

Multi-Objective Optimisation of Community Energy Systems with Electrified Mobility

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Abstract:

The electrification of transport is expected to significantly influence the design and operation of future community energy systems. This study investigates the impact of electric vehicle (EV) penetration on the economic and environmental performance of a community energy system using a simulation–optimisation framework coupling TRNSYS dynamic simulations with multi-objective optimisation. The analysis is conducted for the town of Falset (Spain) over a 40-year project lifetime, considering both building energy demand and mobility demand.

Two mobility scenarios are analysed: the current vehicle fleet and a fully electrified fleet. The results show that electrifying the vehicle fleet substantially improves system performance by eliminating fossil fuel consumption associated with internal combustion engine vehicles. A Pareto analysis is performed to evaluate the trade-off between net present cost (NPC) and environmental impact calculated using the ReCiPe methodology.

The results also demonstrate that renewable energy technologies remain important even under full electrification. Compared with a fully electrified system without renewable technologies, the optimised configurations reduce the net present cost by approximately 9–10% and the environmental impact by about 11%. The analysis further shows that mobility electrification mainly affects the electrical subsystem of the community energy system, particularly the photovoltaic capacity required to supply EV charging demand.

These findings highlight the importance of jointly considering renewable energy deployment and transport electrification when planning future community energy infrastructures.

Keywords:

Community energy systems; Multi-objective optimisation; Electric vehicle; Life cycle assessment; Net present cost

1. Introduction

The transition toward low-carbon energy systems requires the simultaneous decarbonisation of both building energy use and transportation. Buildings account for a significant share of global energy consumption and greenhouse gas emissions, while the transport sector remains heavily dependent on fossil fuels [1]. Electrification of mobility, particularly through the deployment of electric vehicles (EVs), is therefore considered a key pathway for reducing emissions and supporting the integration of renewable energy sources within local energy systems [2,3].

In parallel, the development of renewable energy communities has emerged as an important strategy to promote decentralised energy generation and increase local participation in the energy transition [4]. In such systems, electricity generation, storage and consumption are managed at the community level, often combining renewable technologies such as photovoltaic (PV) systems with local storage solutions [5]. The increasing penetration of EVs introduces additional electricity demand that can significantly affect the design and operation of these community energy systems.

EV adoption can alter both the magnitude and temporal distribution of electricity demand, potentially necessitating adjustments to renewable generation capacity, electrical storage, and grid interactions [3]. As the number of electric vehicles increases, electricity demand associated with mobility may become a significant component of the total energy demand of local communities. Understanding how this additional demand affects the optimal design of renewable-based energy systems is therefore essential for long-term energy planning. However, relatively few studies have examined how large-scale electrification of mobility influences the optimal configuration of community energy infrastructures when both economic and environmental performance are considered over long time horizons.

Understanding these structural impacts is particularly relevant for rural communities, where mobility demand is typically high due to strong dependence on private vehicles [6]. As EV penetration increases, the electrification of transport may become a major driver of electricity demand, potentially reshaping the optimal sizing of renewable generation and storage technologies.

This study investigates the impact of EV penetration on the optimal configuration and performance of a community energy system. A simulation–optimisation framework coupling TRNSYS dynamic energy simulations with a multi-objective optimisation algorithm is employed to analyse the system behaviour under two electrification scenarios, in which conventional internal combustion engine vehicles (ICEVs) are progressively replaced by electric vehicles. The economic and environmental performance of the system is evaluated using net present cost (NPC) and life-cycle environmental impact indicators, while the resulting optimal system designs are analysed to identify how renewable generation and storage capacities evolve with increasing EV penetration.

2. Methodology

2.1 Simulation–optimisation framework

The analysis is performed using a simulation–optimisation framework coupling dynamic energy system simulation with multi-objective optimisation. The overall workflow of the methodology is illustrated in Figure 1.

The framework integrates TRNSYS 18 dynamic simulations with an external optimisation routine implemented in Python. Input data include hourly weather profiles, community energy demand profiles (electricity and heating), electric vehicle (EV) mobility demand, as well as technical, economic, and environmental parameters of the energy system components.

For each candidate system configuration generated by the optimisation algorithm, TRNSYS performs an hourly simulation of the energy system over a representative year. The simulation computes energy production, storage behaviour, and energy exchanges with the electricity grid. The resulting operational data are then post-processed to evaluate system-level performance indicators. The optimisation process searches for system configurations that minimise both economic and environmental objectives. The economic performance is assessed through the total net present cost (NPC), while the environmental performance is quantified using a life-cycle environmental impact indicator based on the ReCiPe 2016 methodology [7].

