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The Cost of CO_2 Emissions Abatement in Micro Energy Communities

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In 2027, Europe will introduce a new cap-and-trade market (EU ETS2) for CO_2 emissions from fuel combustion in buildings and other sectors. The residential sector is firmly moving towards the electrification of thermal services and the development of energy communities with collective energy systems, though these solutions are often perceived as expensive. How do traditional energy systems combined with paying the European emission tax to offset emissions affordability-wise compare to sustainable energy communities that structurally reduce CO_2 emissions in the built environment? Our findings demonstrate that micro energy communities are a viable and cost-effective solution for a sustainable future, given a more balanced electricity-to-gas price ratio.

Introduction

Energy communities are an appealing solution for decarbonizing the residential sector and, by extension, the urban environment when the tertiary sector and part of the transport sector are included. According to the European Commission, energy communities *enable collective and citizen-driven energy actions to support the clean energy transition,* *advancing energy efficiency and lowering bills within local communities*. That collective approach still forms a barrier in countries like Belgium, where citizens tend to think individually when it comes to energy supply. The high number of individual heat generation units – 84% of the Belgian households are heated by individual fossil fuel installations – compared to the collective district heating approach in other EU countries, such as Denmark and Sweden, confirms this. Besides this individual thinking, it is also legally not straightforward to set up an energy community. Consequently, installing individual heat pumps in a Belgian context could be considered a reasonable step toward decarbonizing thermal services. However, from an economic, material use, or sustainability perspective, this individual electrification may not be optimal. Moreover, it could be infeasible in densely built areas due to a lack of space.

A feasible solution involves sharing heat production units among neighbours, promoting smart use of resources, and enhancing overall system efficiency. Energy communities not only aim for a local, citizen-driven, bottom-up approach but also help increase public acceptance of renewable energy projects. A first step in this bottom-up approach could be a Micro Energy Community (MEC), a small-scale energy community, which might be a viable concept in Belgium. This article examines the benefits and the cost of CO_2 emissions abatement of an MEC in a tiny residential cluster of three existing houses in the Belgian context.

Four energy system scenarios

This article presents the CO_2 emissions abatement cost for three electrified energy system scenarios, including one individual and two MEC scenarios, compared to a reference scenario in a tiny residential cluster. The cluster consists of three single-family houses with moderate building envelope qualities and low-temperature radiators, inspired by real houses in Genk (Belgium). The occupancy varies from two adults to two adults with two children. Each energy system supplies heat for Space Heating (SH), heat for Domestic Hot Water (DHW), and electricity for household appliances.

The **reference scenario** represents a typical case in Belgium, where SH and DHW are provided by individual condensing gas boilers. This scenario is schematically presented in Figure 1. The full red lines indicate the thermal connections, the green lines denote the electrical connections, and the yellow lines represent the gas supply. The green and yellow dots signify the electricity and gas meters, respectively, which separate the individual buildings (solid lines) from the public distribution grid (dashed lines).

