.e., crossover. Weighted differences in existing solutions allow DE to automatically adapt its step size and its orientation as convergence occurs, shifting from exploration to exploitation method, i.e., selection [26]. It tends to converge faster to the global optimum than other real-valued optimization methods [28].

Most real-world problems involve simultaneous optimization of several objective functions that are measured in different units and are often competing and conflicting [29]. Multi-objective optimization having such conflicting objective functions gives rise to a set of optimal solutions, instead of one optimal solution because no solution can be better than any other concerning all objectives, also called Pareto-optimal solutions [30]. The non-dominated sorting approach is applied. To sort a population each solution must be compared with every other solution in the population to find if it is dominated [31]. In case the selected solution is not dominated by any other solutions, it is moved to the first front [32]. All solutions in the first front form a non-dominated set and are Pareto-optimal solutions.

For optimization following measures have been selected given in Table 3.

TABLE 3. ENERGY EFFICIENCY, ENERGY PRODUCTION, AND THERMAL STORAGE MEASURE VARIABLES USED IN OPTIMIZATION

Measure	Measurement unit	Minimum value	Maximum value	Increment
Wall insulation thickness	m	0	0.25	0.01
Roof insulation thickness	m	0	0.4	0.01
Basement insulation thickness	m	0	0.15	0.01
Replacement of electrical equipment	%	0	100	1
Heat pump capacity	kW	0	200	1
The rooftop area used for production	%	0	100	1
Photovoltaics share of rooftop area*	%	0	100	1
Buffer tank volume	m^3	0	100	1
Thermal storage volume	m^3	0	500	1
Inverter capacity	kW	0	250	1
Window replacement	%	0	100	1

*Photovoltaic share of rooftop also indicates the PVT share of the rooftop area. A 75 % photovoltaics share equals a 25 % PVT share.

Energy efficiency measures include insulation thickness for building envelopes and window replacement. It is assumed that Rockwool insulation is used with a heat transfer coefficient

of 0.035 W/(m·K) [33]. Windows are replaced with polyvinyl chloride (PVC) windows with a U-Value of 0.7 W/(m^2·K) [34]. Energy production measures are focused on available rooftop areas including the share of total rooftop area used and the share of PV and PVT panels on the rooftop. Inverter capacity for electricity production is also included. For the buffer tank, a maximum volume of 100 m^3 [35] has been selected and it acts as low-temperature heat storage. The capacity of the heat pump [36] determines how much heat can be transferred from the buffer tank to the main thermal energy storage and supplied to the community. The thermal energy storage volume has been restricted to 500 m^3.

Optimizations were made for two variables at a time. For this algorithm a population size of 200, and 100 generations have been chosen at scaling factor of 0.6, and crossover probability of 0.2, this combination was found to be optimal for convergence during optimization tests.

Following objective functions have been chosen – net present value with an economic lifetime of 20 years and an interest rate of 7 %, the net present value shown in results is at the end of the economic lifetime, self-sufficiency share, specific heat consumption, and emission reduction share. All the output variables are minimized except the net present value and Pareto-optimal sets are found by optimizing two output variables at a time. The combinations considered are – net present value and self-sufficiency share, net present value and specific heat consumption, and net present value and emission reduction share.

3. RESULTS

In Fig. 2 the interaction between net present value and self-sufficiency share. The following measures are provided by the optimization algorithm. The largest net present value is gained from window replacement and replacement of electrical equipment. Both measures do not provide energy production therefore there is no change in self-sufficiency share.