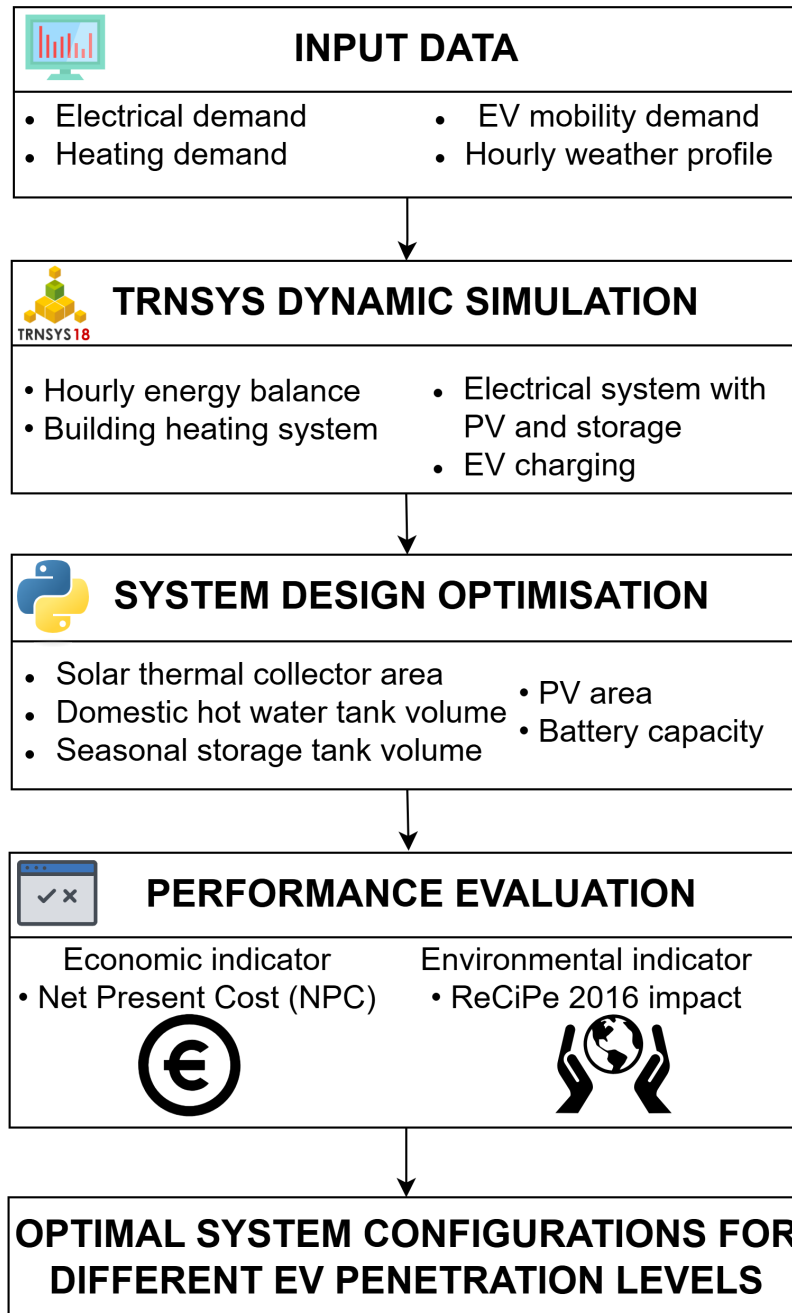


Figure 1. Simulation-optimisation framework used to identify optimal community energy system configurations for different EV penetration levels.

The total net present cost (NPC_{total}) is calculated as the sum of the initial investment cost, operating cost, and replacement cost over the project lifetime:

$$NPC_{total} = IIC + OC + RC \quad (1)$$

where IIC = initial investment cost, OC = operating cost, RC = replacement cost

The total environmental impact (RCP_{total}) is calculated as the sum of the impacts associated with energy consumption (gas, electricity, and ICEV fuel) and the production and installation impacts of the system components:

$$RCP_{total} = I_{gas} + I_{elec} + I_{fuel,ICEV} + \sum_{i=1}^n PII \quad (2)$$

where I_{gas} is the environmental impact associated with gas consumption; I_{elec} is the environmental impact associated with electricity consumption; $I_{fuel,ICEV}$ represents the environmental impact associated with fuel consumption by internal combustion engine vehicles (ICEVs); and PII_i denotes the production and installation environmental impact of component (i).

