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Investment options and cost allocation

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Economic analysis of energy communities: Investment options and cost allocation

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ABSTRACT

Energy communities play an important role in the energy transition to future clean and sustainable energy. The economic feasibility of an energy community is largely affected by its investment options: either a third party or households themselves can invest in distributed energy resources. Another common problem for energy communities is cost allocation among local community members to ensure cost recovery. For these reasons, in this paper, an economic feasibility analysis for energy communities with two investment options is conducted: third party investment and self-investment, while also taking into account various cost allocation methods. An optimization model is developed to solve the optimal operation of the energy community with both investment options. The results indicate that it is economically feasible for a third party to invest in an energy community with the right energy prices and payback time. In this case, the third party makes the highest profits when the payback time is 15 years, which is around 50% percent of its total investment cost. In addition, it is possible for the third party to have multiple cost allocation methods within the same energy community. On the other hand, local community members benefit the most from a joint investment, despite the high initial investment costs. The energy costs of each household are largely affected by the payback time and cost allocation methods. These variations are the largest when payback time is 25 years, which is also the system lifetime. Overall, this study provides insights both for third parties and households to make decisions on investment options and cost allocation.

1. Introduction

1.1. Background and motivation

The growing share of distributed energy resources (DERs) has significantly changed the local landscape from a centralized to a decentralized energy systems. In decentralized energy systems, energy communities play an important role in the energy transition to a clean and sustainable future by incorporating renewable energy projects [1–3]. They are equipped with local DERs where generation mostly comes from renewable energy sources, which are different from the traditional large power systems where generation is primarily fuel-based [4].

Energy communities aim to provide environmental, economic or social benefits to its stakeholders or participants [5]. The emergence of energy communities not only changes the way the energy systems are formulated, but also changes the roles of the households [6,7]. Local citizens are key participants in the local energy communities [8,9]. They actively participate in the local activities, such as local generation, consumption, demand response, decision-making, and local energy trading [10–12]. Hence, their roles are changing from passive consumers to prosumers [11,13].

The investment options for energy communities can be classified into two categories: (1) third party investment where a third party can invest in DERs, and (2) self-investment where consumers themselves can invest in DERs [14–17]. For both investment options, the investors take the ownership of the community energy system and bear the costs and risks. In addition, for both investment options, a common problem they face is the cost allocation among local community members. Cost allocation in an energy community is the process of allocating electricity supply costs between the end-users using electricity price [4, 18]. Since energy communities possess different characteristics than conventional large power systems, it is not always clear how to allocate costs within an energy community [4].

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Nomenclature

$DERs$	Distributed energy resources
T	Total number of hours
N	Total number of houses
$P_t^{buy,grid}$	Electricity purchased from the grid by the community at time $t \in \{1,2,\dots,T\}$ [kWh]
$P_t^{sell,grid}$	Electricity sold to the grid by the community at time $t \in \{1,2,\dots,T\}$ [kWh]
$P_{t,n}^{house,com}$	Electricity purchased from the community by household n at time $t \in \{1,2,\dots,T\}$ [kWh]
$P_{t,n}^{house,grid}$	Electricity purchased from the grid by household n at time $t \in \{1,2,\dots,T\}$ [kWh]
$P_{t,n}^{dem}$	Electricity demand of household n at time $t \in \{1,2,\dots,T\}$ [kWh]
P_t^{PV}	Solar generation at time $t \in \{1,2,\dots,T\}$ [kWh]
P_t^{char}	Electricity charged to the battery at time $t \in \{1,2,\dots,T\}$ [kWh]
P_t^{dis}	Electricity discharged from the battery at time $t \in \{1,2,\dots,T\}$ [kWh]
E_t^{bat}	Electricity stored in the battery at time $t \in \{1,2,\dots,T\}$ [kWh]
$\lambda^{buy,grid}$	Price for buying electricity from the grid [€/kWh]
$\lambda^{sell,grid}$	Price for selling electricity to the grid [€/kWh]
$\lambda_t^{buy,com}$	Price for buying electricity from the community at time $t \in \{1,2,\dots,T\}$ [€/kWh]
y_t	Binary variable indicating whether electricity is purchased/sold at time $t \in \{1,2,\dots,T\}$
u_t	Binary variable indicating whether storage is charged/discharged at time $t \in \{1,2,\dots,T\}$
P_{max}^{grid}	Maximum power that can be purchased from the grid [kW]
P_{max}^{bat}	Maximum power that can be charged to the battery [kW]
E_{max}^{bat}	Maximum energy that can be stored in the battery [kWh]
Cap_{PV}	Photovoltaics (PV) capacity [kW]
E_{PV-kW}^{Y}	Annual PV generation per kW [kWh/kW]
E_{Load}^{Y}	Annual load demand [kWh]
SF_{PV}	PV sizing factor [-]
Cap_{Bat}	Battery capacity [kWh]
E_{Ave}^{Load}	Average daily load demand [kWh]
SF_{Bat}	Battery sizing factor [-]
DOD_{max}	Maximum depth of discharge of the battery [-]
C_{PV}	Costs of PV panels per capacity [€/kW]
C_{Bat}	Costs of battery per capacity [€/kWh]
MC_{PV}	Maintenance costs of PV panels per capacity per year [€/kW/year]
MC_{Bat}	Maintenance costs of battery per capacity per year [€/kWh/year]
C_{invest}	Initial investment cost [€]
Y	System lifetime [Years]
r	Discount rate [%]
$CAPEX$	Total capital costs [€]
$MAEX$	Total maintenance costs [€/year]
$CAPEX^{other}$	Other related costs [€]
$C_{ope}(y)$	Energy exchange costs with the grid [€]
P_{flat}	Flat energy price [€/kWh]
P_f	Flat energy price [€/kWh]
$P_{ToU}(t)$	Time-of-use energy price at hour t [€/kWh]
P_{peak}	Peak energy price [€/kWh]
$P_{off-peak}$	Off-peak energy price [€/kWh]
T_{peak}	Peak hours [Hours]
$T_{off-peak}$	Off-peak hours [Hours]
$P_{seg}(t)$	Segmented energy price at hour t [€/kWh]
P_{over}	Energy price over the threshold [€/kWh]
P_{below}	Energy price below the threshold [€/kWh]
$E(t)$	Energy consumption at hour t [kWh]
E_{th}	The threshold [kWh]
Y_{PBT}	Payback time [Years]
C_{annual}	Annual return [€]
C_{ope}^{annual}	Annual operation cost y [€]
E_{HH}^{annual}	Total energy annual electricity consumption of households [kWh]

1.2. Literature review

1.2.1. Investment options in energy communities

It is essential to obtain investment to purchase necessary equipment and service for constructing an energy community system. Either a third party or the local community members themselves can make the investment. For both investment options, the investors take the ownership of the community energy system and bear the costs and risks.

Third party investment offers an attractive option for facilitating energy communities [16,17,19]. The third party aims to make profits from the investment they made. These can be energy operation companies, grid operators, aggregators or some external investors. An aggregator aggregates different actors in the energy system, such as producers and consumers, to act as a single entity, where they can engage in the electricity market [20,21]. It is also considered a company that operates a virtual power plant with DERs in the study of [22]. In the context of this paper, an aggregator refers to a third party who invests in local DERs and has the ownership of them. They can sell electricity and relevant services to the local community members.

Self-investment is also an attractive investment option for energy communities [23,24]. Local community members are the investors and they take the ownership of the energy system. Four investment options are defined in the study of [16] for roof-top solar power systems: self-investment, utility and public investment, third party investment and solar crowdfunding. Similarly, eight energy community business model archetypes are defined in [17] considering the specification introduced by the Clean Energy for All European legislative package [2]. It is concluded that most of the existing projects are self-investment-based.

The key barrier for self-investment-based energy communities is the high upfront investment, especially for low-income energy communities. For third party investment-based energy communities, the most essential determinant for investors to involve such initiative is the return on investment, as revealed in the study of [25]. It is important to create a good remuneration stream for the third party to recover the investment they made, and to make reasonable profits, for instance, in the form of setting prices. Moreover, for both investment options, the common problems they meet are the long-term payback time and cost allocation. Therefore, cost allocation in an energy community will be introduced in the next section.

1.2.2. Cost allocation in energy communities

Cost allocation is the interconnection between energy system investors and its consumers in the form of, for instance, setting electricity prices. In large power systems, the electricity price is mainly determined by the fuel price based on the supply and demand function. However, the changing landscape of energy system also changes the way the costs are allocated. In an energy community, the generation is primarily from renewable energy sources, whose marginal cost is zero [26,27]. The electricity supply costs mainly include capital investment costs, operation and maintenance (O&M) costs, local network costs (for local connection), and other relevant costs [4], which are mainly fixed. It is challenging to allocate costs in a community energy system with DERs by using the methods adopted in large power system since these two system differ from each other both in physical configuration and cost composition [4].

