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Panel or check? Assessing the benefits of integrating households in energy poverty into energy communities

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ABSTRACT

This research raises the possibility for households in energy poverty to participate in shared photovoltaic systems in renewable energy communities (REC) to reduce their energy costs, with investment costs covered by public institutions. It begins by evaluating the current solution for vulnerable households, which relies on public subsidies to lower energy costs without addressing root causes or improving environmental impacts. The study compares traditional subsidies with REC participation for vulnerable households. By simulating a REC composed of such households, the results indicate that REC participation is more cost-effective for public institutions than energy subsidies. At the economically optimal size of 31 kWp, the cost of subsidies decreases by 58,000 €, a 50% reduction, with household savings increasing by 6%. At 58 kWp, the need for additional support checks is eliminated, increasing household savings by 65% but with a lower NPV of 22,500 €. The largest viable system, 75 kWp, increases average household savings by 82%. This approach also leads to a net reduction in GHG emissions, engaging previously excluded households in the energy transition.

Introduction

In recent years, the European Union (EU) has witnessed a concerning rise in energy poverty, bringing to light a significant societal challenge. This issue, impacting the wellbeing of EU citizens, gained prominence in 2020 when an estimated 35 million individuals, equivalent to 8% of the population, faced a fundamental struggle to maintain adequate warmth in their homes. Though there was a slight improvement, with the rate decreasing to 6.9% in 2021, 2022 witnessed a notable resurgence, with the rate rising to 9.3% [1]. Energy poverty, characterized by the inability to access affordable, reliable, and secure energy services, is a complex and multidimensional problem. As articulated by Day et al. [2], it can be understood as *"an inability to realize essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy services, and taking into account available reasonable alternative means of realizing these capabilities"*. The EU Energy Poverty Observatory (the predecessor project of the Energy Poverty Advisory Hub) provides a complete definition: *"Energy poverty is a distinct form of poverty associated with a range of adverse consequences for people's health and wellbeing - with respiratory and cardiac illnesses, and mental health, exacerbated due to low temperatures and stress associated with unaffordable energy bills. Energy poverty indirectly affects many policy areas, including health, environment and productivity. Addressing energy poverty can bring multiple benefits, including less money governments spend on health, reduced air pollution, better comfort and wellbeing, improved household budgets, and increased economic activity"* [3]. According to Pellicer-Sifres [4], an adequate definition considers both underlying causes and broader consequences, while offering insights into possible policy interventions.

Energy poverty's severity has been exacerbated by a confluence of factors, including the effects of the COVID-19 pandemic, energy price rises, and geopolitical tensions [5]. The pandemic, in particular, underscored the critical importance of access to basic amenities, such as heating and electricity, as more people spent more time at home [6]. Research conducted by Ambrose et al. [7] delves into the lived experiences of energy-poor households, revealing additional consequences for energy-poor households, mostly linked to limited access to third places and other disruptions to their usual coping strategies. This issue goes beyond individual health and wellbeing [8–11] to have profound implications for economic stability and opportunities, education, and employment prospects [12–14]. Bienvenido-Huertas [15] found that social measures were insufficient to avoid energy poverty during the pandemic lockdown, while Bagnoli et al. [12] analyse the effectiveness

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Nomenclature

Indices

b_0 & b_f	Beginning and end of the billing period
j	Load curve index
n	Year of operation index [yr]
s	Simulation scenarios index
t	Time index [h]

Sets

J	Set of all points of consumption
N	Set of years of operations
S	Set of all simulation scenarios
T	Set of all time periods

Parameters

C^G	Annual cost of electricity purchased from the grid [€/yr]
C^{POW}	Annual cost of power term of electricity of the grid [€/yr]
d	Market discount rate
EC	Bill reduction covered by the electricity check [%]
OM	Operation and maintenance annual expenses [€/yr]
$P^D_{j,t}$	Power demand by consumer j at moment t [kW]
P^{PV}_{nom}	Nominal power of the PV system [kW]
POW_j	Contracted power in the load j [kW]
π^{POW}	Price of contracted power [€/kW]