These indicators allow the combined evaluation of stationary energy uses and transport electrification within the community energy system.

2.2 Energy community system model

The community energy system considered in this study combines renewable energy generation, thermal storage, electrical storage and grid interaction to satisfy both building energy demand and electric mobility demand. The system configuration implemented in TRNSYS is illustrated in Figure 2.

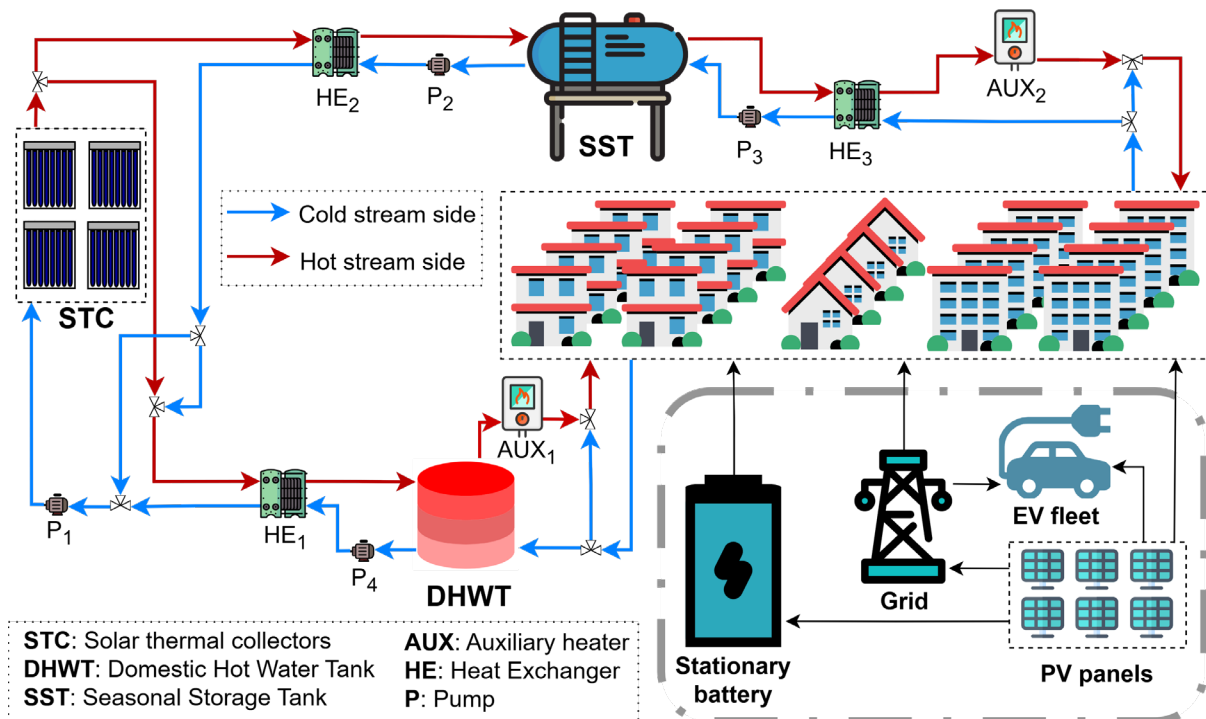


Figure 2. Schematic representation of the integrated community energy system supplying building energy demand and EV charging.

Thermal energy is supplied by solar thermal collectors (STC) coupled with a domestic hot water tank (DHWT) and a seasonal storage tank (SST). Heat exchangers and circulation pumps ensure heat transfer between the different components of the thermal network. When renewable thermal production is insufficient, an auxiliary heater (AUX) provides additional heat to maintain the required supply temperature.

On the electrical side, photovoltaic (PV) panels generate electricity to meet the community demand. A stationary battery is included to store excess electricity and improve the self-consumption of locally produced renewable energy. The community can also exchange electricity with the external grid when local generation and storage are insufficient to satisfy demand.

Electric mobility is represented by an aggregated EV fleet whose charging demand is integrated into the electrical load of the community. In this study, EV charging is assumed to follow unmanaged charging behaviour, meaning that vehicles begin charging immediately after arrival based on their mobility profile.

2.3 System design optimisation

The optimisation process determines the optimal sizing of the main energy system components. Decision variables include photovoltaic capacity, stationary battery capacity, solar thermal collector area, and the volumes of the thermal storage tanks.