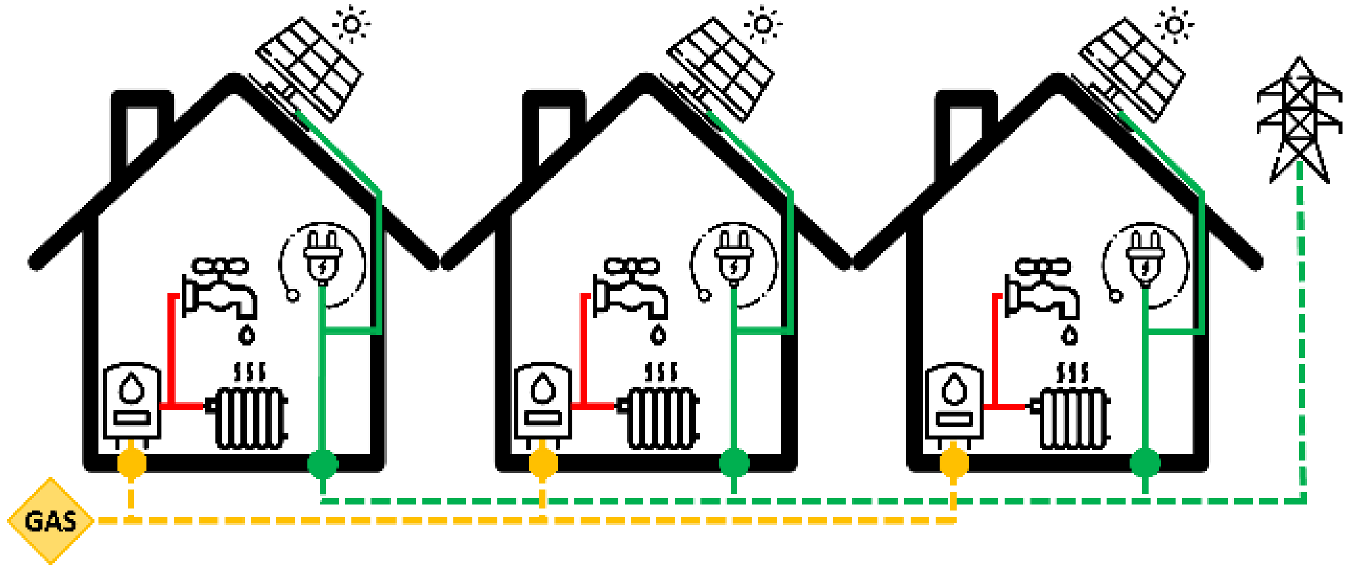

Figure 1: Diagram of the reference scenario.

In the **individual electrification scenario**, thermal services are electrified by replacing the gas boilers shown in Figure 1 by air-to-water heat pumps, as depicted in Figure 2. These air-to-water heat pumps are connected to the electricity grid.

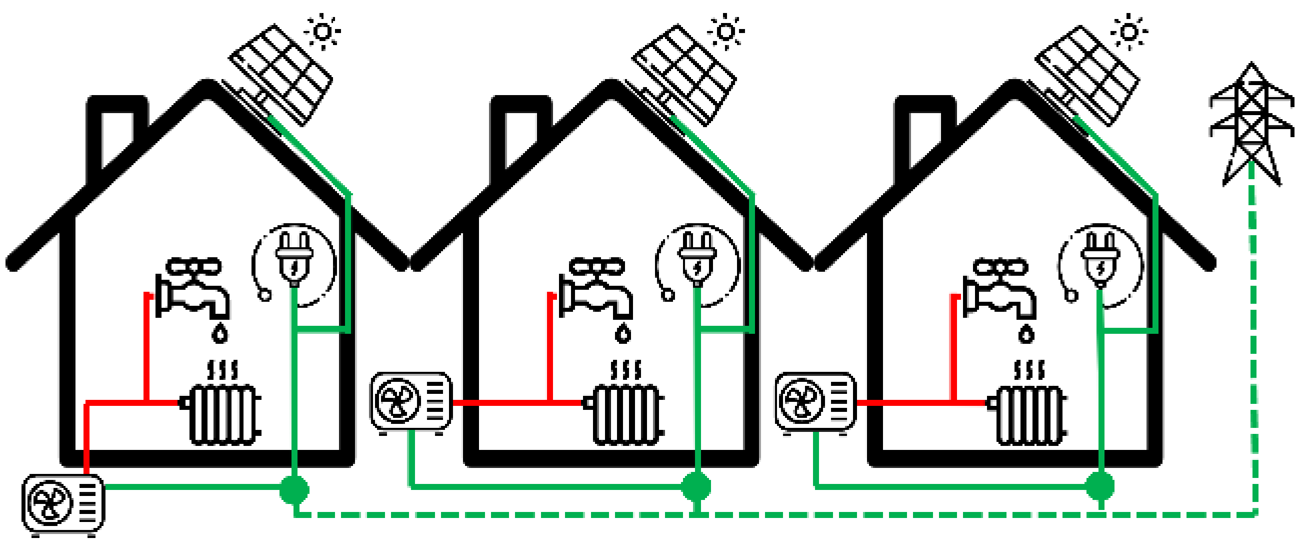

Figure 2: Diagram of the individual electrification scenario.