Variables

β	Allocation coefficient
C^{PUR}_t	Cost of electricity purchased from the grid at moment t [€]
C^{SELL}_t	Cost of electricity sold to the grid at moment t [€]
C^V_t	Cost of the variable term of electricity from the grid at the moment t [€]
CF_t	PV capacity factor at moment t
INV_n	Investment at year n [€]
$P^A_{j,t}$	Power allocated to consumer j at moment t [kW]
$P^{GIFT}_{j,t}$	Power injected into the network without benefit by consumer j at moment t [kW]
$P^{PUR}_{j,t}$	Power purchased from grid by consumer j at moment t [kW]
P^{PV}_t	Power generated by the PV system at moment t [kW]
$P^{SC}_{j,t}$	Power consumed by consumer j directly from the PV system at moment t [kW]
P^{SELL}_t	Power sold to the grid at moment t [kW]
π^{PUR}_t	Price of purchased electricity at moment t [€/kWh]
π^{SELL}_t	Price of sold electricity at moment t [€/kWh]

Metrics

NPV^{INV}_n	NPV of investment at year n [€]
NPV^{REC}_n	NPV of REC at year n [€]
NPV^{OM}_n	NPV of OM at year n [€]
NPV^{SAV}_n	NPV of savings at year n [€]
SAV	Annual billing savings generated by the REC [€]

Acronyms

EU	European Union
NPV	Net Present Value
PV	Photovoltaic
REC	Renewable Energy Communities
RES	Renewable Energy Sources

Subscripts

0	Original situation
REC	After REC implementation

of Spain's electricity social rate's impact on energy poverty. Nevertheless, these policies often overlook underlying energy access issues [16], neglecting lasting solutions like energy efficiency and renewable energy systems.

Meanwhile, public institutions are driving investment in renewable energy infrastructure to meet climate needs and international targets, and rooftop photovoltaic (PV) systems have emerged as an important contributor to this transition in cities [17]. A window of opportunity arises here to optimize investments, and policy measures often operate in silos and interact little with each other [18]. The literature illustrates the interplay between energy and social policies. Kyprianou et al. [19] state that energy poverty should be addressed mainly by creating effective policies while encouraging synergies among policies of different fields. The opportunity is to explore the possible synergy between increasing solar roofs in the city, a new policy for which a new budget is required, and reducing subsidies already provided through this substitute good.

In response to these pressing challenges, this study proposes that a shared renewable energy self-consumption system for energy-poor homes is a superior alternative to traditional energy checks. This support model is demonstrated through a case study in València, Spain, encompassing fifty doubly vulnerable households, including elderly individuals experiencing social isolation and loneliness. We aim to uncover economic and environmental benefits by proposing a sustainable approach to integrating energy-poor households into energy communities, thereby contributing to social welfare and the energy transition. Our goal is to optimize policy design and define how to allocate shared energy coefficients among members to create a cost-effective policy. Additionally, we aim to understand the varying energy needs of different consumers and how this translates into concrete policy measures.

The remainder of the paper is organized as follows: Section "The energy poverty challenge for a just energy transition" discusses the current literature around energy poverty and the two measures to alleviate it discussed in this study, Section "Methodology" presents the methodology and the mathematical model employed. Section "Case study" describes the case study in València. Section "Results" shows the results from the analysis, and Section " Discussion and policy implications" their implications. Finally, Section "Conclusions" concludes by summarizing the paper's main findings.

The energy poverty challenge for a just energy transition

One of the energy transition challenges is energy justice, a key concept to better-informed energy choices from energy planers and consumers [20]. Research by Belaïd [5] highlights how energy prices and the green transition may exacerbate energy poverty in Europe without adequate policies, creating new inequalities and reinforcing existing ones. Energy efficient or renewable energy technologies are often costly, leading to the exclusion of people who cannot afford to adopt them [21]. Moreover, subsidizing the energy-vulnerable may lead to increased energy use and emissions [22]. Therefore, it becomes evident that interactions between energy poverty and carbon emissions need to be recognized, necessitating a holistic approach to energy transition policies.

The European Energy Poverty Advisory Hub (EPAH), the main hub for expertise on energy poverty in Europe, aims to "eradicate energy poverty while accelerating energy transition". This objective aligns with SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all". The objectives of EPAH and SDG 7 were incorporated into the Clean Energy for All Europeans package in 2019 [23]. The Clean Energy for All Europeans package aims to move consumption toward cleaner energy sources while protecting vulnerable consumers from energy poverty. It encompasses a wide array of measures, including enhancing the energy efficiency of buildings, facilitating the integration of Renewable Energy Sources (RES), and reforming the electricity market structure.

