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Renewable energy communities: Do they have a business case in Flanders?

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ABSTRACT

Renewable energy communities (RECs) are prominent initiatives to provide end consumers an active role in the energy sector, raise awareness on the importance of renewable energy (RE) technologies and increase their share in the energy system thus reducing greenhouse gas (GHG) emissions. The economic viability of RECs though, depends on multiple interdependent factors that require careful examination for each individual context. This study aims at investigating the impact of electricity tariffs, ratio of electrification of heating and transportation sectors, prices of RE technologies and storage systems, and internal electricity exchange prices on the annual cost for electricity provision of a REC and its GHG emissions. A mixed-integer linear model is developed to minimize energy provision costs for a representative REC in Flanders, Belgium. The results indicate that RECs have the potential to reduce these costs by 10 to 26% and emissions by 5 to 13% compared to business-as-usual. The cost reduction depends on the type of electricity tariffs and the level of uptake of flexible assets such as heat pumps and electric vehicles. The shift towards a higher power component in the electricity tariff makes electricity storage systems more attractive, which leads to higher electricity self-consumption. The introduction of flexible assets adds the possibility to shift demand when tariffs are lower and makes higher installed capacities of photovoltaic systems economically viable due to the increase in the total electricity demand. However, RECs cost reduction compared to individual smart-homes amounts to only 4%–6% in the best cases. Uncertainties stemming from the costs of setting up a REC may reduce the estimated benefits.

1. Introduction

Renewable energy communities (RECs) are indicated as one of the means to help democratize, decarbonize and decentralize the energy sector across Europe. As defined in the recast of the European Renewable Energy Directive (RED II) [1], a REC is a legal entity entitled to produce, consume, store and sell renewable energy between geographically co-located private citizens, public entities and SMEs. Their objectives are to create economical, environmental and social benefits to the community members, as well as to increase local acceptance of renewable energy projects [2]. After the introduction of the REC concept, the topic has gained considerable attention from the research community and REC developers, as highlighted in the reviews of Bauwens et al. [3], and Lode et al. [4]. Although the RED II provides a framework for the implementation of RECs, the specific conditions for each country depend on the transposition at the individual EU member state level, meaning that there are still uncertainties on the conditions for an extensive uptake of RECs [5]. Ines et al. [6] highlight the transposition problem by comparing regulations of nine different European countries and regions. They identified that the first challenge for RECs implementation is to overcome local legal barriers in order to exploit the opportunities brought by the legal framework at EU level. According to Brummer et al. [7], this dependency on regulations cuts both ways: regulation promoting RECs may be fruitful for their uptake, but it might present a weakness for long term development of RECs.

When the regulation allows the development of RECs, the next question is to understand the motivation of citizens to join a REC. For instance, Conradie et al. [8] focus on better understanding the factors that influence members' participation in a community in Flanders, Belgium. They showed that lowering the practical barriers of entry in a REC are not sufficient alone. Attitude towards renewable energy sources (RES), ecological impact and expected financial gains are also motivators. According to Bauwens et al. [9], acceptance of

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new RES projects is higher for RECs' members than for non-members, highlighting their social impact. The importance of the economical benefits, which will determine how much investment will be done in new REC projects, is analyzed in another work of Bauwens et al. [10]: results show that the return on investment is the most important determinant for members of large communities of interest, while environmental, social and other non-economic drivers tend to dominate financial motives for members of smaller communities of place. This result is also in accord with the RED II [1]: the main objective of a REC should not be a pure financial gain. Tools that allow a broader analysis of the factors that should be considered when setting up a REC are still missing. Therefore, in this study, we propose a mixed-integer linear program (MILP) where we incorporate different non-technical factors, such as electricity tariffs or investment's strategies, that could influence RECs performance. This is done by creating 156 different scenarios and analyzing their impact on the final electricity costs for the users, CO_2 emissions, as well on uptake of PV and BESS. Additionally, we use self-consumption and self-sufficiency measures as indicators of performance.

2. Literature review

A REC can be viewed as economically viable when the total energy cost for the community members are at parity with or lower than other options for energy supply. Community members are assumed to be consumers or prosumers. Electricity tariff directly affects the economic viability of a REC. Therefore a detailed analysis of both technical and non-technical aspects of REC are needed to understand its economic viability. Radl et al. [11] compared photovoltaic (PV) and battery energy storage systems (BESS) profitability in multi-energy RECs for eight different European countries. The authors concluded that except for cases of full-load hours dictated by weather conditions, the electricity tariffs has the highest impact on PV investments. Concerning BESS, they concluded that under current market conditions they are rarely profitable except when capacity based pricing is applied.

Integral part of electricity tariff is the network tariff. New network tariff structures may also impact the REC business case. Traditionally, the main part of consumers' network tariffs are based on their electricity consumption from the grid, in €/kWh. With an increasing share of prosumers, who may both extract and inject electricity to the grid, and a growing challenge of managing power peaks in the grid due to more intermittent generation, the traditional volumetric network tariffs have become outdated. The affordability of decentralized RES has led to an increasing number of consumers with an alternative energy supply and thus an ability to react and momentarily opt out of the energy supply from the grid. Tariffs for prosumers and energy communities should reflect the fact that these types of consumers have an alternative energy supply while being connected to the grid, resulting in a bidirectional power flow [12]. There is a consensus that volumetric tariffs with net-metering are unfit for the future high-RES energy system (e.g. [13]; [14]; [15]). The process of reviewing tariff structures has therefore been initiated in many countries. Abada et al. [16] studied the impact of electricity tariff design on energy community formation. They find that flat-rate tariffs lead to REC formation while also generating the most social welfare and avoiding over-investments. Capacity based and volumetric tariffs incentivize RES investments, but may also lead to a welfare destructive snowball effect of over-investments. The impact of potential future tariff structures on the business case for REC is however not well understood. It is important to better understand the interaction between the new tariffs and the promotion of REC, in order to streamline the policy initiatives.

Another important point mentioned on the RED II [1] is the use of renewable electricity production in heating and cooling and transport sectors for reducing greenhouse gas emissions and fuel dependency. At residential level this can be effectively achieved by increasing the usage of technologies like heat pumps (HPs) and electric vehicles (EVs). The electrification of heating and cooling and transportation sectors at the building and neighborhood level introduces the need for appropriate techno-economic models for multi-energy systems in order to identify optimal investments and operational strategies. However, the challenge for modeling RECs is not only technical but also policy dependent. This increases the complexity and the computational resources needed for such techno-economic models to be used. The literature covering optimization of RECs, or district-level multi-energy systems in general, is already extensive, but the inclusion of the impact of different policy and/or investment possibilities is still under-represented.

Weckesser at al. [17] introduced the regulatory aspects by analyzing different community configurations on the distribution grid, while optimizing the size of PV and battery storage of a REC for minimizing costs and disturbance on the low-voltage distribution grid. In Fioriti et al. [18] the optimal sizing and operation of energy communities is coupled with a study of a business model for the participation of aggregators in a REC while ensuring fair sharing of costs and revenues between all the actors.