In the **electricity-sharing scenario**, the benefits of sharing electricity in the case of electrified thermal services are explored. In Belgium, sharing locally produced electricity with other parties is possible. Consequently, this allows the tiny cluster to be treated as a single entity by the distribution grid. Therefore, in Figure 3, the green dots and the solid and dashed green lines have been modified compared to Figure 2.

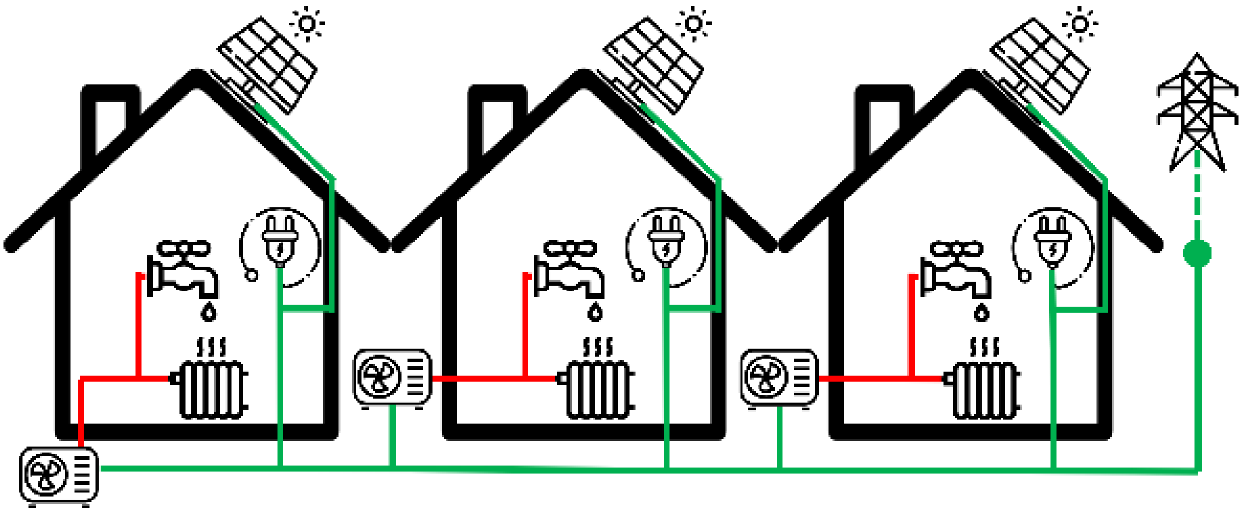

Figure 3: Diagram of the electricity sharing scenario.

In the **energy community scenario**, the benefits of a fully integrated energy community that shares all energy vectors, i.e. heat and electricity, are investigated. In this setup, the individual heat pumps shown in Figure 3 are replaced by a collective air-to-water heat pump and a micro district heating network, as depicted in Figure 4.

