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Mathematical modelling of renewable energy communities for energy-economic assessment

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Abstract. The spread of energy communities worldwide has accelerated in recent years. Energy communities also constitute a promising option for the deployment of renewable-based local electricity generation and use in the European Union, which can play a key role in the green transition and in enhancing the security of energy supply.
Energy communities encourage the creation of new concepts and models, which must be defined so that technical feasibility must be matched with organisational sustainability in order to achieve the desired goals. However, the mathematical modelling of energy systems applicable to energy communities and the optimisation of electricity generation, use and sharing for members and the energy community in regards the defined business model are rarely considered.
The aim of the study is to present a detailed mathematical modelling of a renewable energy community based on a given business model, paying particular attention to their synergies. The research also included the integration of optimisation objectives into the mathematical model, which play a key role in the long-term sustainability of renewable energy communities in the Hungarian regulatory environment and in the current economic situation.

Key words. Renewable energy communities, Business model, Mathematical modelling, Energy-economic assessment, Simulation.

1. Introduction

Nowadays the greatest challenge for the mankind in the 21st century is climate change. Due to industrial development and urbanisation, however, the extent of carbon sinks (mainly forests) steadily decrease, therefore, the surface area that can absorb increasing emissions is shrinking, leading to more intense atmospheric warming. In response to this phenomenon, the world, including the countries of the European Union (EU), is seeking to reduce greenhouse gas emissions, and a series of regulations, incentive programmes and tenders have been defined for this purpose.
The common approach is to increase energy efficiency and reduce greenhouse gas emissions as much as possible. The goal of making Europe the first climate-free continent by 2050 is part of 'The European Green Deal'. In addition, the EU will give priority to improving preparedness and response to the impacts of climate change at national, regional and local levels.
In addition to emission reductions, energy efficiency and the uptake of renewable energy sources will play an increasingly key role in adapting to the current and future high fossil fuel price increases, global political and economic events, growing energy demand and changes in energy security. All this brings to the fore the need for technical and engineering solutions and innovations that can achieve cost-saving and cost-effectiveness.
In a certain sense, such a solution could be the energy community, the concept of which was introduced in the EU energy policy at the end of November 2016 by the 'Clean Energy for All Europeans' package of measures, and then in Hungary by the amendment of Act LXXXVI of 2007 on Electricity [1]and its implementing decree [2], which will enter into force from 1st January 2021.
Within the framework of appropriate policies, members of energy communities can form socially self-organising groupings that can provide significant opportunities for achieving long-term climate and energy policy goals through their energy, economic and social benefits.

Nomenclature	
Acronyms	
BM	Business Model
DSM	Demand-side Management
EC	Energy Community
EU	European Union
LEM	Local Energy Market
OF	Objective functions
P2P	Peer-to-Peer
PV	Solar Photovoltaic Technology
REC	Renewable Energy Community
Indices & sets	
T	Set of time periods indexed by t in [month, quarter of an hour]
n	Number of consumers
m	Number of generating power plants

k	Energy efficiency investment index
i	Index of consumer (i = 1, 2, ..., n)
j	Index of energy generator (j = 1, 2, ..., m)
α	Ratio that characterises the balancing energy demand
η	Energy storage device charging/discharging efficiency
Parameters	
E_{con}	Electricity consumption [MWh]
E_{gen}	Electricity generation [MWh]
$E_{p\text{-}c,balance}$	Electricity production-consumption balance [MWh]
E_{local}	Electricity directly used from own generation [MWh]
E_{ext}	Electricity purchased from an external (non-Community) producer [MWh]
E_{grid}	Electricity purchased from the grid [MWh]
E_{store}	Charging power from the storage [MWh]
E_{spent}	Electricity spent on charging energy storage [MWh]
E_{export}	Surplus electricity generation [MWh]
E_{renew}	Own electricity generation from renewable energy sources [MWh]
R_{renew}	Share of renewable energy [%]
$E_{con,eff}$	Reduced electricity consumption through energy savings from energy saving investments [MWh]
$E_{e,saving}$	Electricity saving [MWh]
$E_{balancing}$	Balancing energy [MWh]
c_{grid}	Unit price of electricity consumed from the grid [EUR/MWh]
c_{EC}	Electricity unit price within the energy community [EUR/MWh]
c_{export}	Surplus electricity sales unit price [EUR/MWh]
$c_{balance}$	Balancing electricity unit price [EUR/MWh]
$C_{balance}$	Balancing electricity price [EUR/year]
C_{OPEX}	OPEX [EUR/year]
C_{CAPEX}	CAPEX [EUR/year]
T_{pbp}	Payback period [year]
SOC	State of charge [%]
Functions	
NPV	Net present value
IRR	Internal Rate of Return