Pye et al. [24] classified EU member state policies into four categories: financial aid, consumer protection, energy savings, and information provision. Their research revealed that approximately 75% of EU member states rely on financial aid as a primary support for vulnerable consumers. Moreover, consumer protection mechanisms are in place in about 80% of these member states to prevent disconnections due to non-payment. The study also emphasizes the considerable scope for improving the degree to which building retrofit measures are targeted to those in need. Another comparative study by Kyprianou et al. [19], covering five EU countries, utilized a similar classification but also included renewable energy systems alongside energy efficiency. Notably, only one of the studied countries (Spain) provides measures for the four categories. Both studies mention that subsidized schemes for promoting energy saving and Renewable Energy Sources (RES) are not usually designed as an energy poverty measure; they include the category because the vulnerable population is occasionally given additional incentives. RES demand high upfront costs, but they will pay off in several years with positive effects in reducing energy poverty [25]. However, this measure assumes that vulnerable populations can provide the remainder of the investment, which is not usually possible in cases of energy poverty. Consequently, as stated by Kyprianou et al. [19], energy poverty should be addressed mainly by creating effective policies while encouraging synergies among policies of different fields.

Energy checks as a solution to energy poverty

Bagnoli et al. [12] analyse the effectiveness of the electricity social rate, the "Bono Social de Electricidad", introduced in 2009 in Spain's electricity market, a policy aimed at increasing electricity affordability by entailing a discount on prices for vulnerable consumers. They found that the policy's introduction effectively reduces the likelihood of energy poverty for eligible households. However, the magnitude of the effect is relatively modest, with only 2% of households escaping energy poverty. Another interesting finding was that it does not alter the quantity of electricity consumed but reacts entirely through a lower expenditure on electricity. The authors proposed two possible interpretations for this finding. First, suppose households do not increase their electricity consumption even though its effective price has decreased despite a decrease in its effective price. In that case, it may be due to electricity being a necessity good. In this scenario, demand was already entirely satisfied before the subsidy, and households do not ration their electricity. The savings from a decreased electricity expenditure could be fully allocated to other essential expenses. The less optimistic interpretation would be that the vulnerable households rationed their electricity consumption before the introduction of the policy and are still rationing their consumption after the policy. Thus, according to Hanke et al. [16], while energy checks can provide short-term relief by identifying households needing assistance and providing one-time financial aid, they do not address the underlying issue of access to affordable energy and do not promote sustainable solutions such as energy efficiency measures and the use of RES, which can help reduce energy costs in the long run.

PV systems and energy poverty

Public institutions are driving investments in renewable energy infrastructure to meet climate needs and international targets, and rooftop photovoltaic systems have emerged as an essential contributor to this transition in cities [17]. However, the energy transition seems to hinder energy affordability. Even if adopting renewable energy is the unique solution to mitigate climate change and reduce its cost, it does not favour energy poverty reduction in Europe [26]. Thus, a fair energy transition must consider specific measures or policies to include the most vulnerable consumers.

The EU must carry out a socially just and equitable transition to a carbon-neutral European Union by 2050 to ensure that no one is left behind and that energy and climate targets are met. One of the best options is to empower citizens by involving them in the energy transition [26]. Furthermore, the profitability of implementing optimally sized PV systems increases when forming REC compared to considering buildings individually [27].

The recast of the Renewable Energy Directive (RED II) [28] highlights REC's social role in energy transition and stipulates *"opportunities for renewable energy communities (REC) to advance energy efficiency at household level and (...) fight energy poverty"*. RED II further links an enabling framework *"to promote and facilitate the development of renewable energy communities"* with the obligation to ensure the participation of all *"consumers, including those in low-income or vulnerable households"*. However, RED II refrains from providing details on achieving RECs' social role in practice. Greece [29], Italy [30], Portugal [31], and Spain [32] link RECs with energy poverty alleviation in their national energy and climate plans. Standal et al. [33] explore the challenges that can be identified for energy justice in RECs from the perspective of potential and existing shareholders and discuss how identified challenges are addressed in the recast Renewable Energy Directive (REDII). Their study concludes that RECs alone have limited capacity to address distributional imbalances. It is up to the states and individual RECs to find appropriate ways in which the aspiration for local benefits, combined with the philosophy of democratic governance, can help to reconcile, at least in part, financial, social and other inequalities.