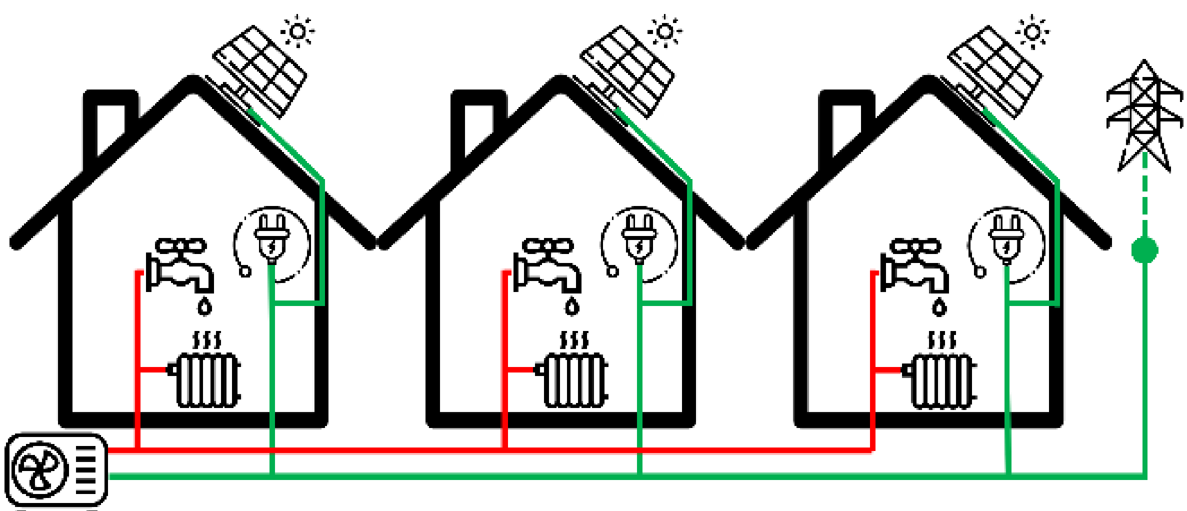

Figure 4: Diagram of the energy community scenario.

Regarding electricity supply, all scenarios include three individual PV installations, with two possible installation sizes (A and B) compared in each scenario. In option A, the PV installation is sized based on the plug load demand in the reference scenario. In option B, the entire roof surface is used for the PV installation. All other energy system components are sized according to established standards. Since both the electricity sharing and energy community scenarios involve energy sharing, they are classified as MECs.

Optimal control

In addition to the energy system design, an appropriate controller acts as the system integrator. The reference scenario employs a simple rule-based on/off control. In contrast, the electrified scenarios use optimal control to fully exploit the non-linear behaviour of the heat pumps and the building's flexibility. The employed optimal controller is an idealized model predictive controller that uses a detailed white-box system model (without model mismatch) and perfect predictions of the boundary conditions such as occupancy, weather data, CO_2 emission intensity, and energy prices, eliminating the need for a feedback loop. All boundary condition data are correlated, time-dependent profiles sourced from 2021 and linked to the city of Leuven (Belgium).

The optimal controller optimizes the control inputs over one year by minimizing a multi-criteria objective function consisting of three criteria: (i) minimization of CO_2 emissions, (ii) minimization of primary energy use (or maximization of energy efficiency), and (iii) minimization of thermal discomfort. Minimizing operational CO_2 emissions primarily targets reducing the climate impact of energy services in the built environment, a key driver for transitioning to energy communities. The operational CO_2 emissions originate from the gas boilers in the reference scenario and the electricity offtake from the distribution grid in all scenarios. Simultaneously, the objective is to maximize thermal comfort while minimizing the use of "primary" energy, thereby enhancing energy efficiency. These criteria ensure that any emission-free electricity generated by the PV installation is used efficiently, avoiding the unnecessary use of resources, including materials. It is important to note that the objective function does not target maximum PV self-consumption or minimum operational costs. Nevertheless, the controller always prioritizes locally generated electricity because electricity generated by the PV installation is emission-free. Moreover, electricity originating from renewable energy sources has a low marginal cost, resulting in a strong correlation between the CO_2 emission intensity and the price of electricity.

Figures 5-6-7-8 present the main results, focusing on (1) the annual electricity balances, (2) the annual operational CO_2 emissions, (3) the annual total costs, and (4) the CO_2 emissions abatement costs.

Annual electricity balance

Figure 5 displays the clusters' total electricity demand (by the bars) and total electricity generation by the PV installations (yellow for option A and green for option B), both represented as positive values. In the reference scenario, there is only an electricity demand for household appliances. The higher electricity demand (≈ 12 MWh) in the electrified scenarios reflects the contribution of the heat pump(s) supplying approximately 54 MWh of heat for SH and DHW. The results show a net positive energy surplus from the clusters in the electrified scenarios when the entire roof surface is used for PV (indicated by the arrow).