2. Literature review

In recent years, many studies have been made on energy communities (ECs) worldwide, but the mathematical modelling of energy systems, the definition of optimisation goals and the business models used are rarely taken into consideration in the studies.

The [3] study provided a detailed review of the literature on energy communities, with a particular focus on mathematical modelling and synergies with business models, and based on this, outlined the state of the art in energy community modelling.

Depending on national and local regulations, energy communities may have different bureaucratic and organisational structures that influence the objectives and constraints of energy communities and their members. Article 21 of the European Union (EU) Directive 2018/2001 [4] regulates the points on self-consumption of renewable energy communities (REC), while Article 22 defines rights and obligations, including the production, consumption, storage, sharing and sale of renewable energy. However, each Member State is free to adopt its own specific legislation, as long as it complies with this Directive.

The following six business models (BM) summarised in the [3] study based on several sources of literature, are typical in terms of the relationships between actors:

1) Producer-consumers: the community is made up exclusively of producer-consumers who not only consume electricity but also have their own renewable energy generators (i.e. roof-mounted photovoltaic (PV) [5] that they use for their own consumption and share the excess energy.
2) Collective producers: a community based on shared generation (usually solar) and storage systems that can be installed on the roofs of multi-family buildings or near consumption points. Members remain passive consumers unless the energy generated is used to cover common loads (condominium) [6].
3) Aggregator: users (producers-consumers, producers, consumers) are grouped in a more or less explicit way by a unit called aggregator. The community can benefit on a large scale by negotiating better contract terms with energy suppliers or by accessing flexibility markets [7].
4) Third-party sponsored model: a community initiated by third-party organisations (public, utilities, energy service companies (ESCOs)) with social or economic objectives such as public welfare, customer acquisition or technology provision [8].
5) Local Energy Market (LEM) model: members share the electricity they generate through peer-to-peer (P2P) platforms. They can work together to maximise community self-sufficiency and reduce grid interchange, or competitively improve efficiency. Trading conditions, such as pricing, can also be negotiated directly between market actors [9], using fixed, time-of-use or dynamic pricing [10]. All consumers can trade their surplus energy within the EC at any time at a higher selling price than the public market. This price is also lower for users compared to the public market price.
6) Co-operatives: members of the co-operative are also members of the EC and they are the managers (households, businesses, public

institutions and other investors) [11], reinvesting part of the income in the community and sharing the rest among the members [12].

In the ECs, the modelling of energy systems according to the means of production and storage used in the community has been described in the literature using the most typical mathematical models or simulation methods for the technology. The models have been grouped according to different classes, namely photovoltaic power plants, battery storage, electric vehicles, wind turbines, hydroelectric electricity generation, heat pumps, solar, biomass, thermal storage, demand-side management and multi-energy applications. A representative mathematical definition for each class was then established [13][14].
The [3] study classified the objective functions (OF) under consideration into four macro-categories depending on the focus of the optimisation: economic, environmental, technical and social. From the literature, it is evident that OFs show a significant degree of heterogeneity. Nevertheless, the different methods used to treat the models were classified into three different classes: exact algorithms, heuristics and simulation approaches. The first term refers to a procedure that is able to find the global optimum, while heuristic approaches were used when the problem structure was too complex or the instance was too large to be solved or even modelled. In addition, some researchers have outsourced optimisation to software packages, called 'simulators', which can assist both the modelling and the solution phases.
Based on the literature reviews and to the best of the authors' knowledge, they point out that none of the previous literature, except for [3], comprehensively addresses the mathematical description of energy system models of renewable energy communities, objective functions (OF), and the analysis of synergies of business models.