Braeuer et al. [19] applied the German Tenant Electricity Law, a particular regulation in place between tenants and owners of multi-apartment buildings, to a MILP optimization model for an energy community composed of multi-apartment buildings. The results show how the legal framework has a direct impact on the economic viability of the REC. Another analysis regarding multi-apartment buildings is presented in [20], where the difference in legislative framework between Austria and Germany results in different profitability of shared PV systems in multi-apartment buildings. Due to policy differences, the profitability of such systems in Austria is very marginal compared to the Germany. A policy-oriented optimization framework was developed in [21], further highlighting the needs of merging techno-economic aspects with regulatory ones. Moreover, Cielo et al. [22] proposed a multi-objective MILP model for comparing different PV and battery systems configurations of a REC under the new Italian regulation. Their objective function aims at maximizing self-consumption and self-sufficiency of the community because of the introduction of an economic incentive for energy shared within the REC. They afterwards calculate economic and environmental KPIs, such as internal rate of return and CO_2 emission reduction, and results shows positive trends on both categories making the Italian context attractive for RECs. Moreover, Moncecchi et al. [23] follow a two-step approach by finding the optimal energy portfolio of the studied community and after applying a game theoretic approach to fairly allocate costs and profits between the members, showing positive results for both investors and passive consumers. Algarvio [24] analyzed the role local citizen energy communities (CECs) in decarbonizing power systems for a case study in Portugal were different CECs' configurations tested. He concludes that CECs in Portugal are economically attractive and could play a key role into providing the flexibility required by the power system through demand–response (DR) mechanisms, EVs and district heating. In [25] we investigated the conditions needed by RECs to operate in an economic positive way in the context of Flanders. Results indicate that even though user type, user consumption and electricity tariffs are important factors, the amount of flexible technology in a REC is the most important factor to reduce operational costs. Secchi et al. [26] proposed a study on the sizing of battery for a generic REC, based on a modified version of the IEEE 906-bus European Low Voltage distribution grid, under different energy sharing schemes and future energy demand scenarios. Their results show that proper BESS sizing can be beneficial for reducing energy losses, GHG emissions and increase economic benefits, where a peer-to-peer energy sharing policy ensues a fairer spread of the mentioned benefits between the REC members compared to a more traditional peer-to-grid policy.

The examples given above show that there is ongoing work on the coupling of regulatory and techno-economic aspect in energy modeling, but these studies are bound to one type of technology or one specific law or regulation. On the other hand, in this study we focus on various technology systems and multiple regulatory aspects such as different electricity tariffs, energy sharing policies and investment strategies. The novelty of this work relies then on the extensive scenarios analysis to simultaneously map the impact of most uncertainties on the selected six techno-economic-environmental KPIs mentioned in Section 1 by using a single model that can accept the various type of scenarios, hence inputs, without any adaptations. Another contribution of this work going beyond state of the art on RECs research is the inclusion of the carbon footprint of PV and BESS manufacturing necessary to set up the REC into the CO_2 emission calculation. To the best knowledge of the authors this is the first study tackling these technological, economic, regulatory and environmental subjects with a single model for RECs. We show the capabilities of our model and methodology using Flanders as case study. This is a region with a substantial tradition on community energy initiatives that has been widely studied (e.g. [9,27]) and these studies have had a wide impact on the research and RECs developers. Due to the expected role of RECs for the energy transition plan in the EU, our work can contribute to inspire similar analysis for other regions or countries, where the same methodology and optimization model can be used provided that local data and REC regulations are available.

3. Methods

3.1. REC set-up

The REC set up is the result of a participatory process between multiple stakeholders. It is a synthetic REC composed by eleven real residential buildings, located in Flanders, with their associated hourly electrical consumption profiles for a whole year. These profiles are all provided by Fluvius, the Flemish distribution system operator. Between these eleven members, nine of them are single-family houses while the last two are apartment buildings. All of them are connected to the low-voltage grid only, no other information were shared to keep the users anonymous. Their yearly profiles are presented in Fig. 1, while their load duration curves in Supplementary Figure A.10. The Distributed energy resources (DER) included in the system are PV, BESS, EV chargers and controllable HP. PV output profiles are calculated by using a single normalized generation profile for Flanders, also provided by the DSO. Fig. 2 shows the yearly standard solar profile, where for 1 kWp installed, 1,000 kWh of energy is produced in a year. This profiles is then scaled with the different capacities installed for every member. EV chargers demand profiles are based on a fixed daily demand of 7 kWh. Only two type of residential heating profiles are simulated in TRNSYS [28] due to lack of additional information. These profiles are created based on the type of buildings, house or multi-apartment, and outside temperature. With the same principle, heat pumps' COP are simulated based on heat demand and outside temperature. The heat demand profiles are then translated in electricity demand of heat pumps using the COP profiles, shown in Supplementary Figure A.11. Table 1 summarize key numbers related to the input profiles, while all the other technical and economical parameters are listed in Table 2.

3.2. Scenarios construction

We create an extensive set of scenarios to evaluate different options of REC set-up for having a positive business-case. The first set of scenarios concerns the presence of HPs, and EV chargers. The penetration of these technologies is varied in order to quantify the impact of different levels of flexible demand present in the system. The second set of scenarios, CAPEX scenarios, show sensitivity of cost of energy provisions on the investment cost of PV and BESS. The third set of scenarios concerns the electricity tariffs, where a comparison between volumetric and capacity tariff is made. The fourth set of scenarios aims at comparing three different investment strategies: business-as-usual (no additional RES are installed), individual investment and community investment. In the community investment case an additional level of sensitivity analysis is performed on the internal energy exchange prices. To further explore the potential role of RECs for GHG emissions reduction, we compare the results achieved with the Belgian electricity mix against two other: the average of the 27 EU member states and France. This choice is made to compare our results with a mix with higher carbon intensity, the EU-27 with 230.7 g CO_2/kWh [29] and a lower one like France, which has an average carbon intensity of 51.1 g CO_2/kWh [29].

Table 1
Input profiles summary.

Buildings	Yearly base demand (kWh)	Yearly HP demand (kWh)	Yearly EV demand (kWh)
Multi-apartment 1	27,535	3,507	2,555
Multi-apartment 2	14,633	3,507	2,555
House 1	982	2,199	2,555
House 2	3,689	2,199	2,555
House 3	2,299	2,199	2,555
House 4	9,930	2,199	2,555
House 5	6,901	2,199	2,555
House 6	1,831	2,199	2,555
House 7	3,892	2,199	2,555
House 8	785	2,199	2,555
House 9	4,000	2,199	2,555

Table 2
Technical and economical parameters.