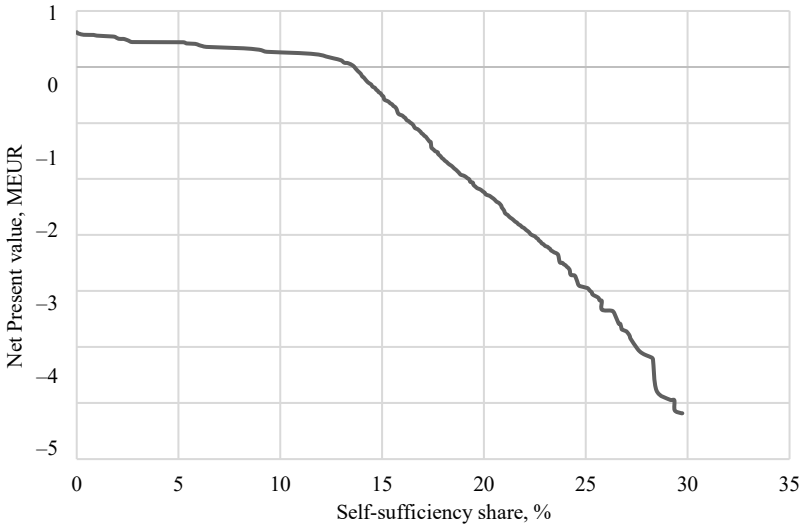


Fig. 2. Pareto optimal solutions in terms of net present value and self-sufficiency share.

By introducing energy production measures self-sufficiency share starts to increase at a cost in net present value. While maintaining positive net present value combinations of the

following measures are considered – PV and PVT use, replacement of electrical equipment, and replacement of windows. As storage volume is increasing more powerful heat pumps are required to supply the heat to the community. The breakpoint occurs at a self-sufficiency share of 13 %. After the breaking point, building insulation measures are included and the available rooftop area is fully covered with PV. As self-sufficiency share increases less PV capacity is installed and the focus shifts on PVT installation to cover electricity and heat demand. To maintain a positive net present value a PV share in the range of 90–100 % of the available rooftop area is required. The largest net present value has been found at 622 thousand Euros and the largest self-sufficiency share is 29.74 %.

Optimizing net present value and specific heat consumption in Fig. 3 gives similar results for net present compared to previous optimization results described above. Although, in this optimization scenario, energy production, and energy storage measures are not provided in the non-dominated solution set.

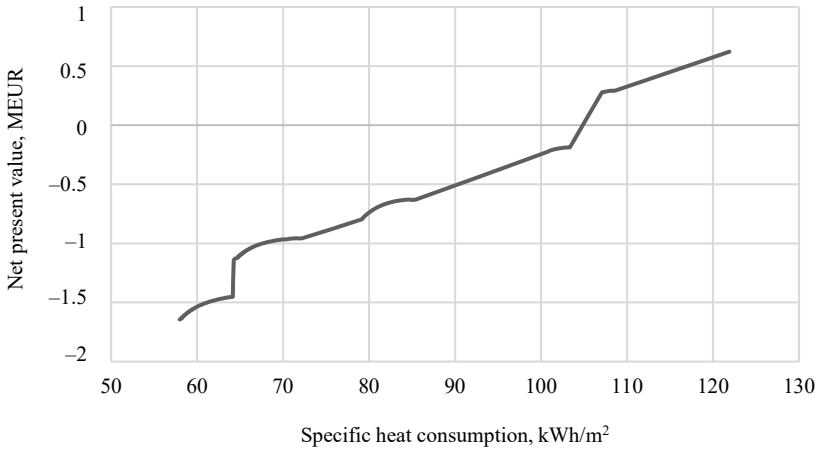


Fig. 3. Pareto-optimal solutions in terms of net present value and specific heat consumption.

The decrease in specific heat consumption at a cost in net present value is provided by energy efficiency policies. Mainly window replacement and base insulation with a thickness of 10–15 cm while maintaining a positive net present value. To decrease specific heat consumption even more roof insulation is required ranging from 22–40 cm in thickness is added. After the specific heat consumption reaches a value of 100 kWh/m^2 combinations of wall insulation and roof are included while maintaining a basement insulation thickness of 15 cm.

Optimization between maximizing the net present value and minimizing emission decrease percentage in Fig. 4 results in similar measures related to net present value and self-sufficiency share optimization. Replacement of electrical equipment and windows could decrease emissions by up to 18 % in the community. Applying thermal storage, energy production measures, and building envelope insulation measures could reduce emissions by up to 57 %.