For each candidate configuration, TRNSYS simulations provide the hourly operation of the system, which is used to calculate the economic and environmental indicators. The optimisation algorithm evaluates the trade-off between these objectives and identifies optimal system designs under different EV penetration scenarios.

The resulting optimal configurations allow the analysis of how increasing electrification of mobility influences the design and performance of community energy systems.

3. Case study

This section describes the case study and the main assumptions used to represent building and mobility energy demand within the community. The system is evaluated over a 40-year analysis horizon in order to assess its long-term economic and environmental performance. The parameters used for the life cycle cost (LCC) assessment are defined within the model. Following the methodology proposed by Tulus et al. (2016) [8], annual maintenance costs are assumed to equal 1.5% of each component's initial investment cost. The unit prices of natural gas and electricity are taken as 0.0878 €/kWh and 0.2436 €/kWh, respectively, based on data from EUROSTAT [9,10]. In addition, the electricity selling price is set to 0.0616 €/kWh according to Red Eléctrica [11]. To account for economic conditions, a general inflation rate of 1.61% is assumed over the system's lifetime, together with a discount rate of 0.64% [4].

For the life cycle assessment (LCA), input data are obtained from the Ecoinvent v3.11 database [12]. The environmental impacts of the system components are evaluated using the ReCiPe 2016 methodology.

The following subsections present the modelling assumptions for the building energy demand and the mobility demand considered in the simulations.

3.1. Buildings energy demand

The town of Falset (41°08'41.5"N, 0°49'05.6"E), located in the Priorat region in Tarragona (Catalonia, Spain), is used as the case study for this work. With a population typical of small Mediterranean towns, Falset represents a context where residential buildings are spatially distributed and daily mobility relies heavily on private vehicles. Such conditions make it particularly suitable for analysing the impact of mobility electrification on local energy systems [6].

The region is characterised by a Mediterranean climate (Csa according to the Köppen–Geiger classification), with mild winters and hot, dry summers [13]. The analysed energy community includes 1,058 buildings comprising 1,712 dwellings [5].

The considered community energy system is designed to meet space heating (SH), domestic hot water (DHW), and electricity demands while also supplying the charging demand of the local vehicle fleet. Space heating is supplied at 50 °C and domestic hot water at 60 °C. Figure 3 illustrates the monthly energy demand profiles used in the simulations, including electricity, heating, and domestic hot water.