Parameter	Symbol	Value
BESS efficiencies	η^{ch}/η^{disch}	95%
BESS minimum SOC	SOC_{min}	0.1
Maximum charging C-rate	$\overline{p^{ch}}$	1
Maximum discharging C-rate	$\overline{p^{disch}}$	2
Maximum power of EV charger	m^{ev}	3.5 kW
Maximum power of type 1 HP	m^{hp1}	1 kW
Maximum power of type 2 HP	m^{hp2}	2 kW
PV lifetime	$lifetime^{PV}$	25 years
BESS lifetime	$lifetime^{BESS}$	10 years
Peak/off-peak electricity price	$\lambda^{ext,im}_{t,n}$	28/21 c€/kWh
Feed-in tariff	$\lambda^{ext,ex}_{t,n}$	3.5 c€/kWh
Capacity tariff	λ^{p}_{n}	4.17 €/kW/month
Discount rate	d	7.5%
Belgian grid carbon content	E^{grid}	161 g CO_2/kWh [29]
PV carbon content	E^{PV}	1,798 kg CO_2/kWp [30]
BESS carbon content	E^{BESS}	90 kg CO_2/kWh [31]

3.2.1. Technologies scenarios

While PV and BESS are variables of the optimal planning problem for all the scenarios, HPs and EV chargers capacities are incorporated as fixed parameters for selected scenarios, and thus not included in the investment cost calculation. This allows us to compare the economic viability of RECs when technologies that provide the services of heating and transportation using electricity, and therefore provide demand-side management (DSM) capabilities, are available or not. Installed capacities of heat pumps are fixed based on the maximum daily demand that needs to be satisfied, while EV chargers' maximum capacities are standards present in the LV grid. In total, four technology scenarios were created to assess the impact of different degree of flexible demand present in the system. In order to limit the number of scenarios, only extreme cases were considered and are summarized in Table 3 with the respective resultant ratio of flexible demand available in the system.

3.2.2. Capex scenarios

As a techno-economic optimization model is used, economic parameters like the investment cost for newly installed PV and BESS play a

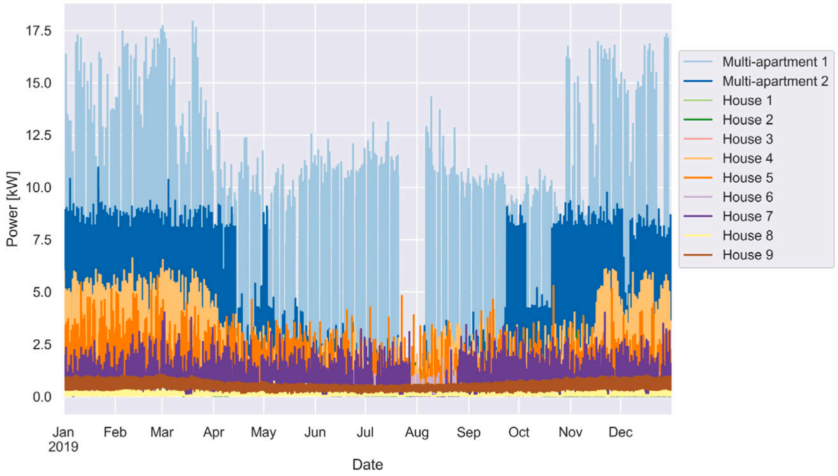

Fig. 1. Hourly consumption profiles of the 11 buildings.

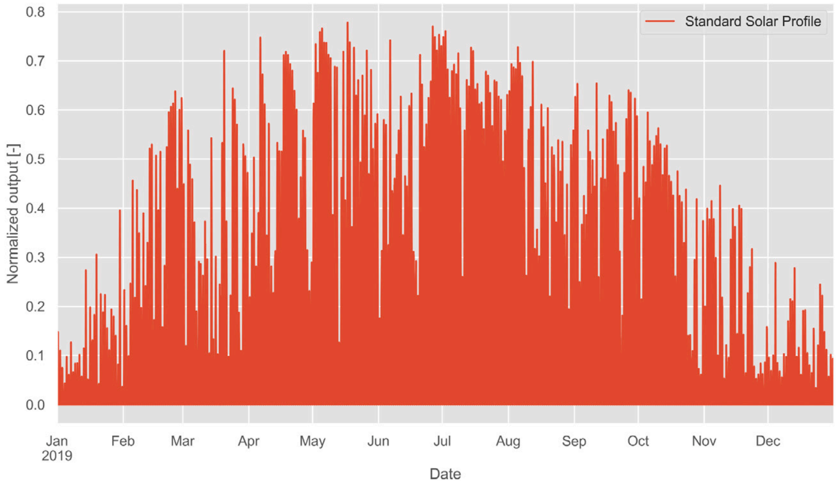

Fig. 2. Hourly standard solar profile.

Table 3
Technology scenarios.

Scenario	% of members with HP	% of member with EV charger	% of flexible demand
1	100	100	41.8
2	100	0	25.6
3	0	100	26.9
4	0	0	0

Table 4
CAPEX scenario.

Scenario	PV installation cost	BESS installations cost
1	1,200 €/kWp	1,000 €/kWh
2	1,000 €/kWp	750 €/kWh
3	800 €/kWp	500 €/kWh

fundamental role on the outcomes of the model. In order to analyze their impact three different prices are proposed for each technology, starting from a higher price which reflect actual cost of installations and ending with a lower price which is expected in the near future, or results from use of government's subsidies. These parameters were defined in iterative consultation with local technology providers, DSOs and research institutions working on RECs in the Flemish context. The three scenarios are summarized in Table 4.

3.2.3. Tariff scenarios

Three scenarios are proposed to analyze the difference in the total annual costs and newly installed DER. We compare a common volumetric tariff to two different capacity tariffs. The reference tariff used for this study is a volumetric one (€/kWh) with peak and off-peak tariffs. This choice has been made in order to exploit the DSM potential of the system, which cannot be done if a flat tariff is used. Peak times are between 7:00 and 22:00 during weekdays, while off-peak times are between 22:00 to 7:00 in weekdays and entire days in weekends. The two capacity-based tariffs are built by first identifying the final cost split of an electricity tariff in Flanders. From [32], a report of the Flemish Regulator of the Electricity and Gas Market (VREG), we have the following structure: 28% is the commodity part, 18% the DSO tariff, 7% the TSO tariff. 17% the VAT and 30% are fees and taxes. The first capacity tariff represent the planned scenario for 2022 in Flanders [32] where the DSO tariff will be billed based on the highest monthly peak consumption (€/kW). For the second capacity tariff all the components except VAT, fees and taxes are kW-based, hence 53% of the total. In all the scenarios, injection price for over-production is fixed over the whole time-horizon. It has to be noted that the values in Table 2 are used as a reference to build all the different tariff and peer-to-peer scenarios explored in this study. The import prices $\lambda_{t,n}^{ext,im}$ (average value for Flanders in 2020 [33]) represent the purely volumetric tariff presented in Table 5, these values are then scaled down to be used for the other

Table 5
Tariff scenarios.

Scenario	Description
1	Volumetric
2	18% capacity-based
3	53% capacity-based

Table 6
Investment scenarios.

Scenario	Description
1	No investment and internal exchange disabled
2	Individual investment and internal exchange disabled
3	Collective investment and internal exchange enabled

tariff scenarios. The same apply for the peak import price λ^p_n, where the value in Table 2 is the reference value for tariff scenario 2 which is scaled up using the percentage of tariff scenario 3.