Various cost allocation methods for local energy communities are proposed in the study of [28], such as time-of-use (ToU) and segmented energy pricing methods. ToU energy pricing method reflects the energy consumption in peak and off-peak hours, in order to incentivize consumers to shift or reduce their energy consumption in peak hours. Segmented energy pricing method reflects their consumption level in order to incentivize consumers to keep their consumption within a threshold to avoid peak demand. These methods are tailor-made for a community energy system with nearly 100% renewable generation. Each method focuses on the different aspect of the cost drivers (energy, capacity and customer services) or combinations of the cost drivers. It is concluded that methods with an energy component perform better in terms of cost reflectiveness (reflect the energy costs consumers should pay in actual) and cost predictability (energy costs are stable in the short-term and gradually change in the long-term). However, the energy community considered in the study did not distinguish between investment options. It is assumed that the investment is already there, and then investigate the cost allocation framework and methods, which are suitable for energy system at a local community level. In addition, it does not take profit making of stakeholders into account.

Similarly, four types of cost allocation methods are proposed in the study of [29], to allocate cost in a net-zero energy community. They are (1) allocating the total costs evenly to each consumer, (2) allocating costs based on the energy consumption of each consumer, (3) allocating costs based on the level of zero energy target, and (4) allocating costs based on both the energy consumption and the level of zero energy target of the consumer. The study in [30] investigates different tariff structures to allocate costs and benefits of a shared PV system between apartment residents in an energy community, including capacity charges, and flat and time-varying volumetric charges. It does distinguish between the investment option; the PV investment could be made by any source, and the system operation is outsourced to a network operator. The costs are allocated between all apartment owners to recover the investments and operation costs. Furthermore, the remaining profits are distributed between all apartment residents either equally or as bill savings for residents. However, an aspect they did not consider is the impact of cost allocation under different investment options.

In addition, there are also studies using game theory to solve cost allocation in an energy community. The widely used cost allocation methods in game theory include nucleolus [31,32] and Shapley value [33,34]. For instance, nucleolus method is used to allocate the cost of a sharing energy community energy storage to address fairness by minimizing dissatisfaction of the end-users [31]. Shapely value method is also used to allocate cost among end-users equipped with rooftop PV and batteries [32], and also among local community members in energy communities [33,34]. In these studies, each local community member in the energy community is considered an independent entity, and cooperation (coalition) among the local community members is possible. However, the local community members in the energy community considered in this study are not an independent entity, and thus there is no cooperation (coalition) between them. Therefore, game theory method is not applicable to allocate costs among local community members under such circumstances. Instead, the methods that allocate costs according to the detailed information of their electricity consumption, such as ToU and segmented energy pricing, are adopted in this research.

1.3. Research gap and contributions of the paper

According to the literature, most of the studies focus on investigating financial options and developing business models for energy communities [16,17,24]. However, it lacks economic feasibility analysis of energy communities with different investment options: self-investment and third party investment. In addition, the rules for cost allocation among local community members for both investment options have not yet been studied so far. Furthermore, the impacts of investment options on cost allocation are not known yet. For these reasons, this paper aims to analyze the economic feasibility of energy communities with the two investment options, while also taking into account cost allocation among local community members.

Different cost allocation methods focus on the different aspects of the electricity demand profile. This will lead to different energy costs of the community members. It is interesting to assess the possibility of having multiple cost allocation methods within the same community. Firstly, it is important to know whether it is feasible for the third party to provide freedom to the local community members to choose from these cost allocation methods. Secondly, it helps local community members to select a cost allocation method that results in the lowest energy costs. Thirdly, it also contributes to increasing social acceptance of cost allocation to the local community members [35].

The main contributions of this paper are summarized as follows:

- Economic feasibility of energy communities with two investment options is analyzed: self-investment and third party investment.
- The impacts of different cost allocation methods on the energy costs of households for both investment options are assessed.
- Possibility of having multiple cost allocation methods within the same community are considered.
- An optimization model is formulated with three case studies based on real-life consumption data.

1.4. Structure of this paper

The remainder of this paper is organized as follows: Section 2 describes the set-up of the energy community, and explains the calculation of the system costs, the three cases and cost allocation methods. Section 3 presents the approaches for solving the two cases with the formulation of these optimization models. Section 4 provides the necessary input data and assumptions to carry out the case studies. Section 5 analyzes the results of the two cases with a discussion. Finally, a conclusion as well as future work recommendations are given in Section 6.

2. System description

2.1. System set-up

The energy community considered in this paper aims to meet load demand by renewable generation to contribute to the energy transition. Therefore, an energy community consisting of several households and DERs (solar panels and batteries) is considered, as depicted in Fig. 1. The local community members have equal access to the energy system. Only the electricity consumption of the households is taken into account in this paper, and the heating demand is not included. The energy community works in grid-connected operation mode. The energy community only sells surplus electricity to the grid and purchases

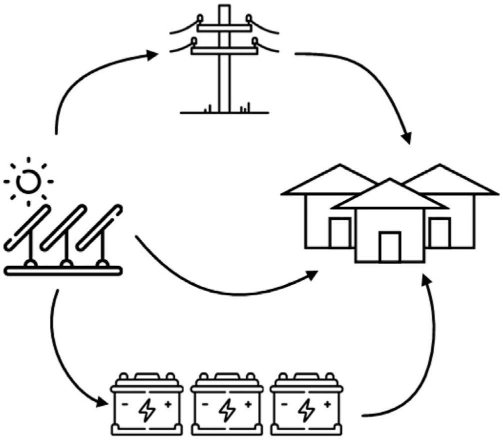


Fig. 1. A typical example of an energy community.

deficit electricity from the grid when necessary. In addition, the energy selling price to the grid is lower than energy buying price from the grid. According to the recent literature on optimal operation of energy communities, approaches for sizing DERs in the energy community are not very detailed. Components' sizes are provided directly or a typical project with certain system sizing is selected in these studies [36–38]. Therefore, in this research, a straightforward approach for sizing the energy system is adopted [39], as optimal sizing is out of the objective of this research. According to the approach described in [39], the annual PV generation equals to the annual electricity demand:

$$Cap_{PV} = \frac{E^{Y}_{Load} \times SF_{PV}}{E^{Y}_{PV-kW}} \tag{1}$$

where Cap_{PV} (kW) is the required PV capacity, E^{Y}_{PV-kW} (kWh/kW) is the annual PV generation per kW installed, E^{Y}_{Load} (kWh) is the annual load demand, and SF_{PV} is the PV sizing factor (usually assumed to be 1.1). It is used to account for the balance of system efficiency incorporating cable losses, inverters, and other system losses [39].

The battery is used to deliver electricity to the load demand when there is no PV generation or PV generation is less than the load demand. According to [39], its capacity is determined by the number of days when the energy system is not dependent on PV generation. In this work, it is assumed that the battery has the capability to deliver electricity to the load for an average entire day without PV generation:

$$Cap_{Bat} = \frac{E^{Load}_{Ave} \times SF_{Bat}}{DOD_{max}} \tag{2}$$

where Cap_{Bat} (kWh) is the required capacity of battery, E^{Load}_{Ave} (kWh) is the average daily load demand, SF_{Bat} is the battery sizing factor, which is similar to the PV sizing factor. It is used to account for the losses and degradation of the battery. DOD_{max} is the maximum allowed depth of discharge of the battery.

2.2. System costs

The total initial investment costs are calculated in the form of net present value, which is:

$$CAPEX = Cap_{PV} \times C_{PV} + Cap_{Bat} \times C_{Bat} \tag{3}$$

$$MAEX = Cap_{PV} \times MC_{PV} + Cap_{Bat} \times MC_{Bat} \tag{4}$$

$$C_{invest} = \sum_{y=1}^{Y} \frac{CAPEX_y + MAEX_y + CAPEX^{other}_y}{(1+r)^y} \tag{5}$$

where C_{PV} (€/kW) and C_{Bat} (€/kWh) are the costs of PV panels and battery per capacity. MC_{PV} (€/kW/year) and MC_{Bat} (€/kWh/year) are the maintenance costs of PV panels and battery per capacity per year. Y (years) is the lifetime of the system. r (%) is the discount rate. C_{invest} (€) is the total investment cost throughout the lifetime of the energy community, including total capital costs $CAPEX$ (€), and total maintenance costs $MAEX_y$ (€/year). $CAPEX^{other}$ (€) is other related costs, such as energy management system cost, grid-connection cost, and cables costs for connecting local community members, which are normally made at the beginning of the energy system. Battery has a shorter lifetime than PV panels, and thus the replacement cost of battery is also included in the total investment cost.

In addition, since the system works in grid-connected operation mode, energy exchange costs $C_{ope}(y)$ (€) with the grid should be included in the calculation of total system costs, which is also the system operation cost. It is assumed that the energy community buys electricity from the grid at the retail price, and sells electricity to the grid at the wholesale market price. The system operation cost is calculated annually.