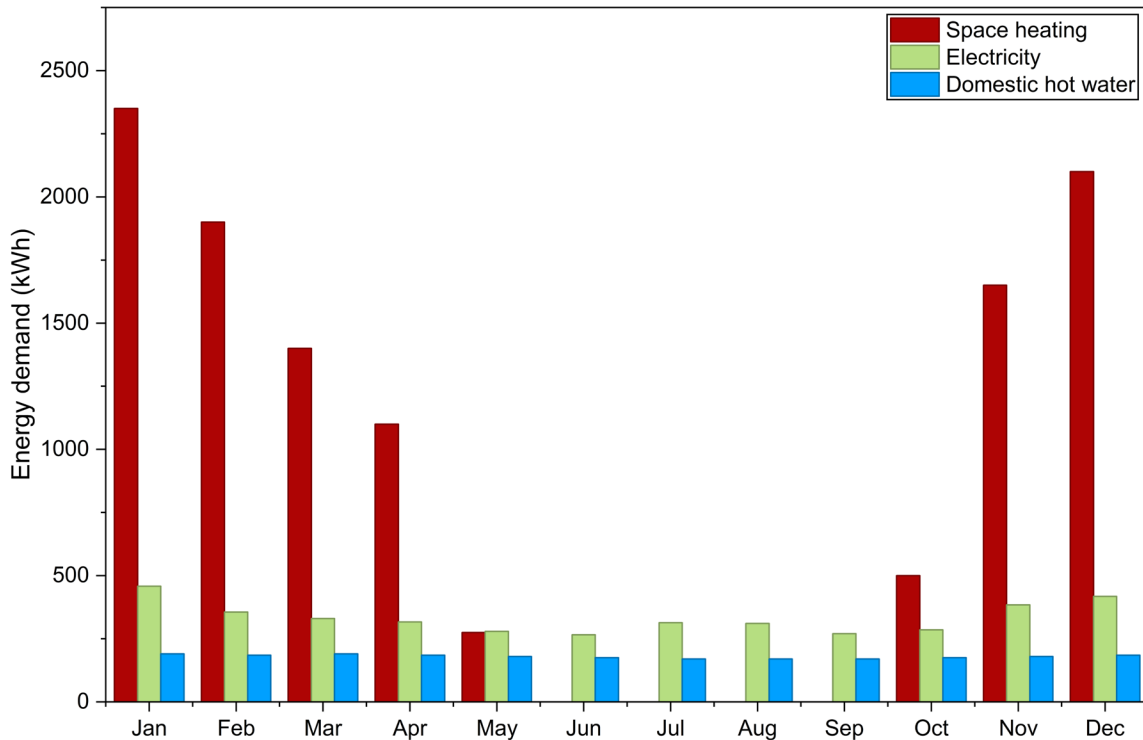


Figure 3. Monthly energy demand profiles of the community, including space heating, electricity, and domestic hot water.

3.2. Mobility energy demand

Mobility demand in the community is represented by a fleet of passenger vehicles associated with the residential dwellings. The total number of vehicles in Falset is estimated at 1,563 based on regional vehicle registration statistics [14]. In the current situation, only a small share of this fleet is electrified.

To estimate the number of electric vehicles (EVs) currently present in the community, a proportional allocation approach based on regional EV adoption is applied [15]. Using population statistics for Catalonia and Falset together with the total number of EVs registered in Catalonia, the number of EVs in Falset is estimated at 29 vehicles [16]. The remaining vehicles are therefore modelled as internal combustion engine vehicles (ICEVs).

Each EV is represented using characteristic parameters derived from commonly sold electric vehicles in Spain [17], assuming a battery capacity of 54 kWh and an average energy consumption of approximately 0.17 kWh/km. Mobility demand follows a high-use driving pattern with average daily driving distances of 72 km on weekdays and 80 km on weekends, reflecting the strong dependence on private vehicles typically observed in rural areas[18,19].

EV charging demand is derived using the Electric Vehicle Charging and Grid Integration Tool developed by the International Energy Agency (IEA) [20], taking into account mobility patterns and local

temperature conditions. Charging behaviour is assumed to follow unmanaged charging, meaning that vehicles begin charging immediately upon arrival. The resulting EV charging demand is incorporated into the electrical demand of the community and used as an input to the TRNSYS simulations.

4. Results and discussion

This section presents the optimisation results obtained for different levels of mobility electrification in the community over a 40-year analysis period. In the current situation, the vehicle fleet consists of 1,563 vehicles, including 29 electric vehicles (EVs), while the remaining vehicles are represented as internal combustion engine vehicles (ICEVs). Full electrification corresponds to a scenario in which the entire fleet is replaced by EVs.

The optimisation framework determines the optimal sizing of the main energy system components, including PV area, battery capacity, solar thermal collectors area, and thermal storage volume. System performance is evaluated using two indicators: the total net present cost (NPC) and the life-cycle environmental impact calculated using the ReCiPe methodology. The following subsections present the economic and environmental results, followed by the Pareto analysis of the fully electrified system.

4.1. Economic performance

The economic performance of the community energy system is evaluated using the total net present cost (NPC) over the 40-year analysis period. Figure 4 compares the NPC of the current vehicle fleet with the full electrification scenario for five representative solutions extracted from the Pareto front.