3.2.4. Investment scenarios

Three investment scenarios are introduced by the mean of three different optimization levels summarized in Table 6. The first one is the business-as-usual case, where no REC is created and investment in PV and BESS are not introduced. This will be used as a reference case. The second scenario is called individual investment scenario: every member makes investment decision based on own needs, without consideration to other members (individual objective function). In this scenario, no REC is created, energy exchange is allowed only with the grid. The third scenario is the community-joint investment, where the optimal investment in PV and BESS is determined at the REC level and each member can own a share of the assets. A REC is created, meaning that energy can be traded inside the community and with the grid. In this last scenario costs of PV and BESS are assumed to be 10% lower than the individual case due to both economies of scale and/or possible future government incentives for RECs, similar to the Italian situation [22]. The peer-to-peer exchange is possible in cases where users are not part of the REC, but we include it only in scenario three to assure extreme cases are analyzed, considering the need to limit the number of scenarios. Such scenario design should already enable to quantify the general impact of different strategies. Another difference between the three optimization levels is in the usage of flexible assets: in the reference scenario, both HPs and EV chargers demand are fixed hourly profiles in order to disable any optimization. While in the individual investment scenario (scenario 2) and in the REC scenario (scenario 3) these two types of profiles are transformed in daily demand to enable hourly optimization of their usage.

3.2.5. Peer-to-peer scenarios

These scenarios only apply for the third investment scenario (creation of a REC). For this particular case additional analysis are done on the impact of the peer-to-peer energy price inside the REC. This exchange price is modeled as the difference between the buying and selling price of energy coming from the assets present in the community. Comparison will be made between free internal exchange, an internal cost that correspond to 65% (DSO cost + VAT + taxes) and 72% (DSO + TSO cost + VAT + taxes) of the buying price from the grid of each tariff scenario, summarized in Table 7. Commodity part of the electricity tariff is not included here because the community owns the PV producing the energy.

3.3. Key performance indicators

In order to analyze the results, six different KPIs are used:

Table 7
Internal price scenarios.

Scenario	Description
1	0% of buying price
2	65% of buying price
3	72% of buying price

- annualized total cost per kWh consumed (€/kWh):

$$\frac{C_{inv} + C_{op}}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n}) \cdot \Delta t} \tag{1}$$

  where C_{inv} represents the equivalent annual cost of investment, while C_{op} is the total cost for operating the energy community, both expressed in €. $l_{t,n}$ is the power demand, $p^{hp}_{t,n}$ the heat demand, $p^{cool}_{t,n}$ the cooling demand, $p^{ev}_{t,n}$ the EV charger demand, all expressed in kW. Δt the timestep size in hours.
- annual CO$_2$ emissions per kWh consumed (g CO$_2$/kWh):

$$\frac{\sum_{\substack{t\in T,\\ n\in N}} (P^{im}_{t,n} \cdot \Delta t \cdot E^{grid}) + \sum_{n\in N} (cap_{PV,n} \cdot E^{PV}/lifetime^{PV})}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n}) \cdot \Delta t} + \frac{\sum_{\substack{t\in T,\\ n\in N}} (cap_{BESS,n} \cdot E^{BESS}/lifetime^{BESS})}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n}) \cdot \Delta t} \tag{2}$$

  which is the sum of the emissions related to the electricity import from the grid $P^{im}_{t,n}$ and the annualized emissions related to the embodied carbon content of PV and BESS manufacturing process, which scale with their installed capacities $cap_{PV,n}$ and $cap_{batt,n}$.
- PV capacity installed per MWh consumed (kWp/MWh):

$$\frac{\sum_{n\in N} cap_{PV,n} \cdot 1,000}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n}) \cdot \Delta t} \tag{3}$$

  with $cap_{PV,n}$ being the installed PV capacity in kW
- BESS capacity installed per MWh consumed (kWp/MWh):

$$\frac{\sum_{n\in N} cap_{batt,n} \cdot 1,000}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n}) \cdot \Delta t} \tag{4}$$

  with $cap_{batt,n}$ being the installed BESS capacity in kWh
- self-consumption ratio (%):

$$100 \cdot \frac{\sum_{\substack{t\in T,\\ n\in N}} p^{pv}_{t,n} - P^{ex}_{t,n}}{\sum_{\substack{t\in T,\\ n\in N}} p^{pv}_{t,n}} \tag{5}$$

  where $p^{pv}_{t,n}$ is the power produced by the PV and $P^{ex}_{t,n}$ the power exported to the grid
- self-sufficiency ratio (%):

$$100 \cdot \frac{\sum_{\substack{t\in T,\\ n\in N}} p^{pv}_{t,n} - P^{ex}_{t,n}}{\sum_{\substack{t\in T,\\ n\in N}} (l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n})} \tag{6}$$

Annualized total cost per kWh consumed, PV capacity installed per MWh consumed and BESS capacity installed per MWh consumed, allow the comparison between scenarios that do not have the same total electrical consumption. Self-consumption ratio represents the ratio of energy produced from PV that is used inside the system and not sold. It can be seen as an indicator of over-sizing of PV. Self-sufficiency ratio is instead the ratio between the energy locally produced and consumed and the total energy demand, it is a measure of independence from the main grid.

3.4. Optimization-problem formulation

In this section, the optimization problem for finding the minimum annualized cost for energy provision for each REC configuration is presented. The mathematical formulation presented here refers to the third investment scenario (see Section 3.2), the community case. In the cases of the first and second investment scenarios part of the equations become simply zero due to the lack of investments or no peer-to-peer exchange. The objective function for the whole time-horizon is

$$min\ C_{inv} + C_{op} \tag{7}$$

where C_{inv} is the equivalent annual cost of investment, while C_{op} is the total cost for operating the energy community. The equivalent annual cost of investment can be calculated as

$$C_{inv} = \sum_{\substack{i \in I, \\ n \in N}} y_{i,n} \cdot cap_{i,n} \cdot C_i \cdot CRF_i \tag{8}$$

with I being the set of all technologies included, N is the set of all REC members. $y_{i,n}$ is a binary variable indicating if the installed capacity of technology i of member n, $cap_{i,n}$, is newly installed or was already part of the system. Furthermore, C_i is the cost for the installation of technology i and CRF_i is the calculated capital recovery factor for technology i, which is defined by

$$CRF_i = \frac{d(1+d)^{lifetime_i}}{(1+d)^{lifetime_i} - 1} \tag{9}$$

where d represents the discount rate and $lifetime_i$ is the lifetime of technology i. The operational cost C_{op} introduced in Eq. (7) is calculated as

$$\begin{aligned} C_{op} = & \sum_{\substack{n \in N, \\ t \in T}} (P^{im}_{t,n} \cdot \lambda^{ext,im}_{t,n} - P^{ex}_{t,n} \cdot \lambda^{ext,ex}_{t,n}) \cdot \Delta t \\ & + \sum_{\substack{n \in N, \\ m \in M}} (P^{p}_{m,n} \cdot \lambda^{p}_{n}) + \sum_{n \in N} C^{int}_{n} \end{aligned} \tag{10}$$

which is composed by three summation terms. The first one represents the difference between the cost of importing energy and the gain for injecting energy back to the grid. $P^{im}_{t,n}$ and $P^{ex}_{t,n}$ are the power imported from and exported to the main grid for every timestep t and member n, while $\lambda^{ext,im}_{t,n}$ and $\lambda^{ext,ex}_{t,n}$ are the tariffs for importing an exporting energy respectively. In order to link power values with cost per energy, we introduce Δt as the difference between two timesteps in hours. The second term is the sum of peak consumption cost for every month of the year, with $P^{p}_{m,n}$ being the peak power imported from the grid for month m and member n and λ^{p}_{n} is its associated cost. Finally, the last summation term is the peer-to-peer exchange costs C^{int}_{n} for each member. The peer-to-peer exchange cost for each participant is calculated in a similar way as for the energy exchange between the community and the grid:

$$C^{int}_{n} = \sum_{t \in T} (Q^{im}_{t,n} \cdot \lambda^{int,im}_{t,n} - Q^{ex}_{t,n} \cdot \lambda^{int,ex}_{t,n}) \cdot \Delta t \tag{11}$$

where internal power flows ($Q^{im}_{t,n}$, $Q^{ex}_{t,n}$) and tariffs ($\lambda^{int,im}_{t,n}$, $\lambda^{int,ex}_{t,n}$) are used. Eq. (12) assures that the power balance inside the community is satisfied, which is based on the community-based market concept presented in [34]. Eq. (13) takes care of the power balance of the internal and external power exchange with the power flows of each member of the REC and Eq. (14) represents the power balance at each users level.