2.3. Cases

Three cases of the energy community are proposed in this paper to show the economic feasibility of the different investment options on the actors (mainly investors and local community members) involved in the energy community, as illustrated in Fig. 2. Households are the basic units of the local community members.

2.3.1. Reference case

In the reference case, the households buy electricity directly and only from the grid. It is considered the baseline case for comparing the energy costs of the households under different investment options.

2.3.2. Case 1: Third party investment

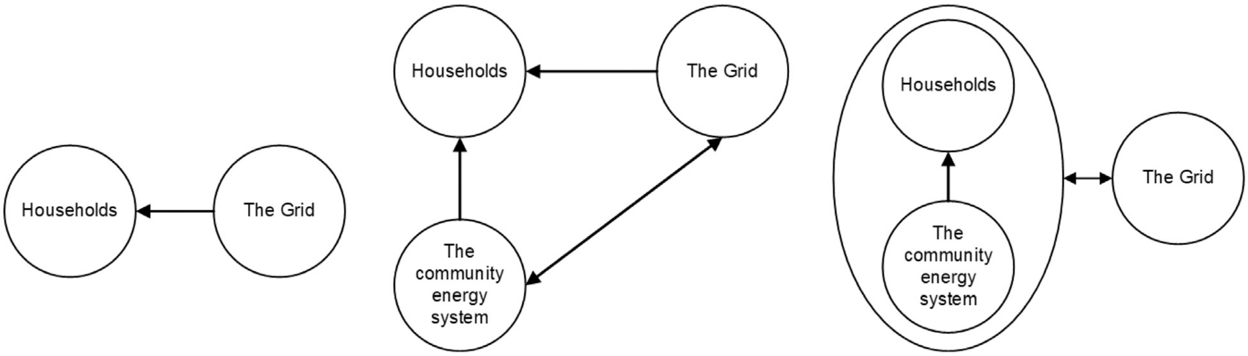
In case 1, a third party, such as an aggregator [40,41], invests in the DERs in the energy community, and offers electricity to the households. Households are allowed to either purchase electricity from the energy community or from the grid according to the prices given by the two parties. Households pay the community electricity price if they buy from the energy community, whereas they pay the grid price if they buy from the grid. The energy community needs to supply the electricity the households buy from them either by generation by DERs within the community, or by buying electricity from the grid. However, it does not affect cost allocation result as these costs are added together. The third party can recover their investments both from the energy bills of households, and selling electricity to the grid.

2.3.3. Case 2: Self-investment

In case 2, the households in the energy community invest in the DERs collectively. They share the investments and operation costs of the energy community. In this case, the community electricity demand is supplied either by generation by DERs or by electricity purchase from the grid when necessary. Local community members are assumed to have equal access to the DERs. In case 2, the energy community and the households are considered as a single entity.

2.4. Cost allocation

In this research, we adopt the methods applicable for cost allocation in local energy communities as the methods to allocate cost in the energy community, as proposed in the study [28]. To be specific, the methods with energy component in the pricing structure are adopted since the energy exchange cost with the grid is also energy component-based: flat energy pricing, time-of-use (ToU) energy pricing, and segmented energy pricing methods.



Reference case
(1) Households buy electricity from the grid directly.

Case 1
(1) A third party invests in the community energy system.
(2) Households buy electricity either from the community energy system or the grid, depending on the electricity prices provided by the two parties.

Case 2
(1) Households invest in the community energy system jointly.
(2) Households buy electricity from the community energy system, and the community energy system exchanges electricity with the grid.

Fig. 2. Three cases considered for the energy community.

2.4.1. M1: Flat energy pricing

The electricity rate of this method is fixed (€/kWh), households pay at the same rate for the electricity consumption [42,43].

$$P_{flat} = P_f \tag{6}$$

where P_{flat} and P_f (€/kWh) are the flat energy prices.

2.4.2. M2: Time-of-use energy pricing

Time-of-use (ToU) energy pricing aims to distinguish the electricity prices between peak and off-peak hours [44,45]. The electricity price is fixed in each time period, high in peak hours and low in off-peak hours. It incentives households to consume electricity in off-peak hours (which is also peak generation hours of renewable energy sources) instead of peak hours (which is off-peak generation hours of renewable energy sources).

The main concept of ToU energy pricing is firstly to classify the total costs into peak and off-peak hours by using a factor. The costs are allocated based on the energy consumption in each time period. In the context of this research, 16:00–23:00 is selected as peak hours, and 23:01–15:59 is selected as off-peak hours. The two electricity prices are expressed as:

$$P_{ToU} = \begin{cases} P_{peak} & t \in T_{peak} \quad \text{(a)} \\ P_{off-peak} & t \in T_{off-peak} \quad \text{(b)} \end{cases} \tag{7}$$

where P_{peak} (€/kWh) is the peak energy price, $P_{off-peak}$ (€/kWh) is the off-peak energy price. T_{peak} (hours) is the peak hours, $T_{off-peak}$ (hours) is the off-peak hours.

2.4.3. M3: Segmented energy pricing

Segmented energy pricing aims to distinguish the electricity price between consumption thresholds [28,46]. The electricity price is low when electricity consumption is below the threshold, and high when electricity consumption exceeds that threshold. The excess part is the difference between the electricity consumption at that hour and the threshold.

The main concept of segmented energy pricing is that the total costs are allocated for electricity consumption below the threshold and over that by using a factor. Two electricity prices are determined by the electricity consumption below and over the threshold. The electricity price is typically low when electricity consumption is below the threshold, and high above the threshold. The two electricity prices are expressed as:

$$P_{seg} = \begin{cases} P_{over} & E(t) > E_{th} \quad \text{(a)} \\ P_{below} & E(t) \le E_{th} \quad \text{(b)} \end{cases} \tag{8}$$

where P_{over} (€/kWh) is the energy price over the threshold, and P_{below} (€/kWh) is the energy price below the threshold. $E(t)$ (kWh) is the energy consumption at hour t. E_{th} (kWh) is the threshold.

3. Approach

The objectives of cases 1 and 2 vary from each other because of the investment made by different parties. This leads to different approaches to achieving the goals. In this section, the approaches for solving cases 1 and 2 are discussed in detail. In both cases, it is necessary to set a long-term agreement between the investors and the households to ensure investment costs recovery since the financial efforts and risks are put on the investors' side once the investment is made. Therefore, it is of great importance to set a reasonable and acceptable price for the long-term agreement to make sure the investments in the energy community are economically feasible for all the actors involved. In this paper, it is also assumed that once the electricity price is set at the beginning of the project, it will remain the same for the entire lifetime of the energy community.

3.1. Approach for case 1

In case 1, the households are allowed to purchase electricity either from the energy community or the grid, depending on the electricity prices provided by the two parties. The energy community optimizes its operation cost according to the electricity demand from the households. Therefore, it is a two-layer optimization problem. Firstly, households optimize their energy costs according to the energy prices provided by the energy community and the grid. Secondly, the energy community optimizes its operational costs according to the electricity consumption decision-making from the households. Several steps are involved in this approach, which are summarized in a flowchart, as demonstrated in Fig. 3.

The energy community needs to provide electricity price beforehand in order to facilitate the households to make decisions on where to buy electricity. Therefore, the first step is to determine the payback time and provide the community electricity price where the energy community can make benefits. The payback time is the time for the investor (in case 1, it is the third party) to recover the investments they made. In this paper, a simple approach of payback period is adopted, which does not take the time value of money into account [47,48]. The payback time is the total investment cost divided by the annual return in terms of third party investment. The annual operation cost is added

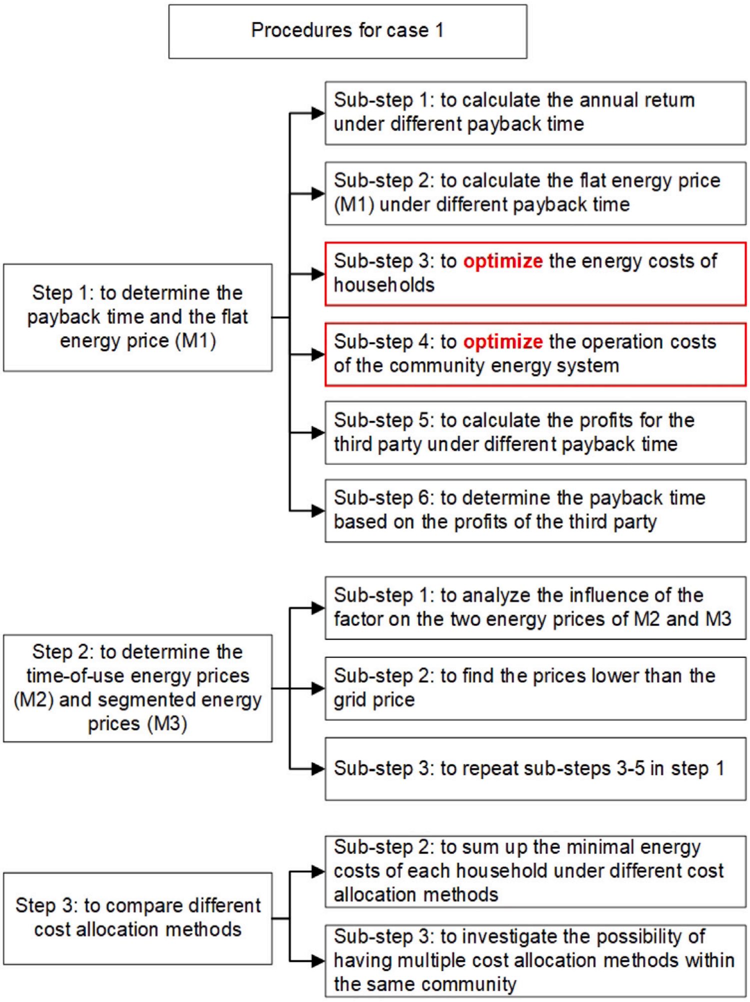


Fig. 3. The approach for case 1.