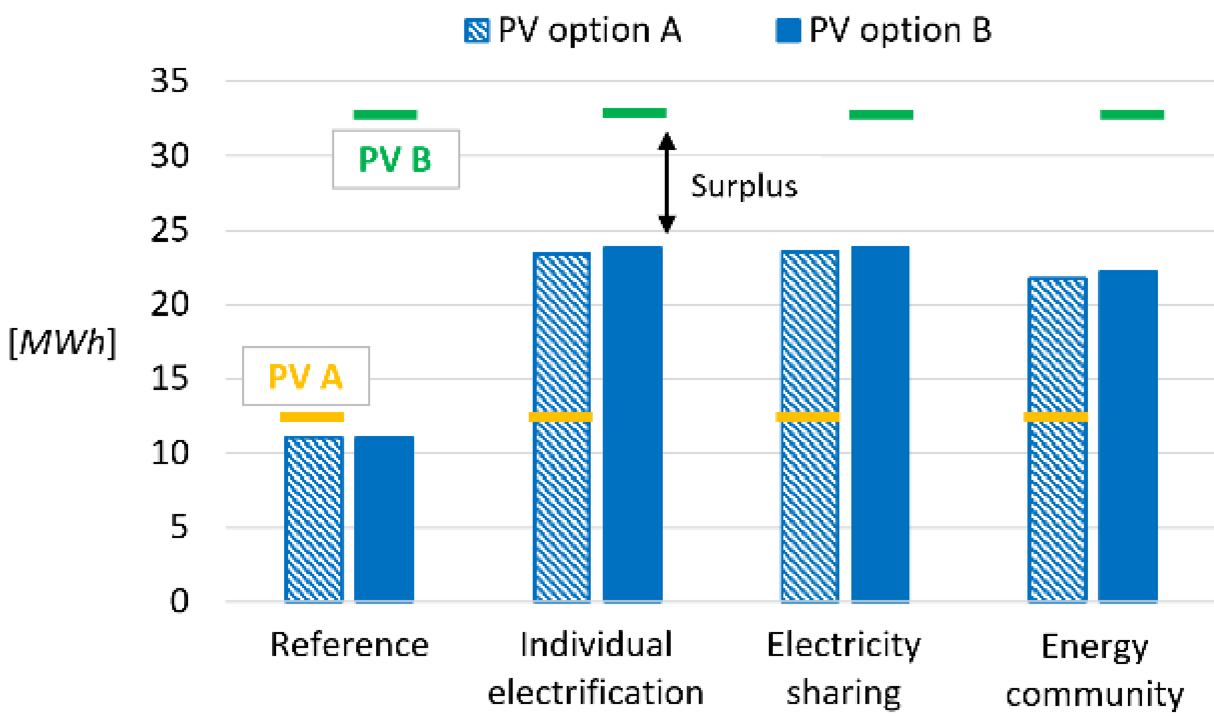

Figure 5: Annual electricity balances.

Annual operational CO_2 emissions

Figure 6 shows the cluster's total operational CO_2 emissions. Moving from the reference scenario to the electrified scenarios results in a reduction of over 93% in CO_2 emissions. Furthermore, shifting from the individual electrification scenario to the energy community scenario reduces the CO_2 emissions by approximately 10%, which increases to about 20% when the entire roof surface is used for PV in the electrified layouts. However, the absolute difference between PV option A and PV option B is relatively small due to the temporal mismatch between the peak demand for residential SH in winter and the peak PV electricity generation in summer. It is important to note that the optimal controller minimises the CO_2 emissions in the electrified scenarios and that the cluster does not receive any CO_2 emissions compensation for injecting emission-free electricity into the grid.