3. Legal environment in Hungary

In the case of energy communities emerging in Hungary, electricity generation is expected to come mainly from renewable energy sources. Currently there is no legal possibility for the implementation and use of biogas or renewable heat production, such as geothermal, solar or co-generation power plants. Consequently, in the near future, the activities of energy communities will be limited to solar electricity generation, with a lower probability of electricity generation from small-scale hydroelectric or biomass power plants and potentially other related activities (electricity trading, sharing, etc.).
In regards renewable energy generation, the action-based renewable energy support scheme (METÁR, FiP – feed in premium) for higher capacity (above 50 kWp) electricity generation systems (power plants) might create serious barriers for energy communities to sell the electricity generated (risk rating, lack of energy economists, low sales price).
In Hungary, overcoming the hurdles of plant licensing and other bureaucratic processes can also be a major obstacle for renewable energy communities with citizen members.
Scheduling and joining or forming a balancing group is essential for the sale of electricity. The energy community, as a member of or responsible for the balancing group, is therefore (financially) responsible for the scheduling and possibly for the settlement of imbalances, but this raises further legal issues. The EU Directive [15] stipulates that Member States may have different rules on balancing regulation liability for renewable power plants below 400 kW, but Hungary has not taken the opportunity to harmonise its legislation accordingly [16].
Energy sharing is also a key issue for the creation and operation of an energy community. Our country's National and Climate Energy Plan specifically targets support for the creation of local energy communities, both for electricity within a given transformer district and for district heating within a given municipality ('village heating plants') [17]. Local energy sharing of decentralised energy generation can greatly reduce grid usage, but currently this is not accompanied by any (price) discount. This acts as a barrier to energy communities.

4. The business model under investigation

The aim of the study is to present a business model for renewable energy communities based on the ambitious expectations of Hungarian market players and the technical and legal possibilities offered by the current regulatory environment, which is suitable for a complex economic analysis and evaluation of the start-up and long-term operation of a new (non-profit) company.
The business model defined in the study is schematically illustrated in Figure 1. The members of the renewable energy community include citizens (with residential buildings), companies (with sites, industrial parks), municipal buildings, public institutions, as well as higher capacity generating units (solar power plants) and centralised energy storage (battery).