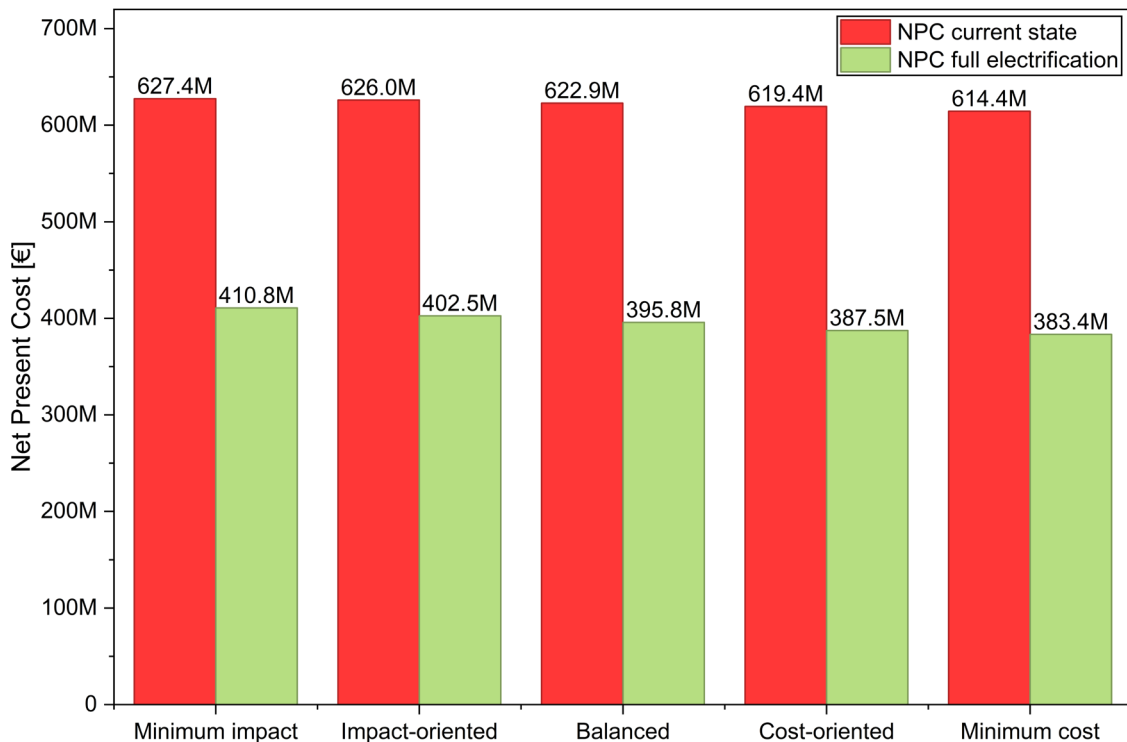


Figure 4. Net present cost (NPC) comparison between the current fleet and the full electrification scenario for the five representative Pareto solutions.

The results indicate that full electrification significantly reduces the total system cost for all Pareto solutions. NPC decreases from approximately 614–627 M€ in the current fleet scenario to about 383–411 M€ in the fully electrified case. This reduction is primarily driven by the elimination of fuel costs

associated with internal combustion engine vehicles, which dominate the operational expenses over the project lifetime.

4.2. Environmental performance

The environmental performance of the community energy system is evaluated using the total life-cycle environmental impact calculated with the ReCiPe methodology. Figure 5 compares the environmental impact of the current vehicle fleet with the full electrification scenario across the five representative Pareto solutions.

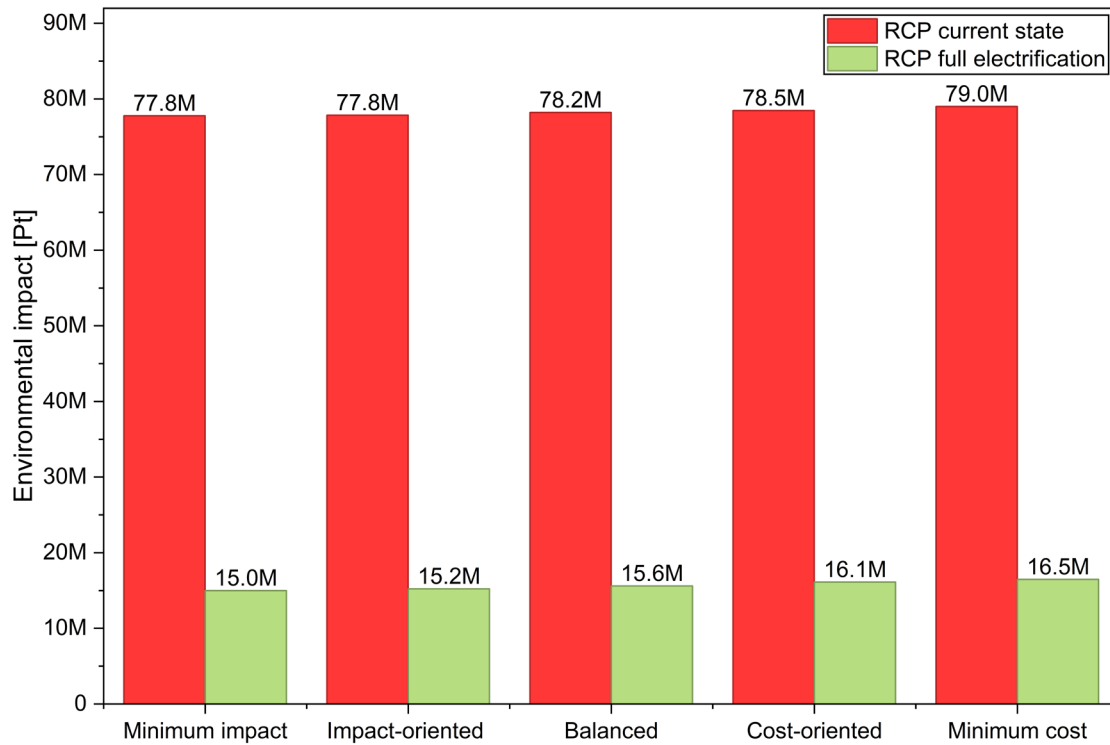


Figure 5. Comparison of the environmental impact (RCP) for the current vehicle fleet and the full electrification scenario across the representative Pareto solutions.