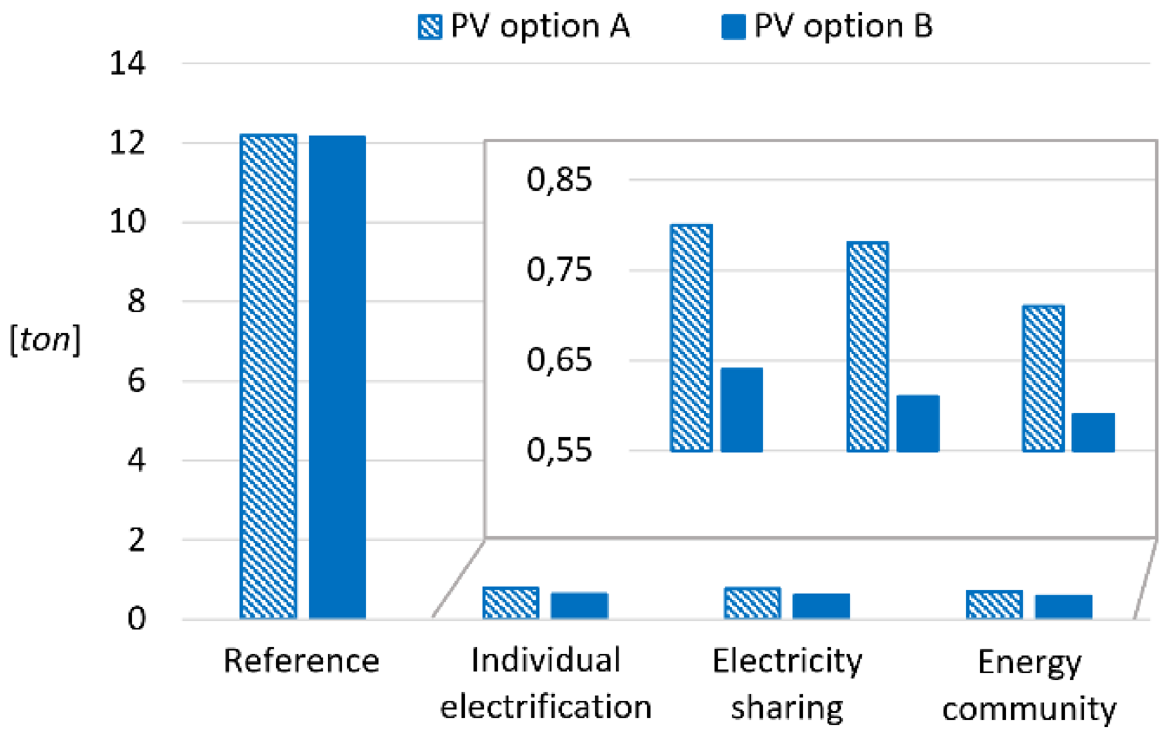

Figure 6: Annual CO_2 emissions.

Annual total costs

Figure 7 presents the annual total costs. These costs comprise annual investment costs (annualized investment costs considering component lifetimes and a discount rate of 7%) along with yearly maintenance costs, which together form the annual fixed costs and yearly operational costs. In the electrified scenarios, the fixed costs are higher compared to the reference scenario, while the operational costs are lower, resulting finally in higher total costs. Installing PV on the entire roof surfaces (PV option B) has a similar effect compared to PV option A, higher fixed cost, lower operational costs and higher total costs. Electricity sharing results in only a limited reduction of approximately €100 (or $107) in operational costs. However, the energy community scenario benefits from a larger, more cost-effective heat pump instead of three smaller ones.