Despite institutional guidelines linking renewable energies with social justice and even referring to it as a solution to energy poverty, policies and aids for implementing these systems are not connected with policies and aids to energy poverty. They are usually focused on consumer protection policies, energy checks, and subsidized schemes for energy efficiency and the use of renewable technologies [19].

Some scientific literature supports the link between energy policy and social policy. According to a study conducted in the United Kingdom [34], community solar PV appears to favour areas of higher deprivation, implying that community groups advocating for solar PV installations have successfully delivered feed-in-tariff benefits to low-income communities. Moreover, according to Primc et al. providing universal access to modern energy infrastructure developed nationally requires significant investment. However, this cost can be somehow compensated for the decrease in the amount granted each year through social support [35].

Methodology

To conduct this research, we followed the methodology described in Fig. 1. The starting point is the computational model of the operation

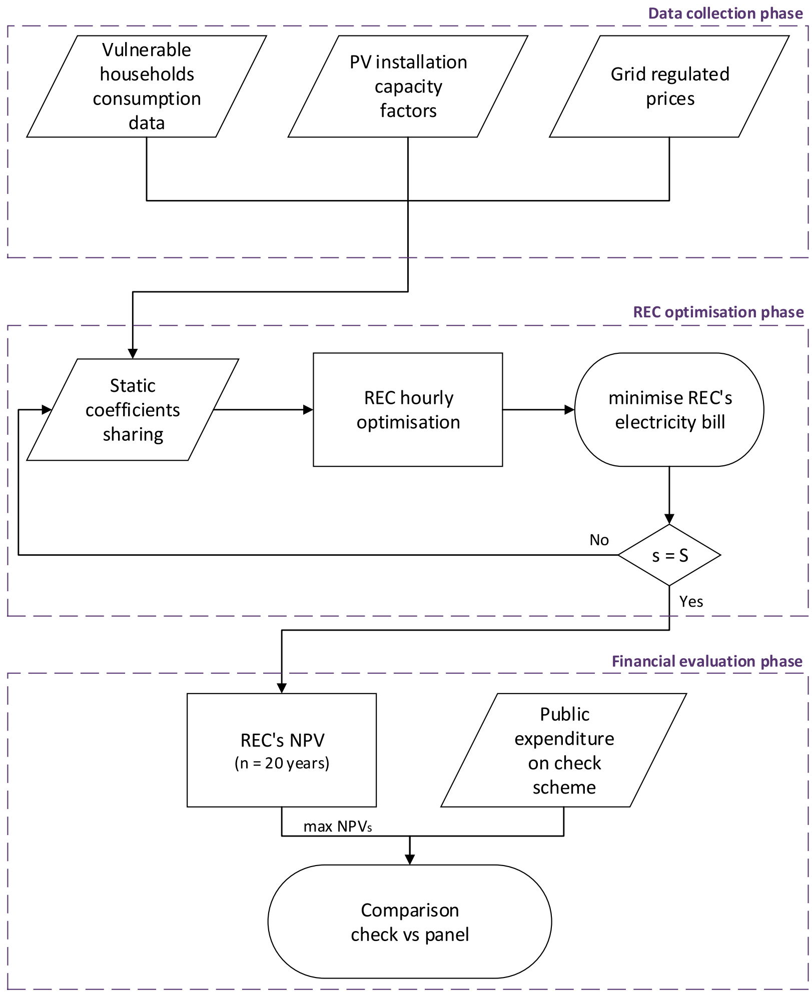

Fig. 1. Methodology workflow.

of a REC that we have developed in previous projects and explained in papers such as [36,37]. The model allows the input of the different load curves of the dwellings that will form the REC. The first phase is data collection, where we obtain information about the generation, consumption and electricity price. We use metered hourly electricity consumption data from vulnerable households for one year, accessed via smart metres. Spanish government forces vulnerable dwellings to get the regulated electricity bill to access public subsidies. Thus, we used the public electricity price of the regulated tariff for this work. The simulation software PVSyst [38] provided the hourly photovoltaic system capacity factors for the case study solar installation.

Optimizing the REC is the next phase once we have gathered all the data. The energy sharing of the REC uses static coefficients, meaning that the sharing rates among all households remain constant all year. This allocation method is more manageable for public authorities to implement and for energy users to understand while not significantly worsening the financial results [36,39]. The objective of the optimization is to minimize the electricity bills of the REC as a whole. Therefore, households will not necessarily all save the same with this scheme, and those whose consumption matches better to energy generation will experience more significant bill reductions. The REC optimization is run considering a range of PV system capacities to identify several potential sizing recommendations.