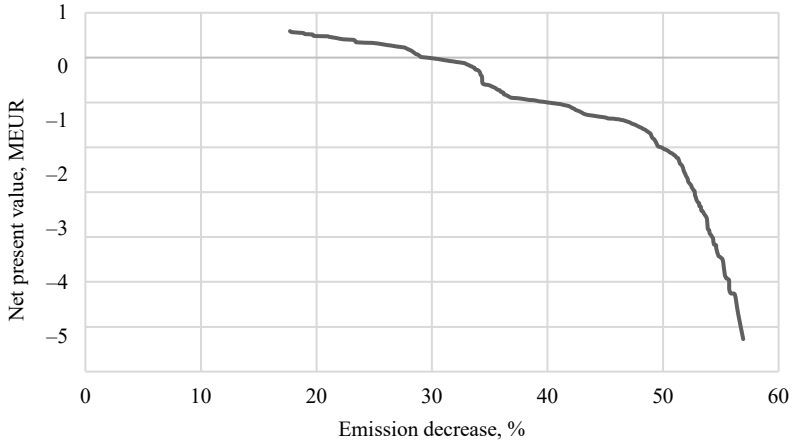


Fig. 4. Pareto-optimal solutions in terms of net present value and emission reduction share.

4. DISCUSSION

The multi-objective differential evolution optimization method allows to quickly explore the possible outcomes for energy communities based on the defined payoffs. Previous works have focused on applying linear optimization methods. In the case of large models with various combinations of possible measures, linear optimization might be unfavorable, due to the complex nature of these systems. The optimization used in this study focused on two variables at a time whereas multiple payoff dimensions can be defined, e.g., search for measures providing the least emissions, maximizing net present value, and self-sufficiency share. Therefore, differential evolution optimization is favorable in this case.

Each energy community has its purpose whether to reduce energy costs, and emissions or to increase the share of renewable energy used. Based on findings in this research, there are many directions that energy communities can go in their goals. Although, the limitation of this study is the exclusion of private vehicle measures such as the shift from fossil fuel vehicles to electric vehicles, car sharing, and electric vehicles' use for demand response in the energy community.

External factors such as subsidies, and decreased loan rates could potentially provide a larger incentive for engagement in energy communities and a wider range of solutions regarding the financial outcome. Various business models could be introduced into the community such as a land lease for renewable energy production outside urban/suburban areas. Energy communities could potentially unite outside the traditionally provided scope and become focused on various business options around the community such as tourism and paid workshops related to the transformation towards an energy community. These business models could potentially reduce investment payback time.

Results show that with this combination of measures the analysed energy community will not become carbon neutral and with a self-sufficiency share of a maximum of 29.74 % will have to rely on centralized energy production. Larger thermal storage volume and inclusion of electricity storage could increase both self-sufficiency share and emission reduction share at a cost in net present value. Available area for storage installation could be a problem and must be investigated. Another investigation must be done into different energy communities.

The residential area chosen for this study has windows with low thermal resistance and a large electricity consumption share. Based on these two factors measures like replacement of electrical equipment and replacement of windows are standing out as primary goals of the energy community.

Energy community available measures depend on the costs associated with implementing these measures, energy consumption profiles of the community residents, specific energy consumption, available funding, etc. Applying this methodology may result in a similar structure of the results, but with different measures being superior to other measures.

5. CONCLUSION

Energy communities are expanding as European climate goals require rapid and systematic changes in every sector. The transformation of a multi-family residential building area into an energy community is explored via the multi-objective differential evolution optimization method. The results show that, based on defined payoffs, the priority for the chosen residential area would be the replacement of electrical equipment and the replacement of windows providing a positive net present value and reduced emissions by 18 %. Emissions in the community can be reduced up to 57 %, the specific heat consumption can be reduced up to 58 kWh/m^2, and self-sufficiency can be increased up to 29.74 %.

Based on the results energy communities should consider their current situation and assess possible measures based on their goals. Provided measures in this study could favour some energy communities more than others and each community could use this study as a benchmark for goal prioritization.

Future studies should consider optimization sensitivity analysis of various community types and measures, by changing specific investment costs, energy tariffs, etc. As each energy community would have to find the best combination of energy efficiency measures, energy production, and storage technologies for their current situation.

ACKNOWLEDGEMENT

This study has been funded by the Latvian Council of Science within the research project 'Bridging the carbon neutrality gap in energy communities: social sciences and humanities meet energy studies (BRIDGE)' No. lzp-2020/1-0256.

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