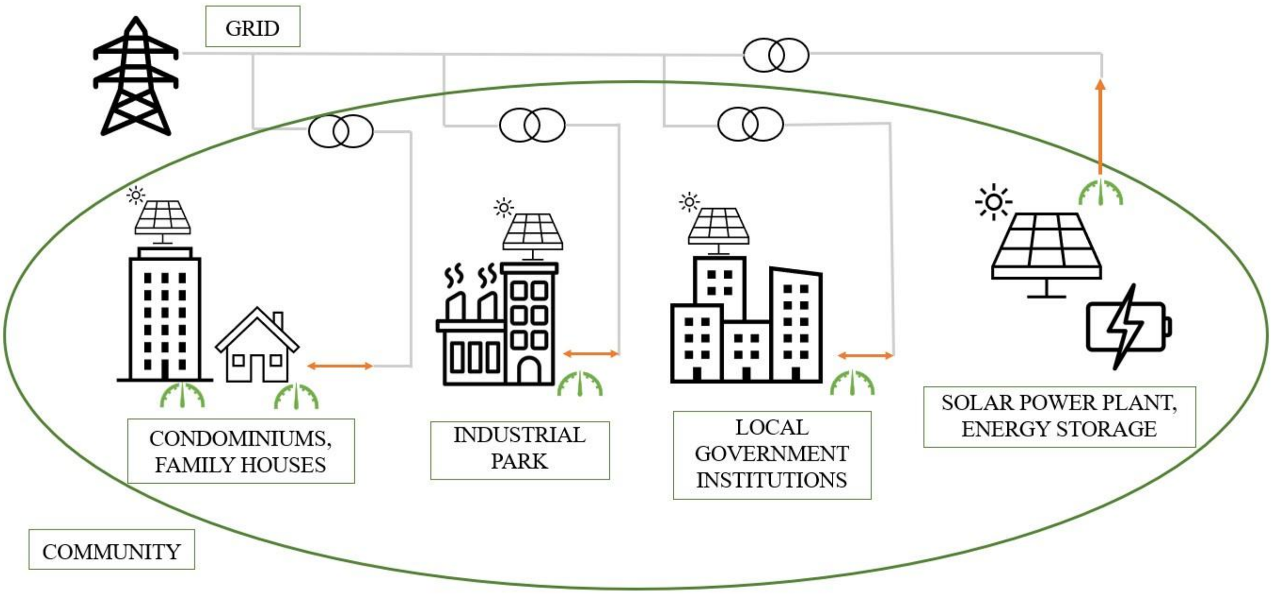

Fig.1. Business model schematic representation

Members of the community can be producer-consumers, producers, and consumers only. An important aspect of implementing and maintaining energy community projects is the economic considerations related to electricity prices and the way benefits are distributed. The business model is based on the joint purchase of energy by the REC members, hence the importance of modelling and detailed analysis of energy flows. The BM favours dynamic pricing, which involves real-time adjustments of electricity prices based on factors such as supply-demand ratios, congestion or market conditions. This approach can promote efficient energy use and grid stability by encouraging consumption during periods of low demand and discouraging it during peak periods when prices are higher. Central energy storage also serves this purpose: part of the surplus generation is used to charge the energy storage, thus storing the energy produced in-house for later use. When the market prices are high, it is possible to reduce the grid purchase by discharging the storage.
The BM is limited to electricity only.

5. The mathematical model

The three crucial parts of an energy community simulation based on a mathematical model are the precise definition of input parameters and their values, the modelling of energy systems to determine energy flows inside and outside the energy community, and the building of an economic model based on these parameters to determine costs and revenues.

A. Considerations in defining the model

The simulations are based on quarterly disaggregated electricity consumption and generation data series. The simulation is able to freely select which generators and consumers make up the energy community, and thus can test multiple scenarios, as the resulting electricity consumption and generation profiles are determined based on the members and generating units that make up the energy community, mapped for each quarter hour. The simulation also handles changes due to planned energy efficiency investments in the respective members.
electricity consumption, the resultant electricity generation, the energy pool balance, the grid purchase rate, the excess electricity generated by the solar power plants in the energy pool, the amount of electricity immediately consumed from generation, the energy storage load level and the energy quantities of discharges/charges. The simulations are based on the assumption that the energy community has a centralised energy storage. The management of the energy storage is designed to discharge at higher market price hours and store at lower price hours.
In addition to simulating electricity flows, the model can also be used to analyse the evolution of electricity costs, so that the question of when it becomes economically viable to implement the energy community can be examined.
In the simulation, you can set when the energy community will be realised (month, year) and the test period will be based on the set parameters. In all cases the test lasts 10 years from the start of the energy community.
The simulation is limited to electricity only, i.e. the following activities of the energy community are considered:

- electricity consumption,
- electricity generation, sharing and sale,
- electricity storage.

B. Definition of input parameters

The most important first step in the simulation is to define the input parameters and set them as accurately as possible. Our simulation can handle the following input parameters:

- date of formation of the energy community,

- electricity tariffs settled within the energy community,
- the sales price of electricity generated from renewable sources,
- inflation,
- depreciation of solar PV systems,
- exchange rates,
- electricity system charges in different categories,
- other electricity prices,
- balancing energy prices,
- deviation from the planned schedule,
- operating costs,
- quarterly electricity consumption and production of energy community members,
- time to implement energy efficiency investments and energy savings achieved,
- centralised energy storage performance, capacity, allowable discharge depth, implementation time.

C. Modelling energy systems

The electricity generation and storage tools and demand side management (DSM) methods used in ECs are described together with mathematical models or simulation methods.

First, the mathematical formulas for energy flows are presented. The electricity consumption or generation of the members of the energy community can be described by the following formula:

$$E_{\text{con}}(t) = \sum_{i=1}^{n} E_{\text{con},i}(t) \tag{1}$$

$$E_{\text{gen}}(t) = \sum_{j=1}^{m} E_{\text{gen},j}(t) \tag{2}$$

Based on (1) and (2), the balance of the energy community can be determined:

$$E_{\text{p-c, balance}}(t) = E_{\text{gen}}(t) - E_{\text{con}}(t) \tag{3}$$

Taking into account the amount of electricity consumed directly from the energy community's own production and purchased from external (non-community) producers, as well as the electricity consumption from the grid, the electricity consumption from the energy storage and the electricity used for charging the energy storage, the energy balance of the energy community can be described by the following formula:

$$\begin{aligned} E_{\text{con}}(t) = E_{\text{local}}(t) + E_{\text{ext}}(t) + \\ + E_{\text{grid}}(t) + E_{\text{storage}}(t) \end{aligned} \tag{4}$$