$$\sum_{n \in N} (Q^{im}_{t,n} - Q^{ex}_{t,n}) = 0 \tag{12}$$

$$p_{t,n} - Q^{im}_{t,n} - P^{im}_{t,n} + Q^{ex}_{t,n} + P^{ex}_{t,n} = 0 \tag{13}$$

$$p_{t,n} = l_{t,n} + p^{hp}_{t,n} + p^{cool}_{t,n} + p^{ev}_{t,n} - p^{pv}_{t,n} + p^{ch}_{t,n} \cdot y^{ch}_{t,n} - p^{disch}_{t,n} \cdot y^{disch}_{t,n} \tag{14}$$

With $p_{t,n}$ being the resulting power balance, $l_{t,n}$ the power demand, $p^{hp}_{t,n}$ the heat demand, $p^{cool}_{t,n}$ the cooling demand, $p^{ev}_{t,n}$ the EV charger demand, $p^{pv}_{t,n}$ the PV power production, $p^{ch}_{t,n}$ the charging power of the battery and $p^{disch}_{t,n}$ the discharging power of the battery. Heating and cooling loads of the heat pump and electric vehicle all have their own power balance, shown in Eq. (15). Their demand $d^{j}_{d,n}$ has to be satisfied on a daily basis by optimizing the hourly usage of the assets taking in consideration the availability $Y^{j}_{i,n}$ of the asset. Eq. (16) ensures that the maximum power of each assets is respected.

$$\sum_{i \in I^d} (p^{j}_{i,n} \cdot Y^{j}_{i,n}) = d^{j}_{d,n} \tag{15}$$

$$p^{j}_{t,n} \leq m^{j}_{n} \tag{16}$$

Eq. (17) sets the power output of the PV installation based on the normalized electricity production from PV G_t and its capacity $cap_{pv,n}$.

$$p^{pv}_{t,n} = cap_{pv,n} \cdot G_t \tag{17}$$

Eq. (18) represents the energy balance of the battery: $e_{t,n}$ is the energy content of the BESS, η^{ch} its charging efficiency and η^{disch} its discharging efficiency. The inclusion of binary variables $y^{ch}_{t,n}$ and $y^{disch}_{t,n}$ ensures that the battery is not charging and discharging at the same time (Eq. (19)).

$$e_{t+1,n} = e_{t,n} + \Delta t \cdot (y^{ch}_{t,n} \cdot p^{ch}_{t,n} \cdot \eta^{ch} - y^{disch}_{t,n} \cdot p^{disch}_{t,n} / \eta^{disch}) \tag{18}$$

$$y^{ch}_{t,n} + y^{disch}_{t,n} \leq 1 \tag{19}$$

In addition boundaries for the charging and discharging powers of the battery based on maximum C-rates are introduced:

$$p^{ch}_{t,n} \leq \overline{p^{ch}} \cdot cap_{batt,n} \tag{20}$$

$$p^{disch}_{t,n} \leq \overline{p^{disch}} \cdot cap_{batt,n} \tag{21}$$

as well as a minimum and maximum state-of-charge:

$$SOC_{min} \cdot cap_{batt,n} \leq e_{t,n} \leq cap_{batt,n} \cdot SOC_{max} \tag{22}$$

4. Results

Results are presented in boxplots in order to make the comparison between the 156 scenarios more readable. The box contains the values in the interquartile range, 25th to 75th percentile, with the median of the dataset represented as horizontal line inside the box. The minimum and the maximum are represented by the whiskers which extend from the box to a maximum of 1.5 times the interquartile range. Any values laying outside the minimum and the maximum is represented as a point and is called outlier. To interpret the results one needs to compare the same points between a group of boxplots (minimum with minimum, median with median, etc.), as such points represent the same set of scenarios. Three of the scenarios' categories results – CAPEX, tariff and investment – are presented in separate groups of boxplots in order to assess their individual impact on the KPIs. Additionally, the variation between different scenarios in the technology scenario set has a large impact on the KPIs. This is the reason why when presenting the results, the technology scenario set of 4 scenarios are presented alongside each of the three previously mentioned scenario sets. Finally, internal price scenarios apply only within the third investment scenario, the REC.

4.1. CAPEX scenarios results

The comparison between different CAPEX for PV and BESS on the total annualized cost is shown in Fig. 3. Predictably, lower investment cost results in lower total cost of electricity. Regarding the GHG emissions, Fig. 4 shows that in all the scenarios the emissions are lower compared to the business-as-usual case, where the final emissions are equal to the carbon intensity of the electricity mix, shown with the red line as a reference.

Moreover, lower prices for assets lead to higher PV capacities installed (see Figure A.12), and also in this case we can see that the optimal size of PV increases with the electrification of heating and

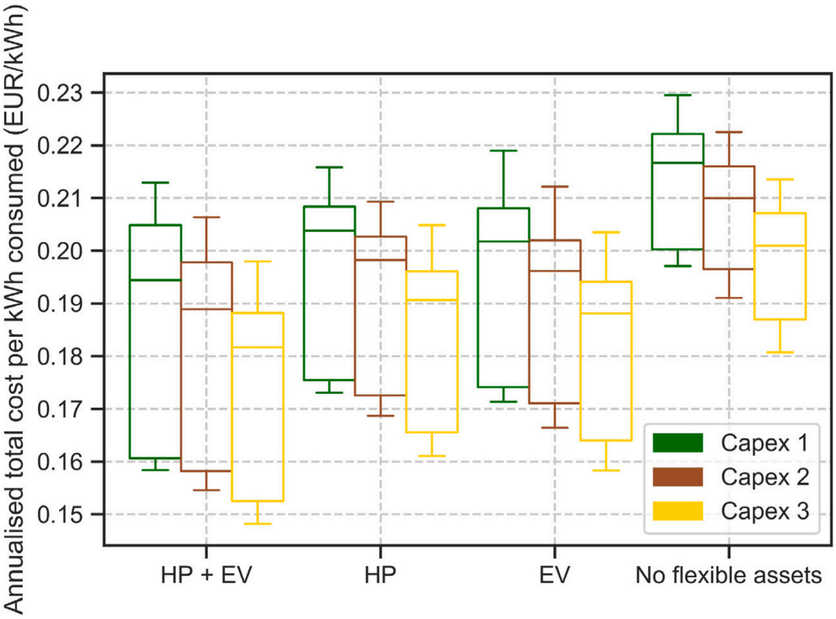

Fig. 3. Total annualized cost per kWh–CAPEX scenarios comparison.