The results show a very large reduction in environmental impact when the vehicle fleet is fully electrified. Across all Pareto solutions, the environmental impact decreases from approximately 78–79 MPt in the current fleet scenario to about 15–17 MPt in the full electrification case, corresponding to a reduction of roughly 75–80%. This reduction is significantly larger than the economic improvement observed in the previous subsection and highlights the dominant contribution of ICEV fuel consumption to the life-cycle environmental impact of the mobility subsystem. Over the 40-year analysis period, the cumulative emissions associated with fossil fuel use in ICEVs represent a major environmental burden, which is largely eliminated when the vehicle fleet is electrified.

4.3. Pareto analysis of the fully electrified system

To further analyse the trade-off between economic and environmental performance, a Pareto front is generated for the fully electrified scenario. Figure 6 presents the optimal solutions obtained from the multi-objective optimisation, together with a reference configuration representing a fully electrified system without renewable energy technologies.

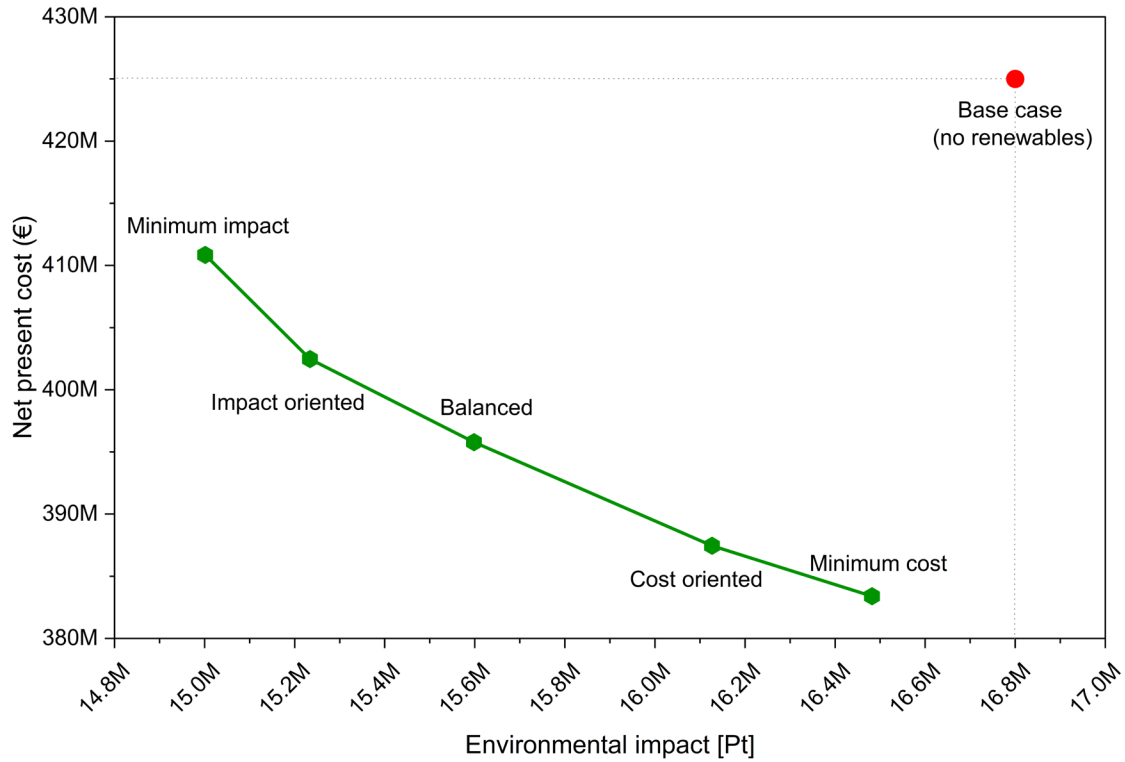


Figure 6. Pareto front of the fully electrified system showing the trade-off between environmental impact and net present cost.