The surplus electricity generation of the energy community is as follows:

$$E_{\text{export}}(t) = \max\left(0,\ E_{\text{p-c,balance}}(t)\right) \tag{5}$$

The charge of the energy storage is described by formula (6):

$$\begin{aligned} SOC(t) = SOC(t-1) + \eta_{\text{in}} \cdot E_{\text{spent}}(t) - \\ - \frac{E_{\text{storage}}(t)}{\eta_{\text{out}}} \end{aligned} \tag{6}$$

Based on the above, the renewable share of the energy community is as follows:

$$R_{renew}(t) = \frac{E_{renew}(t)}{E_{con}(t)} \tag{7}$$

The impact of energy efficiency investments made or to be made by members is described by the following formula:

$$E_{\text{con,eff},i} = E_{\text{con},i} - \sum_{k=1}^{K} x_k \cdot \Delta E_{\text{e,saving},i,k} \tag{8}$$

Where $x_k \in \{0,1\}$, i.e. whether or not the investment is realised.

D. Modelling costs and revenues

An analysis of the electricity costs, investment and operating costs for the energy community, as well as the revenues from excess electricity generation, completes the analysis of the success of the business model. Building on the energy studies described above, the simulation examines the following economic parameters:

The balancing energy cost can be determined using the following formula:

$$C_{\text{balancing}}(t) = E_{\text{balancing}}(t) \cdot c_{\text{balancing}}(t) \tag{9}$$

Where the amount of balancing energy:

$$E_{\text{kiegy}}(t) = \alpha \cdot E_{\text{term}}(t) \tag{10}$$

The cost of electricity purchased from the grid is determined by (11) and the revenue from excess electricity generation is determined by (12).

$$C_{\text{háló}} = \sum_{t=1}^{T} c_{\text{hálózat}}(t) \cdot E_{\text{hálózat}}(t) \tag{11}$$

$$R_{\text{export}} = \sum_{t=1}^{T} c_{\text{export}} \cdot E_{\text{export}}(t) \tag{12}$$

The total cost of the energy community can be summarised by the following formula:

$$\begin{aligned} C_{\text{SUM}} = C_{\text{grid}} + C_{\text{EC}} + C_{\text{balancing}} + \\ + C_{\text{OPEX}} - R_{\text{export}} \end{aligned} \tag{13}$$

C_{SUM} is optimal if

$$R_{\text{export}} > C_{\text{grid}} + C_{\text{EC}} + C_{\text{balancing}} + C_{\text{OPEX}} \tag{14}$$

When calculating costs and revenues, the simulation takes into account exchange rates, inflation, taxes, interest rates and discount rates.

E. Results of the simulation

The simulation examines the main results presented for a time interval of 10 years from the start date set as input parameter.

Based on the evaluation of the simulation results, the economics of the energy community can be compared and evaluated from an energy-economic point of view for several scenarios. The conclusions drawn from the simulation results will contribute to the technical design phase of the energy-economic benefits and drawbacks of the energy community under study, as well as the potential risks of its implementation. In the case of a realised energy community, the simulation can be used to monitor the actual energy flows, costs and revenues by changing the real values of the input parameters.

6. Conclusion

The study provided a brief overview of the main literature on energy communities that can be used to outline the current picture of mathematical modelling of energy communities.

We presented the legal environment for energy communities, which significantly affect the implementation and sustainability of energy communities in Hungary. The study highlighted the current technical potential of energy communities in Hungary and their impact on the electricity system. Based on these circumstances, the business model, on which the presented mathematical model was built, was defined.

The conclusion can be drawn that the presented mathematical algorithms can be used to model the energy systems and the economics of the energy community, and the simulation can be used to determine the energy-economic benefits and their distribution among the members of the energy community. The model presented can be used as part of decision support material for the energy-economic assessment of a planned energy community, or, in the case of an established energy community, for monitoring based on energy use and production, internal accounting and analysis of the potential for upgrading the energy community.

In their upcoming work, the authors aim to extend the model to other energy carriers and to upgrade it with a number of optimization algorithms in order to increase the energy efficiency and economic benefits of the energy community.

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