to the annual return since it is also required to be recovered from the energy costs of households.

$$C_{annual} = \frac{C_{invest}}{Y_{PBT}} + C_{ope}^{annual} \tag{9}$$

$$P_{flat} = \frac{C_{annual}}{E_{HH}^{annual}} \tag{10}$$

where C_{annual} (€) is the annual return, Y_{PBT} (years) is the payback time, C_{ope}^{annual} (€) is the annual operation costs. E_{HH}^{annual} (kWh) is the total annual electricity consumption of households.

The longest payback time is the lifetime of the energy system. Otherwise, cost recovery is at risk. Firstly, the flat energy pricing is used since the grid electricity price is also flat and fixed during the year. The community energy prices are calculated under different payback time. Given the energy prices, several other procedures are involved in step 1: households optimize their energy costs (sub-step 3), the energy community optimizes their operational cost based on the electricity demand from the households (sub-step 4), the third party then calculates the profits gained in the remaining years of the system lifetime (sub-step 5). The timeline is shown in Fig. 4. Based on this, the payback time can be determined from when the third party can make profits (sub-step 6).

Step 2 is to calculate the prices for ToU and segmented energy pricing methods based on the payback time selected in step 1. The ToU energy pricing and segmented energy pricing are affected by a factor as explained in Sections 2.4.2 and 2.4.3. In this step, the influence of the factor on the two prices is analyzed in order to find the ones that are just lower than the grid electricity price, further to incentivize households to consume electricity within the community. Thus, it is better for the third party to recover the investments they made. However, the prices should not be too low because the third party needs to make profits. Based on these prices, the energy costs of the households and the operation costs of the community energy system are optimized, which will be explained in the following subsection. Afterwards, the profits for the third party are calculated based on the two prices. In step 3, the results of different cost allocation methods are compared to investigate the possibility of having multiple cost allocation methods within the same community.

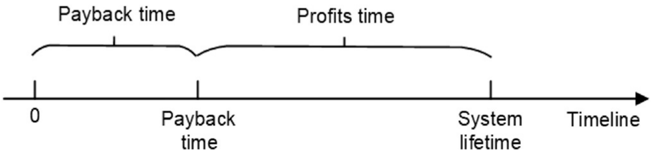


Fig. 4. Timeline for investment payback and profits.

3.2. Optimization for case 1

In case 1, households are allowed to either purchase electricity from the energy community ($P_{t,n}^{house,com}$) and pay at the community electricity prices ($\lambda_{t,n}^{buy,com}$), or to purchase electricity from the grid ($P_{t,n}^{house,grid}$) and

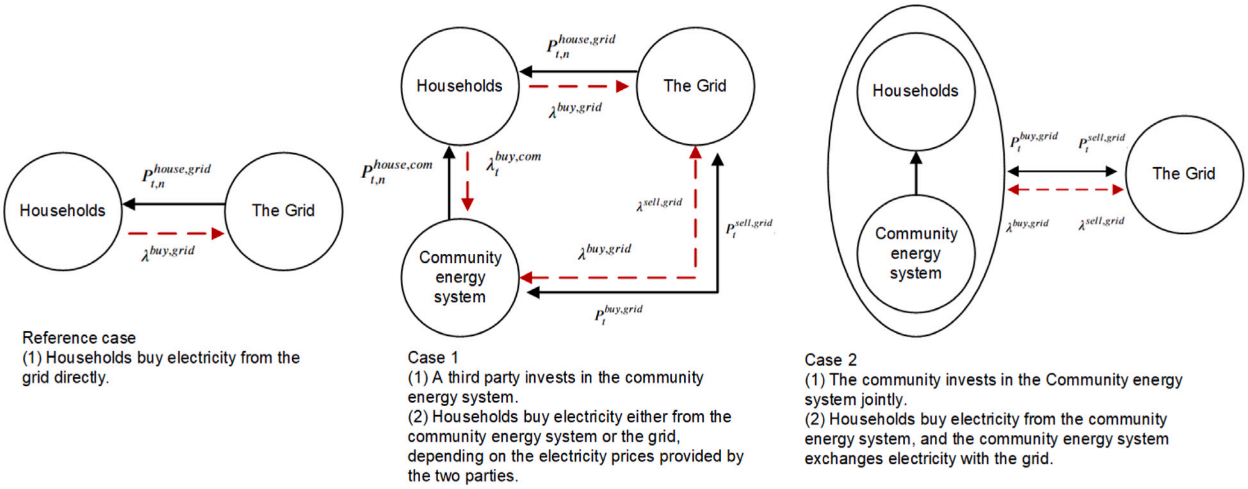


Fig. 5. Three cases on the energy community with electricity and price exchange. Electricity exchange is depicted with black lines, whereas price exchange is depicted with red lines.

pay at the grid electricity prices ($\lambda_{t,n}^{buy,grid}$). This is depicted in Fig. 5 with electricity and price exchange. Firstly, the households make decisions on either buying from the energy community or the grid depending on the prices given by the two parties to minimize their energy costs. Secondly, based on the electricity consumption decision-making from the households, the energy community optimizes its operation costs for energy buying and selling to the grid.

The objectives of the households and the energy community are formulated in a two-layer optimization problem: (1) household layer and (2) energy community layer. Note that this is not a bilevel optimization problem where there is a leader and a follower [49]. These optimization layers are run one after another: firstly the household layer, and secondly the community layer. The equations in these two layers are given below.

3.2.1. Household layer

Households aim to minimize their electricity costs by deciding to buy electricity from the grid ($P_{t,n}^{house,grid}$) or from the energy community ($P_{t,n}^{house,com}$), based on the electricity prices, which is formulated in Eq. (11).

$$\text{Minimize} \sum_{t=1}^{T} P_{t,n}^{house,grid} \lambda^{buy,grid} + P_{t,n}^{house,com} \lambda_t^{buy,com} \tag{11}$$

The power balance constraint in Eq. (12) considers the entire system: both the households and the energy community. It ensures that the demand from the households is satisfied by the supply at all times. The demand (P_t^{dem}) can be met by electricity bought from the community ($P_t^{house,com}$), or electricity bought from the grid ($P_t^{house,grid}$), as given in Eq. (13). Moreover, the electricity bought from the community can be satisfied by solar power generation (P_t^{PV}), from the battery (P_t^{char} and P_t^{dis}), or from the grid ($P_t^{buy,grid}$ and $P_t^{sell,grid}$).

Eq. (14) describes the charging/discharging process of the battery, whereas Eq. (15) makes sure that the state of charge within the battery remains within certain limits. Eqs. (16) and (17) make sure the charging and discharging of the battery occur within the power limits of the battery. It should be noted y_t is a binary variable indicating whether the battery is being charged or discharged. Similarly, the amount of power that can be purchased or sold to the grid is limited within the grid requirements in Eqs. (19) and (20). A second binary variable u_t is introduced in Eq. (21), which is equal to 1 if electricity is purchased, and 0 if electricity is sold.