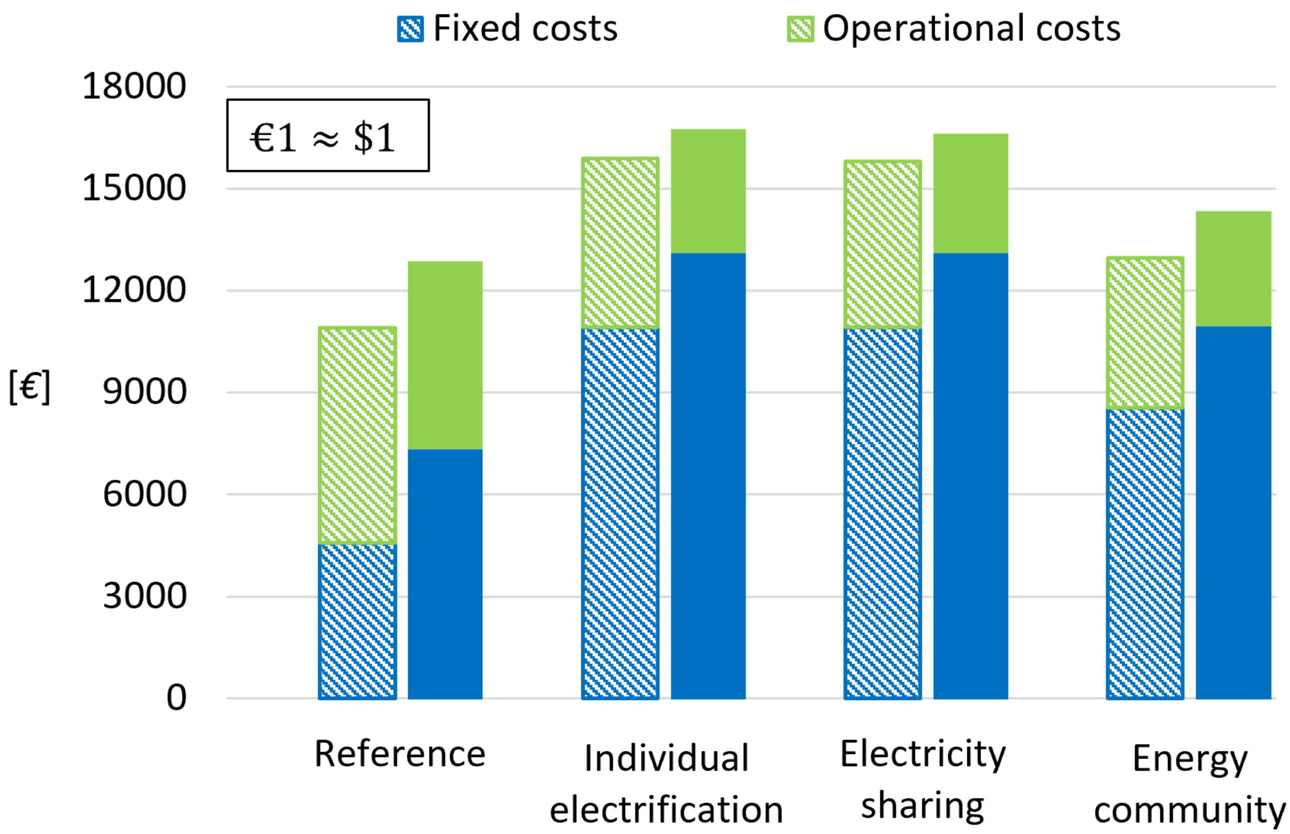

Figure 7: Annual total costs (PV option A: shaded, PV option B: filled).

CO_2 emissions abatement costs

Combining the annual costs from Figure 7 and the annual CO_2 emissions from Figure 6 results in the cost of CO_2 emissions abatement in the electrified scenarios, illustrated in Figure 8. The results indicate that transitioning to a more collective approach lowers the cost of CO_2 emissions abatement. However, installing additional PV capacity (option B) increases the CO_2 emissions abatement cost. In this specific case of a tiny residential cluster, the most effective energy system features a collective heat pump and a PV installation sized according to the plug load demand. This system achieves a 94% reduction in operational CO_2 emissions at a cost of 179 (or $192).