The Pareto front illustrates the trade-off between net present cost and environmental impact for the fully electrified system. Moving from the minimum impact solution toward the minimum cost solution reduces system cost while slightly increasing environmental impact. The reference configuration without renewable energy technologies lies outside the Pareto front, exhibiting both higher cost and higher environmental impact than the optimised solutions. This indicates that renewable energy technologies remain important even under full electrification of the vehicle fleet.

The optimal system configurations corresponding to the representative Pareto solutions are summarised in Table 1. The table reports the main design variables of the energy system together with the associated economic and environmental indicators. The following abbreviations are used: *NPC* denotes the net present cost, *RCP* represents the total environmental impact, *STC* denotes the solar thermal collector area, *SST* refers to the seasonal storage tank, *DHWT* represents the domestic hot water tank, *PV* corresponds to the photovoltaic area, and *Bat* indicates the stationary battery storage capacity.

Table 1. Optimal system design variables for the representative Pareto solutions and the reference case without renewable energy technologies.

	<i>RCP</i> [M Pt]	<i>NPC</i> [M€]	<i>STC</i> [10 ³ m ²]	<i>SST</i> [10 ³ m ³]	<i>DHWT</i> [m ³]	<i>PV</i> [10 ³ m ²]	<i>Bat</i> [MWh]
Min impact	15.0	410.8	17.4	156.5	385	21.2	7.6
Impact oriented	15.2	402.5	17.6	158.9	385	40.3	7.6
Balanced	15.6	395.7	17.4	159.9	640	59.4	7.6
Cost oriented	16.1	387.4	17.6	158.9	385	65.7	0.4
Min cost	16.5	383.3	17.4	166.9	673	79.3	0
Base case	16.8	425.0	0	0	0	0	0

The results highlight that the optimal configuration of the heating subsystem remains relatively stable across the Pareto solutions. The solar thermal collector area and the seasonal storage tank volume vary only slightly, indicating that the design of the thermal system is not significantly affected by the electrification of mobility. In contrast, the electrical subsystem exhibits larger variations. In particular, the photovoltaic (PV) capacity increases progressively when moving toward cost-oriented solutions, reflecting the economic advantage of local electricity generation to supply the additional demand from electric vehicles. At the same time, battery capacity decreases along the Pareto front and is completely removed in the minimum cost configuration, suggesting that increasing PV deployment combined with grid interaction can be economically preferable to large electrical storage investments. Overall, these results indicate that mobility electrification mainly influences the electrical infrastructure of the community energy system, while the thermal subsystem remains comparatively stable.

5. Conclusion

This study analysed the impact of mobility electrification on the economic and environmental performance of a community energy system using a simulation–optimisation framework. The analysis was carried out for the town of Falset over a 40-year project lifetime, considering both building energy demand and transport energy demand.

The results show that electrifying the vehicle fleet significantly improves the overall performance of the community energy system. Replacing internal combustion engine vehicles with electric vehicles leads to substantial reductions in both net present cost and environmental impact, mainly due to the elimination of fossil fuel consumption associated with conventional vehicles.

The Pareto analysis also highlights the importance of integrating renewable energy technologies within the electrified system. Even under full electrification, the reference configuration without renewable technologies results in both higher costs and higher environmental impacts than the optimised solutions. In particular, integrating renewable energy technologies reduces the net present cost by approximately 9–10% and the environmental impact by about 11% compared to the fully electrified system without renewables.

The analysis of the optimal system designs further shows that mobility electrification mainly influences the electrical subsystem of the community energy system. Photovoltaic capacity increases significantly to supply the additional electricity demand associated with EV charging, while battery storage becomes less economically attractive in cost-oriented configurations. In contrast, the design of the thermal subsystem remains relatively stable across the different Pareto solutions.

Overall, the results highlight the importance of jointly considering renewable energy deployment and mobility electrification when planning future community energy systems. Future work could further investigate the role of advanced EV charging strategies and vehicle-to-grid integration, which may provide additional flexibility and further improve system performance.

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Nomenclature

EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
PV	Photovoltaic panel
NPC	Net Present Cost
IIC	Initial Investment Cost
OC	Operational Cost
RC	Replacement Cost
RCP	Environmental impact calculated using the ReCiPe methodology
I	Environmental Impact
PII	Production and Installation Environmental Impact
STC	Solar Thermal Collector
DHWT	Domestic Hot Water Tank
SST	Seasonal Storage Tank
AUX	Auxiliary heater
Bat	Battery capacity

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