$$P_t^{PV} + P_t^{buy,grid} - P_t^{sell,grid} = P_t^{dem} + P_t^{char} - P_t^{dis} \quad \forall t \in \{1, 2, \dots, T\} \tag{12}$$

$$P_{t,n}^{dem} = P_{t,n}^{house,com} + P_{t,n}^{house,grid} \quad \forall t \in \{1, 2, \dots, T\} \tag{13}$$

$$E_t^{bat} = E_{t-1}^{bat} + \eta P_t^{char} - (1/\eta) P_t^{dis} \quad \forall t \in \{1, 2, \dots, T\} \tag{14}$$

$$0.2 E_{max}^{bat} \leq E_t^{bat} \leq 0.95 E_{max}^{bat} \quad \forall t \in \{1, 2, \dots, T\} \tag{15}$$

$$0 \leq P_t^{char} \leq P_{max}^{bat} y_t \quad \forall t \in \{1, 2, \dots, T\} \tag{16}$$

$$0 \leq P_t^{dis} \leq P_{max}^{bat} (1 - y_t) \quad \forall t \in \{1, 2, \dots, T\} \tag{17}$$

$$y_t \in 0, 1 \quad \forall t \in \{1, 2, \dots, T\} \tag{18}$$

$$0 \leq P_t^{buy,grid} \leq P_{max}^{grid} u_t \quad \forall t \in \{1, 2, \dots, T\} \tag{19}$$

$$0 \leq P_t^{sell,grid} \leq P_{max}^{grid} (1 - u_t) \quad \forall t \in \{1, 2, \dots, T\} \tag{20}$$

$$u_t \in 0, 1 \quad \forall t \in \{1, 2, \dots, T\} \tag{21}$$

$$P_t^{dem} = \sum_{n=1}^{N} P_{t,n}^{dem} \quad \forall t \in \{1, 2, \dots, T\} \tag{22}$$

$$P_t^{house,com} = \sum_{n=1}^{N} P_{t,n}^{house,com} \quad \forall t \in \{1, 2, \dots, T\} \tag{23}$$

$$P_t^{house,grid} = \sum_{n=1}^{N} P_{t,n}^{house,grid} \quad \forall t \in \{1, 2, \dots, T\} \tag{24}$$

3.2.2. Energy community layer

The energy community aims to minimize its costs by deciding how much electricity to buy from the grid ($P_t^{buy,grid}$), and how much electricity to sell to the grid ($P_t^{sell,grid}$). It is important to emphasize that the electricity purchased from the community ($P_t^{house,com}$) of the households is already determined in the household layer, and hence it is not a decision variable in the energy community layer.

$$\text{Minimize} \sum_{t=1}^{T} P_t^{buy,grid} \lambda^{buy,grid} - P_t^{sell,grid} \lambda^{sell,grid} - P_t^{house,com} \lambda_t^{buy,com} \tag{25}$$

Eq. (26) indicates that the power balance equation where the electricity purchased from the community is satisfied by solar power generation (P_t^{PV}), from the battery (P_t^{char} and P_t^{dis}), or from the grid ($P_t^{buy,grid}$ and $P_t^{sell,grid}$). The rest of the Eqs. (14)–(21) remain the same.

$$P_t^{PV} + P_t^{buy,grid} - P_t^{sell,grid} = P_t^{house,com} + P_t^{char} - P_t^{dis}$$
$$\forall t \in \{1, 2, \dots, T\} \tag{26}$$

Equations (14)–(21)

3.3. Approach for case 2

In case 2, the investment is made by the local community members. It makes more financial sense for households to consume electricity in

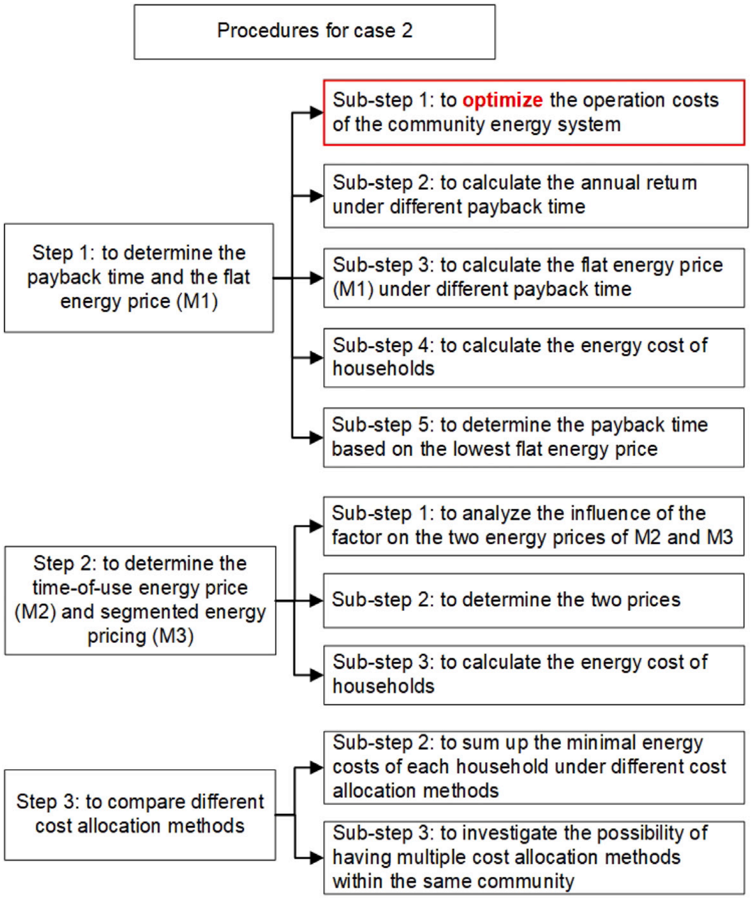


Fig. 6. The approach for case 2.

the energy community as it is more rational for them to consume as much as self-generation to save energy cost since they sell electricity at a lower price than buy electricity from the grid. The energy community acts as an aggregator that sells/buys electricity to/from the grid on behalf of all the households. Several steps are involved in the approach for solving problems in case 2, which are summarized in the flowchart in Fig. 6. The main steps in case 2 are the same as in case 1. However, the procedures in step 1 differ from each other since the households made the investment and they consume electricity within the community energy system in case 2. Therefore, the first sub-step is to optimize the operation costs of the community energy system, and then calculate the annual return under different payback time (following Eq. (9)). Based on this, the flat energy prices and energy costs of households (following Eq. (10)) are calculated. Finally, the payback time is determined based on the lowest flat energy price, which is also higher than the grid price. Steps 2 and 3 are similar to the ones in approach for case 1: (1) to study the influence of the factor on the energy prices of the two cost allocation methods and determine their prices, and (2) to investigate the possibility of having multiple cost allocation methods within the same community.

3.4. Optimization for case 2

Different from case 1, in case 2, the energy community members invest in the DERs collectively. The energy community minimizes its operation cost with the grid on behalf of all the households to satisfy their load demand. For this reason, the objective function in Eq. (11) aims to minimize the electricity cost of the energy community, which is the sum of the cost of buying electricity, and the revenue obtained from selling electricity to the grid.

$$\text{Minimize} \sum_{t=1}^{T} P_t^{buy,grid}\lambda^{buy,grid} - P_t^{sell,grid}\lambda^{sell,grid} \tag{27}$$

The power balance constraint in Eq. (28) ensures that the demand from the households is satisfied by the supply (PV, grid or the battery) at all times. The Eqs. (14)–(21) remain the same.

$$P_t^{PV} + P_t^{buy,grid} - P_t^{sell,grid} = P_t^{dem} + P_t^{char} - P_t^{dis} \qquad \forall t \in \{1, 2, \dots, T\} \tag{28}$$

Equations (14)–(21)

4. Data & assumptions

This section elaborates on the necessary input data and assumptions in this paper.

4.1. Hourly energy demand

The hourly energy demand of the households is from the household electricity consumption data from the UK Power Networks project in 2012 [50]. The annual electricity consumption is between 2500–5000 kWh.

4.2. Hourly PV power generation

The hourly PV generation data is obtained from the open data platform Renewables.ninja in the year of 2019 [51].

Table 1
Techno-economic parameters.

	Capital costs	O&M costs (€/kW(h)/year)	Lifetime (years)	Source
PV	240 €/kW	1.2	25	[53]
Battery	230 €/kWh	2.3	12	[54]
EMS	10000 €	–	25	–
Grid-connection	20000 €	–	25	–
Cables	1000 €/House	–	25	–

Table 2
The energy costs in 25 years of each household for the reference case.

House number	1	2	3	4	5	6	7	8	9	10	Total
Energy costs in 25 years (€)	19184	23110	22439	16358	21763	18284	14153	23028	17226	14402	189951

4.3. Techno-economic parameters

The techno-economic parameters of PV panels and battery are summarized in Table 1, including capital costs, O&M costs and lifetime. These costs are based on the current available data in the commercial market in 2022. The capital costs of PV and battery include inverter/converter costs. The lifetime of the battery is 12 years, the system lifetime is set to be the same as the PV lifetime (25 years). Therefore, it is required to replace the battery at the end of year 12. It is assumed that its capital cost reduces to be half of its initial costs by that time. In addition, since energy exchange is enabled between the energy community and the grid, it is also required to take the grid electricity prices into account. In this paper, the average electricity price for households in 2019 in the Netherlands for consumption around 2500–5000 kWh is taken as the energy buying from the grid [52]. The price given on the website is bi-annual in 2019, the average value of the two values is taken as the average price in the year, which is 0.2061 €/kWh. An assumption is made for energy selling price to the grid, which is 0.10 €/kWh. Since the net present value is considered in the cost calculation, the discount rate is assumed to be 5%. Another assumption made in this paper is that a fixed contract is made between the investors and the households once they agree to join the energy community. The contract sets a fixed price for the households. In other words, the energy price will remain the same in the following years after it is set in the first year. This assumption is made because the objective of this paper is to show the economic feasibility of third party investment and self-investment.