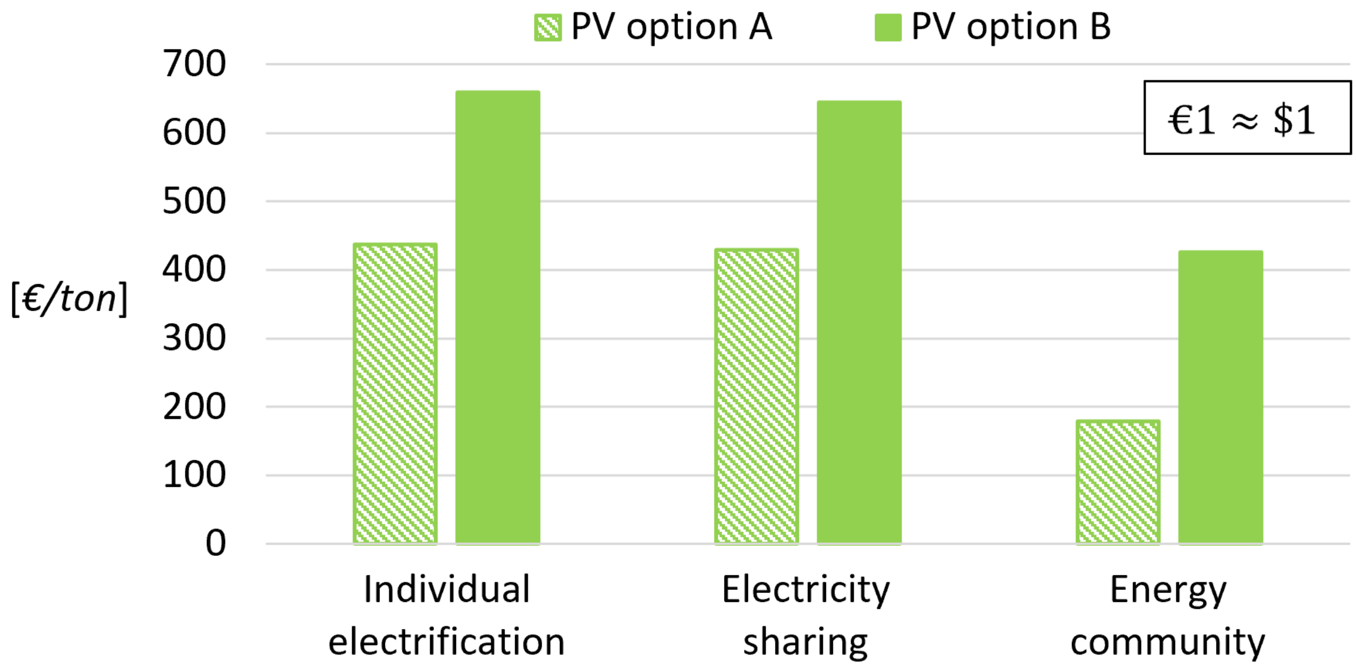

Figure 8: CO_2 emissions abatement costs.

Europe's emission trading system can put these CO_2 emissions abatement costs into perspective. Currently, the EU Emissions Trading System (ETS) is implemented as a cap-and-trade carbon market aimed at reducing Europe's CO_2 emissions in industry and aviation. As an extension, Europe plans to introduce a new emission trading market, ETS 2, in 2027, targeting emissions from fuel combustion in buildings and other sectors. It is projected that the cost of one allowance under EU ETS2 will be €46 per ton of CO_2 at its inception, after which the allowance cost will vary according to the market. In 2021, EU ETS prices fluctuated between €32 and €80 per ton of CO_2. The calculated CO_2 emissions abatement costs within micro energy communities are significantly higher than anticipated future emission taxes, primarily due to high investment costs and a high electricity-to-gas price ratio in Belgium.. This underscores the need for an equitable electricity-to-gas price ratio, which is expected to be more balanced in the future.

Conclusions

This study demonstrates that micro energy communities, where both thermal and electrical energy are shared, can achieve significant CO2 emission reductions compared to fossil fuel-based reference scenarios at a cost of €179 (or $192) per ton of CO2 abated. This cost is significantly higher than the emission taxes that Europe plans to implement in the residential sector in 2027, due to a high electricity-to-gas price ratio in Belgium. However, more balanced and equitable electricity and gas prices are expected towards the future, making these energy community scenarios feasible and cost-effective solutions for structurally reducing CO2 emissions in the built environment, even in clusters of buildings with moderate building envelope qualities. For more details on the methodology and the discussion of the assumptions, we refer to Verleyen et al. (2024).

References

- This article is a summary of:
  Verleyen, L., Arroyo, J., Helsen, L. 2024. The cost of CO_2 emissions abatement in a micro energy community in a Belgian context. [Revised version submitted to Smart Energy]
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