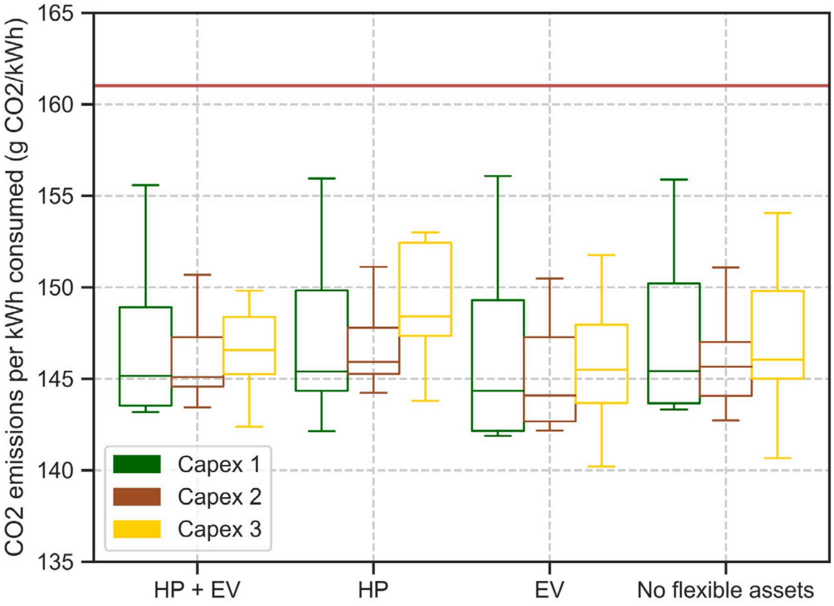

Fig. 4. Total annualized CO_2 emissions–CAPEX scenarios comparison.

transportation because more of the renewable electricity can be consumed at the moment it is produced. BESS will benefit even more than PV of a reduction of investment cost because current prices (CAPEX scenario 1) will result almost every time in non installing any storage system as optimal choice (see Figure A.13) and BESS become more cost-efficient in absence of flexibility in the system. Higher installation of PV (CAPEX scenario 3) will decrease self-consumption ratio (Figure A.14) and increase self-sufficiency ratio (Figure A.15) because more electricity will be produced to cover the immediate demand but at the same time the proportional increase of surplus electricity without immediate demand is even higher. The relation between installed capacity of PV, self-consumption and self-sufficiency ratios also explains why the emissions shown in Fig. 4 are quite even between the different scenarios. Increase of BESS capacities, which also happen mostly for the third CAPEX scenario, should theoretically increase both the self-consumption and self-sufficiency ratios. However, BESS capacities are relatively smaller than PV ones and therefore they do not have a large impact on the results.

4.2. *Tariff scenarios results*

The total annualized cost per kWh consumed compared by tariff is shown in Fig. 5, where we can see that increasing the amount of capacity-dependent component in the electricity tariff will reduce electricity cost. The smaller variability between results in each tariff scenario compared to other scenario comparison (investment, CAPEX and technology scenarios), indicates that tariffs are one of the main parameter affecting the results. The outliers are the business-as-usual results. Fig. 6 shows that tariff 2 results in a small variation of results compared with the other two tariffs. This can be explained by looking at PV and BESS installations trends with the different tariffs.

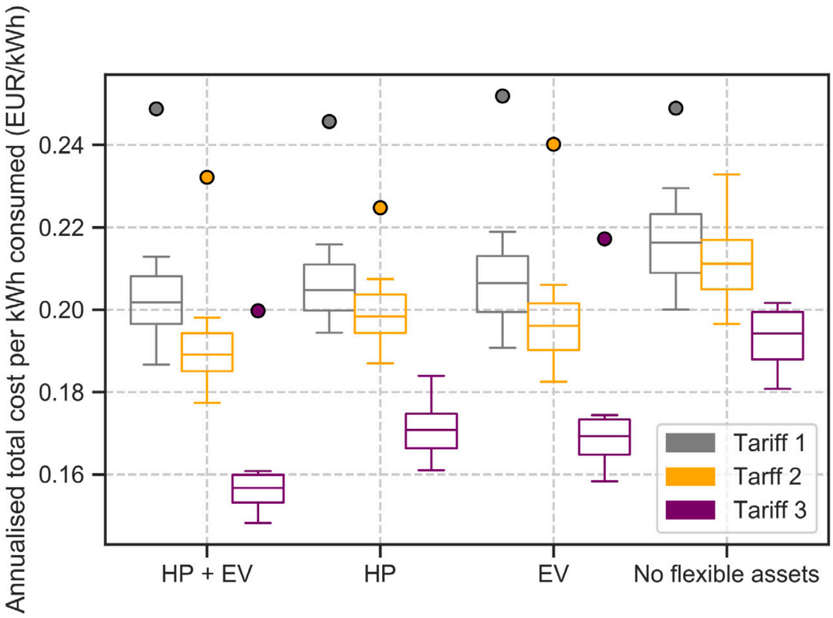

Fig. 5. Total annualized cost per kWh–Tariff scenarios comparison.

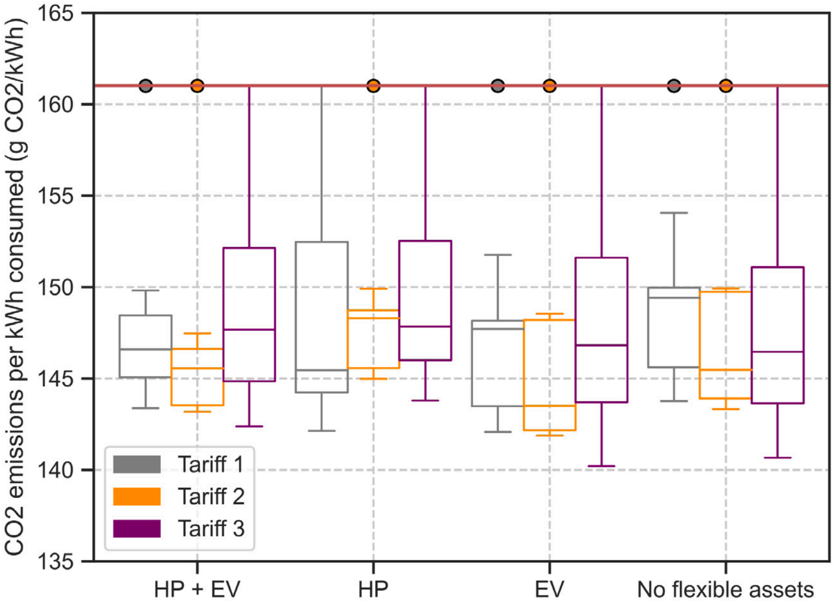

Fig. 6. Total annualized CO_2 emissions–Tariff scenarios comparison.