5. Results analysis and discussions

5.1. Results for the reference case

In the reference case, the households buy electricity from the grid directly at the rate of 0.2061 €/kWh. The energy costs of each household are summarized in Table 2.

5.2. Results for case 1

5.2.1. Results for step 1: Flat energy prices under different payback time

The most important thing for a third party is to recover the investment they made and make profits. In case 1, the households are allowed to buy either from the energy community or the grid, depending on the electricity prices provided by the two parties. The more electricity the households buy from the energy community, the better for the third party to recover the investment they made. It is essential for the third party to provide a price that is lower than the grid electricity price to attract households to buy electricity from the energy community. The energy prices are affected by the payback time for recovering the investment costs. In the first step, the flat energy price under different payback time is calculated based on the input data provided in Section 4, which are shown in Fig. 7. The objective is to find the payback time when the flat energy price is lower than the grid electricity price. The result indicates that when the payback time is 15 years, the flat energy price is 0.1989 €/kWh, which is just below the grid electricity price (0.2061 €/kWh) in 2019 in the Netherlands. The flat energy price continues to decrease as the payback time increases until the end of the lifetime of the energy system.

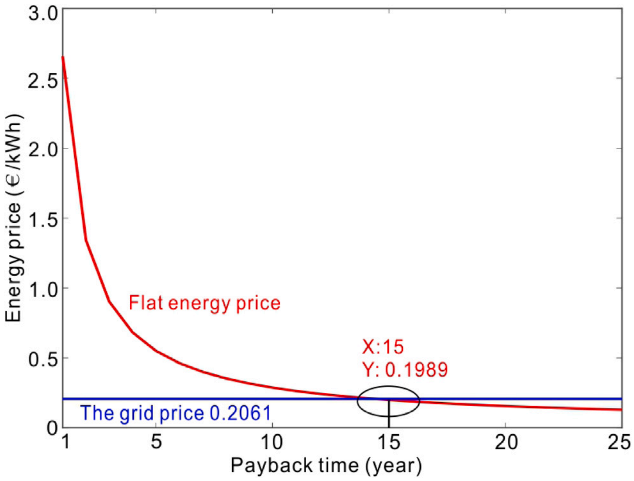


Fig. 7. The impact of payback time on flat energy price in case 1.

According to the approach in Section 3.1, the households first optimize their energy costs by deciding between purchasing electricity from the grid or the energy community. Then, the energy community optimizes its operation costs based on the energy demand from the households. The profit the third party gained in the lifetime of the energy system and the total costs paid by the households in 25 years are calculated based on the flat energy prices given in Fig. 7. The profit of the third party is illustrated in Fig. 8.

For payback time from 1 to 14 years, the energy community sells all its generation to the grid at 0.1 €/kWh. The results show that the energy community can recover the investment costs with a small profit. Considering the fact that the investors aim to make high profits, it is not wise for them to sell all the generation to the grid. From payback time from 15 to 25 years, the households start to buy electricity from the energy community since it is cheaper than buying from the grid. The energy community makes profits in the following years, and the households pay less than buying from the grid. In addition, the third party gains the highest profits for payback time of 15 years since the energy price is close to the grid electricity price and is the highest among payback time from 15 to 25 years. The households have the lowest energy costs for payback time of 25 years. Overall, the third party

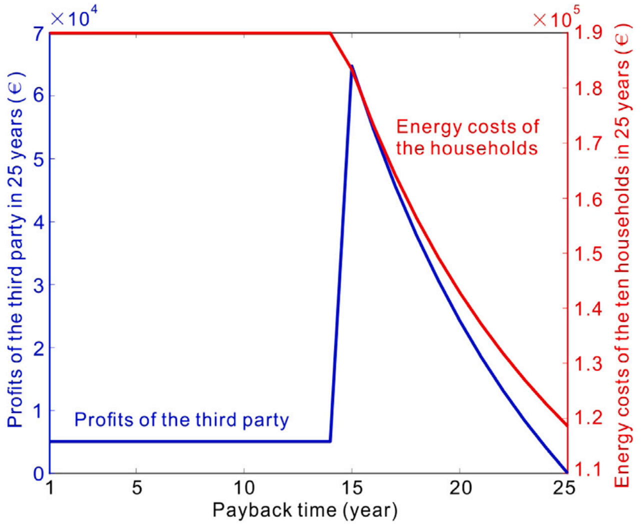


Fig. 8. Profits of the third party and energy costs of the ten households in 25 years for payback time from 1 to 25 years in case 1.

benefits from investing in the energy community, and the households benefit from joining and consuming energy in the energy community.

5.2.2. Results for step 2: Time-of-use and segmented energy pricing

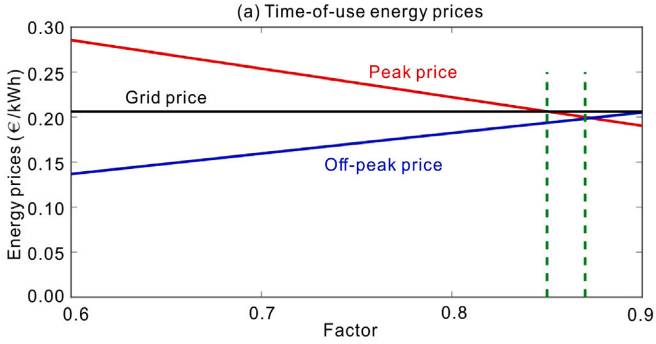
According to the analysis above, payback time of 15 years is selected since the third party gets the most profits and households also pay less than purchasing from the grid. In this section, the energy prices for cost allocation methods: ToU and segmented energy pricing, are determined. The objective of having ToU and segmented energy prices is to incentivize households to consume energy efficiently and effectively, such as shifting peak demand to peak generation hours. The two prices are determined by a factor, as is explained in Section 2.4. However, the peak energy price or energy price over the threshold sometimes is higher than the grid electricity price. Then the households will buy electricity from the grid, which is not desirable for the energy community. Therefore, it aims to find the two prices that are both lower than the grid electricity price. In addition, the peak energy price for ToU energy pricing method (or the energy price over the threshold for segmented energy pricing method) should be higher than the off-peak energy price (or the price below the threshold). However, as the factor increases, the prices go the opposite way. Therefore, the rules for selecting the two prices are:

$$\text{For time-of-use energy pricing method:} \quad P_{grid} \geq P_{peak} > P_{off-peak} \tag{29}$$

$$\text{For segmented energy pricing method:} \quad P_{grid} \geq P_{over} > P_{below} \tag{30}$$

The energy prices for ToU and segmented energy pricing methods are depicted in Fig. 9 when the factor varies from 0.6 to 0.9. The area between the two dashed green lines shows feasible solutions for satisfying the selection rules in Eqs. (29) and (30). When the difference between the two prices becomes larger (e.g. peak and off-peak prices for ToU energy pricing), it provides a better economic incentive with households to respond to these pricing signals. Therefore, the prices close to the left dashed green line are selected in the feasible area, where their difference is the largest. The factors and selected prices are summarized in Table 3. The peak energy price (0.2031 €/kWh) and the energy price over the threshold (0.2029 €/kWh) are just below the grid electricity price (0.2061 €/kWh). The off-peak energy price (0.1960 €/kWh) and the energy price below the threshold (0.1974 €/kWh) are close to the peak energy price and the energy price over the threshold. These prices are used in the following calculations. In addition, the profits gained by the third party is calculated under the two cost allocation methods. The results are the same as the profits under flat energy pricing method, as shown in Fig. 8, which is €64767 since the annual return for each cost allocation method is the same when payback time is 15 years.

(a) Time-of-use energy prices



(b) Segmented energy prices

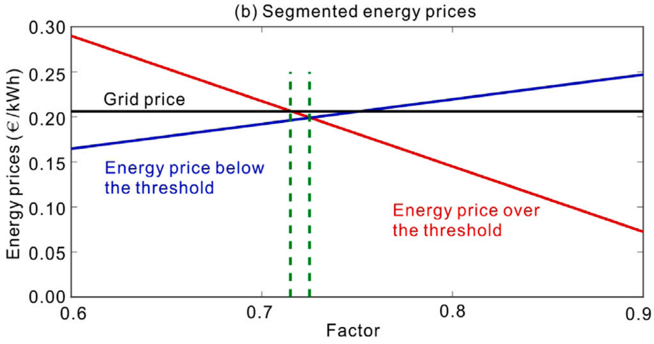


Fig. 9. Energy prices of time-of-use and segmented energy pricing methods under various factors for payback time of 15 years in case 1.

Table 3
The selected energy prices of time-of-use and segmented energy pricing methods for payback time of 15 years in case 1.