Regarding PV, we observe that capacity tariffs lead to decrease in the optimal capacity installed (see Figure A.16). This confirms that the size of the PV installation is proportional to the total electricity demand as the capacity installed per consumption unit is very similar for each technology scenario. When it comes to batteries installation, we can see that the optimal installed capacities follow a different tendency than what was seen for PV: BESS are used in the optimal scenario in cases where capacity tariffs are used (see Figure A.17). For the investment scenarios, a lack of flexibility in the system will also increase the amount of BESS installed. The underlying reason for these is that BESS provide the necessary flexibility to the system to reduce the peaks of required capacity to fulfill the demand.

Moreover, tariff 2 results for PV and BESS explain the lower variability in the results of CO_2 emissions: it is a trade-off between decrease in emissions coming from the grid and an increase of emissions due to DER installations. This argument is further supported by Figure A.18 and Figure A.19: use of capacity tariffs also leads to increase in self-consumption compared to more volumetric tariffs due to less PV and more BESS present in the system. On the other hand, for the same reasons, self-sufficiency ratio decreases when the tariff is moving towards a capacity-based one.

4.3. Investment scenarios results

In general, independently of the technology scenarios the community investment option always results in a better economic result. As presented in Fig. 7 in the case where investments are made, having more flexible assets (hence, higher electricity consumption) leads to lower electricity cost per kWh consumed. It also can be seen, that (i) the variability of results (height of the boxes) increase with higher penetration of flexible assets and (ii) investing in PV and BESS leads to a lower annualized total cost per kWh compared to the BAU scenarios.

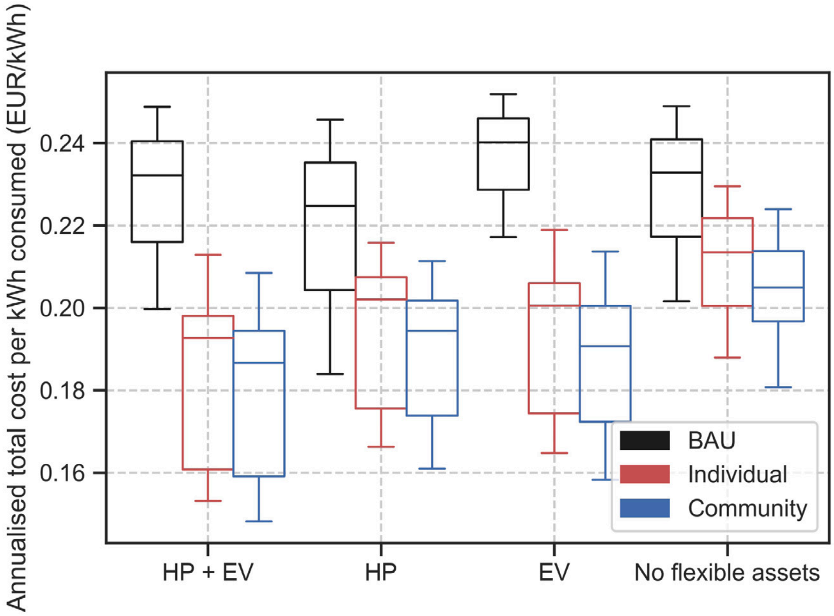

Fig. 7. Total annualized cost per kWh–Investment scenarios comparison.

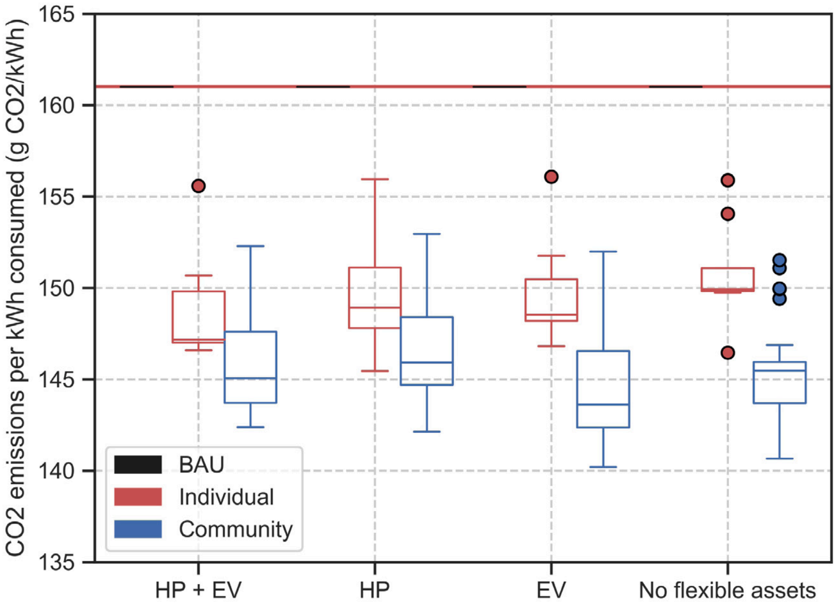

Fig. 8. Total annualized CO_2 emissions–Investment scenarios comparison.

Additionally, the creation of a REC also have environmental benefits, as shown in Fig. 8 where we can see the community cases outscores the other configurations due to more RES installed.

Furthermore, PV capacity installed per consumption unit stays very similar for each technology scenario, i.e. a higher electricity consumption (HP + EV scenario) will increase the PV capacity installed for optimal solutions (see Figure A.20). It should be also noted that community investment scenarios allow the highest PV and BESS integration. However, the cost-efficiency of PV and BESS follow different trends in relation with the amount of existent flexibility in the system. Higher capacity of BESS is more cost-efficient when less flexibility is already available in the system (see Figure A.21) while the opposite applies for PV. Concerning the last two KPIs, the self-consumption ratio balances out between technology scenarios (see Figure A.22) while the self-sufficiency ratio increases due to higher flexibility assets and PV penetration (see Figure A.23). For both KPIs, the community scenarios give the best results.

Concerning the internal price scenarios results (for the RECs), the impact on varying the internal energy exchange price is shown in Fig. 9. We can see how a higher cost for internal exchange will reduce the already small gain, maximum 6% at best on the annualized cost per kWh consumed, of the REC over the individually optimized buildings. This is happening because one of the two reasons RECs are slightly better than the individual optimized buildings, is the opportunity of sharing surplus energy. If an increasing cost is applied to this shared energy, the benefits will of course decrease. The only other advantage remains the CAPEX reduction of 10% for RECs, which only account for a small reduction of costs since both cases, REC and individual buildings, are optimized.

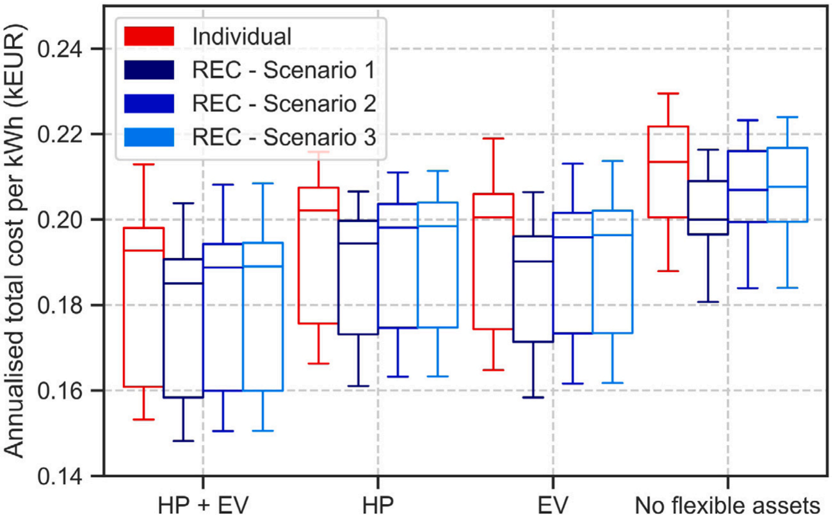

Fig. 9. Internal cost impact.