Cost allocation method	Factor	Prices (€/kWh)	
Time-of-use energy prices	0.86	P_{peak}	0.2031
		$P_{off-peak}$	0.1960
Segmented energy prices	0.72	P_{over}	0.2029
		P_{below}	0.1974

5.2.3. Results for step 3: Cost allocation methods

According to the results in steps 1 and 2, the community energy prices for the three cost allocation methods (flat energy pricing, ToU energy pricing, and segmented energy pricing) are determined. In this step, the energy costs of each household under the three methods for the selected prices are calculated. The results are shown in Fig. 10(a). The energy cost of each household differs based on their electricity demand. Moreover, there is no significant difference among the three cost allocation methods, because the energy prices are close to each other, as show in Table 3.

The total energy costs of the ten households in 25 years under the three cost allocation methods are shown in Table 4. The total energy costs are the same under the three cost allocation methods since the total costs required to be recovered are equal. Comparing the results with the reference case, there is a minor difference for the total costs in 25 years: the households pay €6602 less in the energy community than the reference case. Furthermore, we select the minimal cost for each household among the three cost allocation methods, which are also presented in Table 4. The total minimal energy costs of the ten households in 25 years are slightly lower than the total costs under the three cost allocation methods, which is €305 lower. Therefore, the third party can allow to have multiple cost allocation methods within the same community without losing substantial profit.

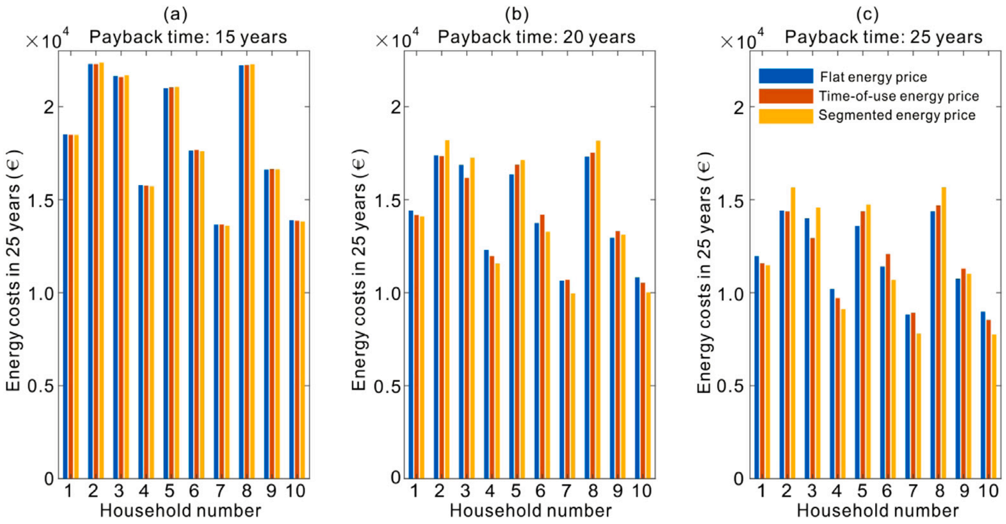


Fig. 10. Energy costs of each household in 25 years under the three cost allocation methods for payback time of 15, 20 and 25 years in case 1.

Table 4
Energy costs of the ten households among the three cost allocation methods for payback time of 15 years in case 1.

Energy costs under flat energy pricing (€)	Energy costs under time-of-use energy pricing (€)	Energy costs under segmented energy pricing (€)	Minimal energy costs (€)
183349	183349	183349	183044

5.2.4. *The impacts of payback time on energy prices and energy costs*

According to the results shown in Fig. 8, the third party starts to make profits from payback time of 15 years when all the households buy electricity within the energy community. Payback time of 15 years is selected for the analysis carried out in the previous sections. In this section, the impacts of different payback time on the prices of the three cost allocation methods are analyzed, and thus the energy costs of the households. Hereby, the payback time of 15, 20, and 25 years are taken to analyze the impacts of cost allocation methods on the energy prices and energy costs of the households. The selection of the energy prices for ToU and segmented energy prices follow the same rule as mentioned above. The energy prices for the three cost allocation methods for payback time of 15, 20, and 25 years are depicted in Fig. 11. The flat energy price decreases with the increase of the payback time since the costs are recovered in a longer time horizon. The peak price for ToU energy pricing and the energy price over the threshold for segmented energy pricing are close to but less than the grid electricity price, which is determined by the selection rule. The differences between the peak and off-peak prices (for ToU energy pricing) and energy prices over and below the threshold (for segmented energy pricing) increase as the increase of the payback time due to longer time horizon to recover the investment costs.

Based on the energy prices determined above, the energy costs of each household in 25 years under the three cost allocation methods for payback time of 15, 20, and 25 years are obtained. The results are presented in Fig. 10. The total energy costs decrease with the increase of payback time because the prices decrease with the increase of payback time, as shown in Fig. 11. The energy costs of the households among the three cost allocation methods vary significantly as payback time increases, due to large gaps between energy prices.

Based on the energy costs calculated for each household, the minimal energy costs of each household among the three cost allocation methods are selected. The total energy costs of the ten households in 25 years are shown in Fig. 12. The red and blue lines show the total energy costs before and after selecting the minimal costs for each household, respectively, while the black line depicts the total system costs. As the payback time increases, the total energy costs decrease, again owing to lower energy prices in longer payback time.

The difference between the red line (or blue line after selecting the minimal costs for the households among the three cost allocation methods) and the black line is the profits gained by the third party. Between payback time of 15 and 23 years, the third party makes profits, even though the profit declines to a small degree after selecting the minimal costs for the households. This indicates that it is economically feasible for the third party to have multiple cost allocation methods in the energy community between a payback time of 15 and 23 years. Nevertheless, for payback time of 24 and 25 years, the third party loses benefits by enabling multiple cost allocation methods. Hence, it is necessary for the third party to select a payback time that can make sure they can recover the investment costs in the case of allowing multiple cost allocation methods within the same community.

5.3. *Results for case 2*

Following the approach in Section 3.3, the results for case 2 are provided in this section. In case 2, the energy community optimizes its operation cost. Since the investment is made by the households, they consume electricity within the community as much as possible. This is the same as case 1 where all the households buy electricity within the community as the energy prices are lower than the grid electricity price. Therefore, the flat energy prices in case 2 are the same as those in case 1, as shown in Fig. 7. The difference between case 1 and case 2 is that households consume electricity for free after the investment costs are recovered in the defined payback time. Yet, they still need to pay for the operation cost, which is very small. However, in case 1, households still need to pay at the same price after the payback time, which is defined at the beginning of the project. This is also how the third party makes profits. For this reason, households pay less in case 2, when it is a self-investment-based energy community. The total energy costs paid by the households in the lifetime of the system under different payback times in cases 1 and 2 are summarized in Table 5. The total energy costs paid by the households in the lifetime of the system in case 2 are always the same since they made the investment. However, in case 1, the energy prices decrease as the increase of payback time, and the energy costs paid by households reduce.

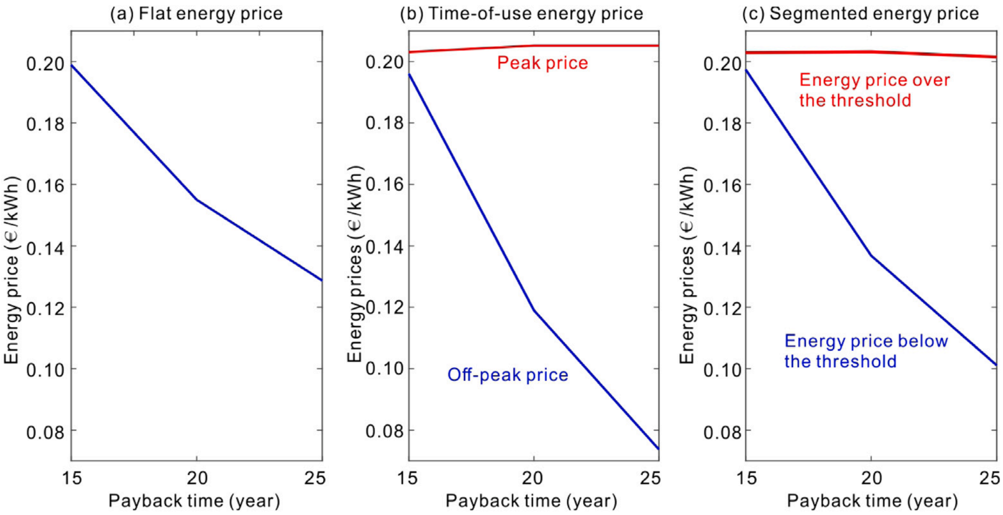


Fig. 11. Energy prices for the three cost allocation methods for payback time of 15, 20 and 25 years in case 1.