4.4. Sensitivity analysis of carbon intensity of electricity mix

As shown in Figure A.24 to A.29 the impact of RECs, and RES adoption in general, on CO_2 emissions reduction increase when a higher carbon content for the grid is considered and become detrimental when a low carbon electricity mix is considered. For the EU-27 case, all the scenarios give a reduction in the emissions. On the other hand, for the French electricity mix, all the scenarios result in an increase of the emissions. The increase in emissions is in this case higher for the scenarios with more RES installation (CAPEX 3, Tariff 1 and Community), as the carbon footprint is higher than the carbon content of the electricity mix. The key factor is that we included the carbon footprint of PV and BESS manufacturing, which means that CO_2 savings due to increased self-sufficiency comes with an environmental cost, exactly like cost savings need an initial investment.

5. Discussion

With the electricity prices for Flanders, the switch towards a larger power component in the electricity bill results in a lower final cost for the users, especially in the presence of optimal control of BESS or a HP and EV charger. This is achieved by the ability to reduce the peak consumption, which is also a positive outcome for the network operator. However, our findings show that in this situation it is more convenient to install smaller capacities of PV compared to traditional volumetric tariffs in order to reach the cost-optimal solution. This reduces the potential of RECs to add RES generation capacity and limits their impact in the decarbonization of the energy system. This is also supported by the CO_2 emissions analysis, where we saw that the cheapest solution, tariff 3, results on higher emissions than the other tariffs. On the other hand, a move towards a more capacity-based tariff will trigger more investment into BESS, as found by Radl et al. [11] for other European countries. In general, a more dynamic pricing mechanism would be beneficial for RECs, as highlighted by Fernandez et al. [35], where the higher profit is reached when real-time pricing is used.

Investments in DER such as PV and storage systems such as batteries generate a positive business case for the users. The creation of a REC always results in a cost reduction compared to the reference case, with a reduction varying from 10% to 26%. Similar numbers were found in an equivalent study in the Austrian context [36], where the creation of a REC becomes eventually the economical best solution for all the scenarios included. However, the economic advantage only slightly increases with the creation of a REC compared to individual investment and operation. RECs can decrease the annualized total cost per energy consumed of at maximum 6% compared to single user of an optimized building. This is achieved by introducing the possibility to exchange the surplus energy from the commonly owned assets between REC participants and the 10% discount on investment costs. This means that the potential of energy sharing between residential users is limited, which is normal since peak consumption, that happens at the same hours for every user, and peak PV production do not happen at the same time. On top of this one also needs to considers the legal, IT and IoT costs of setting up and running the RECs which can completely erase this small gain. Subsidies might help but could create unjust societal situations that have to be studied from an entire system perspective. Regarding the environmental aspect, REC scenarios always provide the highest CO_2 emissions reduction due to more RES installed, even when accounting for the GHG emissions due to manufacturing of PV and BESS. This is in line with other similar studies [37,38] that include manufacturing emissions. However, grid emissions are always considered to be high enough to make RES a better alternative. Other previously cited similar works (e.g., [19,26,36]) often include CO_2 emissions too, but only due to the grid carbon content and not from the technologies manufacturing, which overestimate the GHG emissions reduction potential.

Moreover, on site DER production for countries with such a high population density and low levels of direct solar radiation, like Belgium, can expect limitations for RECs related to be a community of place (where there is a proximity constraint) and not of interest (where the proximity to the energy generation assets does not necessarily play a role). This will limit technological options for renewable self production of energy to PV. Moreover, reaching high levels of self-sufficiency and self-consumption requires high levels of electrification of multiple energy vectors, like heat and transport.

One of the main limitations of the optimization model developed in this study is that it works with a perfect foresight of the input profiles – consumption and solar radiation – which considerably reduces the uncertainty in the operation of the system and could lead to larger or smaller system configurations than the ones that could be optimally operated. Possible future work could be the introduction of stochastic input parameters to further handle these uncertainties. Another difficulty encountered in this work is to create a general model for REC because it could have all sorts of prosumers/consumers and costs of setting up the REC. The consultation process with stakeholders allowed us to include typical diversity that can be found in Flanders but efforts have to be invested in the creation of typologies of RECs, which would allow the diversity necessary to conduct system wide analysis.

Lastly, our results hold for cases where heating and transportation services are already electrified. For assessments of smart-homes and RECs that still would have to adopt HP, EVs (charging infrastructure), the investment costs of these technologies and of the technologies that they are replacing should also be included in the total annual cost calculation, as well as a retribution for flexibility services provided by these technologies.

6. Conclusions

The creation of a REC is always outperforming the other scenarios in both economical, between 4 to 26% cost reduction, and environmental, between 5 to 13% emissions reduction, KPIs. However, there is never a substantial economical advantage for REC over individual smart-houses with own electricity generation assets. The advantage is never higher than 6% of the annualized cost of electricity. Furthermore, although the transposition of RED II in Flanders was recently done, uncertainties on the potential business case still remain. The reason is that the cost for setting up a REC, both administrative and technical costs, are still unclear and thus not included in this or any other similar analysis. Hence, the small gain of constituting a REC could potentially be erased by these additional costs. Still, joining a REC from a business-as-usual situation is a positive business case and also help in increasing the share of RES and reducing CO_2 emissions. The shift towards a capacity tariff would encourage the installation of BESS due to their peak shaving potential. This will correspond to less PV installed to reach the optimal situation compared to volumetric tariff. This means that the capacity-based tariff will have a smaller impact on GHG emissions reduction, average reduction of 7.4%, compared to the others: 9.3% for tariff 1 and 10% for tariff 2. However, if we look at the total cost comparison between volumetric and capacity-based tariff, the latter gives the best results (average final cost of 0.174 €/kWh against 0.200 €/kWh of tariff 2 and 0.210 €/kWh of tariff 1) and in general are one of the two most influential factors on the final cost of electricity. The other very impactful factor on the annualized cost of energy is the amount of flexibility present in the system. In fact, electrification of heat and transport will add more possibilities to reduce costs (up to 17% compared to the same cases where no flexible assets are available) in a smart energy system. The consequent increase of electrical demand will also make PV installations more cost-efficient with respect to situation where heat and transport are not powered by electricity.

CRediT authorship contribution statement

Alex Felice: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Software, Writing – original draft, Writing – review & editing, Visualization. **Lucija Rakocevic:** Conceptualization, Methodology, Writing – review & editing. **Leen Peeters:** Conceptualization, Methodology, Resources, Project administration, Funding acquisition, Writing – review & editing. **Maarten Messagie:** Resources, Project administration, Funding acquisition. **Thierry Coosemans:** Conceptualization, Methodology, Resources, Project administration, Funding acquisition. **Luis Ramirez Camargo:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, 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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.119419.

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