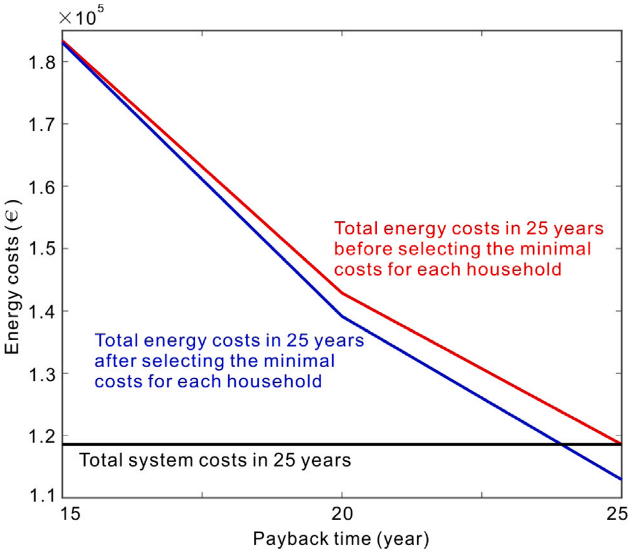


Fig. 12. Energy costs of the ten households in 25 years before and after selecting the minimal costs among the three cost allocation methods in case 1.

Table 5
Total energy costs of households in the lifetime of the system under different payback time in cases 1 and 2.

Payback time (years)	Case 1 (€)	Case 2 (€)
15	183349	118582
20	142870	118582
25	118582	118582

In case 2, households are able to decide on the payback time themselves since they made the investments. As the payback time increases, the energy prices decrease since the total investment costs are equal in the lifetime of the energy system. In this case, the payback time of 25 years is selected for the rest of the analysis due to lower energy prices, and large gaps between the two energy prices of ToU and segmented energy pricing methods.

The same results also apply to the energy prices for ToU and segmented energy pricing methods, which are depicted in Fig. 11. The total energy costs for the households in the lifetime of the energy system are the same. If the payback time is 25 years, the results are the same as those in Fig. 10(c). As shown in Fig. 12, when the payback time is 25 years, it is not possible to have multiple cost allocation methods within the same community, since it is not possible for them to recover the investment costs, as discussed in Section 5.2.4.

5.4. Discussions

Investment options and payback time:

The economic feasibility of an energy community is affected by many factors, such as costs of DERs, the grid electricity prices, and the payback time. The results in this paper show that it is economically feasible for a third party to invest in an energy community; they are able to recover their investment and to make profit. However, in order to make their investment feasible, it is crucial for them to determine proper energy prices to offer to the households, as well as the payback time. Payback time is found to be one of most important factors affecting the economic feasibility of an energy community. As indicated in the results, the highest profits made by the third party is around €64,767, which is 54.62% of its total investment costs when the payback time is 15 years. In this case, it is still beneficial for households to join a third party investment-based energy community, as they will pay €6602 less than buying electricity from the grid.

In a third party investment-based energy community, households still need to pay the same energy price after the payback time is reached, since the third party aims to make profits. Nevertheless, for a self-investment-based energy community, the households can avoid paying the profits to the third party. In this case, households can determine the payback time themselves, and they will use the energy for free after the defined payback time. The selection of payback time affects the energy prices of these cost allocation methods, thus their energy costs. As the payback time goes down, energy prices rise. The energy prices of ToU and segmented energy pricing methods and the energy costs of these households have the largest variations when payback time is 25 years. Some households benefit from this while some households need to pay more compared to other payback time scenarios.

Overall, in this paper, we provide insights for the third party investors to decide on the aforementioned factors that can provide them with the most financial benefits from the energy community, while still making it attractive for the households. It is essential to find an appropriate payback time to determine a price (1) that is affordable by the households, and (2) the third party is able to make profits. For households, they financially benefit from both a third party investment-based or a self-investment-based energy community, compared to the case buying from the grid directly. They benefit the most from the case of self-investment, with the main challenge being the high initial investment costs.

Cost allocation methods:

In this paper, multiple cost allocation methods are considered in order to allocate energy community costs between the households. The energy cost of a household can largely vary with different cost allocation methods, depending on its electricity demand profile, e.g., energy consumption in peak and off-peak hours. For instance, when the payback time is 25 years, household 1 pay less under ToU and segmented energy pricing method compared to flat energy pricing method, while household 8 shows the opposite. Household 3 pay the least under ToU energy pricing compared to the other two cost allocation methods, owing to their relatively low energy consumption in peak hours.

Furthermore, it is possible for the third party to offer multiple cost allocation methods within the same energy community. This provides the opportunity for the households to choose freely among cost allocation methods where they can pay the least for their energy costs. For the case of third-party investment, it is economically feasible to have multiple cost allocation methods within the same energy community, provided that the right payback time is chosen. In other words, the third party is able to make profits without losing considerable amounts, also when multiple cost allocation methods are offered. In this study, the third party loses only €305 when the payback time is 15 years and if multiple cost allocation methods are allowed within the same community.

Having the freedom to choose the cost allocation method which better suits households' electricity demand, might get them more motivated to engage in an energy community. Hence, it is recommended that the third party considers offering multiple cost allocation methods in an energy community. Nonetheless, our results show that for the case of self-investment, it is not possible for households to have multiple cost allocation methods since it possesses the risk of not recovering the investment costs.

Other investment options:

The third party can also be a different actor from the power system, such as distribution system operators. The cross-sectoral electrification increases the demand for electricity, which further causes congestion for the distribution grid. The emergence of energy communities can effectively help distribution system operators mitigate the grid congestion problem. Thus, it creates an opportunity for distribution system operators to invest in energy communities. In addition, the investment options considered in this paper are either self-investment or third party investment. Yet, it may be also a hybrid investment case where, for instance, households invest in PV panels, and a third party invests in community energy storage. This hybrid investment can help reduce the burden of high initial investment, which will attract more households to join the energy community. Game theory approach can be introduced in such cases to allocate the investment cost among different actors as a cooperative investment in shared infrastructures reduces costs compared to individual independent investment.

Final remarks:

The implementation of energy communities requires support from various sectors and actors, such as local authorities, policy makers and regulators. It is essential for them to define proper regulations to manage such energy community activities, such as energy prices and energy exchanges. Based on the current energy crisis all over the world, particularly for the countries relying on energy supply or energy sources from other countries, such energy communities and investment options provide a solution to satisfy electricity demand locally and reduce the dependency on the grid. Overall, the research done in this paper is to present investment options and cost allocation mechanisms for energy communities, which is beneficial for various actors involved in the energy system. A successful implementation of energy communities will definitely contribute to the transition to future green and sustainable energy systems.

6. Conclusions and future work

6.1. Conclusions

With the current energy crisis and increased attention to transition to renewable generation, energy communities play a significant role in the energy transition. This paper presents an economic analysis of energy communities considering two different investment options: third party investment and self-investment. Various cost allocation methods are taken into account: flat energy pricing, time-of-use energy pricing, and segmented energy pricing for allocating costs among local community members. An optimization model is developed to solve the optimal operation of the energy community with both investment options. The results indicate that it is economically feasible for a third party to invest in an energy community with the right energy prices and payback time. The third party makes the most profits when the payback time is 15 years. Moreover, it is also financially possible to have multiple cost allocation methods within the same energy community in the case of third party investment. The third party makes €305 lower profits when allowing households to choose cost allocation methods freely within the same energy community. By doing so, it provides more incentives with households to engagement in such energy communities. When considering self-investment, local community members benefit the most from making a joint investment where they do not need to pay for the profits made by a third party, despite the barrier of high initial investment. It is important to allocate cost fairly in a self-investment-based energy community. The energy cost of a household can largely vary with different cost allocation methods, depending on its electricity demand profile, e.g., energy consumption in peak and off-peak hours. Overall, this research provides insights both to third parties and households in energy communities for the decision making in investments and cost allocation options. It is essential to set an appropriate payback to determine a price that is affordable by the households, and also beneficial to the third party investors. The methodology developed in this paper is generic and can be applied to any energy community with minor modifications. A successful implementation of energy communities can further expedite the energy transition.

6.2. Future work

Besides the insights provided by this paper, there are also some limitations to the work, which lead to some recommendations for future work. Firstly, for the self-investment-based energy community, the energy prices are set lower than the grid electricity price. It is possible to set energy prices higher than the grid electricity price, especially for ToU and segmented energy pricing methods. It is interesting to see how the pricing signals can affect the energy costs of households. Secondly, it is suggested to have energy prices for the energy community that vary every year, as long as the price is lower than the grid electricity price. However, this might bring the risk for the investors if the grid electricity price decreases in the following years. Therefore, it is recommended to have a risk-benefit analysis for the third party. Thirdly, besides the two investment options investigated in this paper, it is interesting to study the economic feasibility of hybrid investment options, e.g., households invest in PV panels, and a third party invests in community energy storage. Furthermore, with the hybrid investment, the allocation of operation costs to the two parties can be studied by using game theory.

CRediT authorship contribution statement

Na Li: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Özge Okur:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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