Finally, we measured each scenario's Net Present Value (NPV) for 20 years of operation. The savings are those of the public institution, instead of the household bill reductions, as they undertake the investment. We selected the best NPV obtained that guaranteed the same level of service as the electricity social rate and compared them. Hence, we measured the schemes regarding financial results for the public institution, bill reduction and overall benefit for the vulnerable users.

Mathematical model

We define the mathematical model in this section, including the REC operation, how electricity gets billed from the grid and the financial evaluation. First, the objective of the optimization function is to minimize the costs (C^G) that households belonging to the REC pay for electricity.

All the power generated in the REC must be appropriately allocated to a consumption point or fed into the grid. Thus, at every moment, the power generated (P_t^{PV}) is the product of the nominal power (P_{nom}^{PV}) with the capacity factor (CF_t), Eq. (1). Similarly, the hourly power allocated to each household ($P_{j,t}^{A}$) is the product of the power generated and the allocation coefficient ($\beta_{j,t}$), Eq. (2).

Nevertheless, the allocated power to a household will rarely match the demand. Hence, in case of surplus, as expressed in Eq. (3), although part of the allocated energy will be self-consumed ($P_{j,t}^{SC}$), another part can be fed into the grid by selling ($P_{j,t}^{SELL}$) or giving it away ($P_{j,t}^{GIFT}$) as the excess PV generation sales are capped to keep the bill positive. In other cases, we may face a power deficit, and the REC has to purchase ($P_{j,t}^{PUR}$) some power from the grid to meet the demand ($P_{j,t}^{D}$), Eq. (4).

The sum of the allocation coefficients of all households must always be one, Eq. (5). Besides, we use static coefficients to develop this work. These coefficients are constant throughout all years for each point of consumption, meaning that the power-sharing is performed as though each household has a dedicated portion of the community PV system.

$$P_t^{PV} = P_{nom}^{PV} \cdot CF_t \qquad \forall t \in T \tag{1}$$

$$P_{j,t}^{A} = P_t^{PV} \cdot \beta_{j,t} \qquad \forall t \in T, j \in J \tag{2}$$

$$P_{j,t}^{A} = P_{j,t}^{SC} + P_{j,t}^{SELL} + P_{j,t}^{GIFT} \qquad \forall t \in T, j \in J \tag{3}$$

$$P_{j,t}^{SC} + P_{j,t}^{PUR} = P_{j,t}^{D} \qquad \forall t \in T, j \in J \tag{4}$$

$$\sum_{j=1}^{J} \beta_{j,t} = 1 \qquad \forall t \in T \tag{5}$$

The electricity bill and the financial indicators are obtained as indicated in Appendix A and Appendix B, respectively. The savings for the public entity are the difference between the initial economic support and the support once the REC is established. The initial economic support is the annual cost of electricity purchased from the grid multiplied by the percentage of the bill covered by the energy check or electricity social rate. Once the REC is established, the public entity will cover the difference if any household's savings fall short of achieving the same savings as in the initial case with the social rate. This covering will be a direct bill reduction as it is currently done with the electricity social rate.

Case study

Spanish energy poverty framework

In 2019, the Ministry of Ecological Transition of Spain established the National Energy Poverty Strategy 2019–2024 [40], which implements the mandate set out in Article 1 of Royal Decree-Law 15/2018 of 5 October on urgent measures for the energy transition and the protection of consumers. For the first time, the Strategy defines the situation of energy poverty and vulnerable consumers, diagnoses the situation in Spain, determines lines of action, and sets targets for reducing this social problem that affects more than 3.5 million people in the country.

The Strategy includes measures at the palliative and structural levels, with short, medium, and long-term actions. The aim is not to make financial aid measures the main policy action but rather transitional instruments. This framework proposes measures in the four categories mentioned in Section "The energy poverty challenge for a just energy transition": financial aid, consumer protection, energy efficiency, and information provision. Regarding the structural and energy efficiency measures, the Strategy states that it requires a thorough knowledge of the situation of households and their shortcomings, how to approach these, and how to focus these actions on achieving the best cost–benefit ratio. In other words, the best possible results should be obtained with the least necessary investment. The Strategy also refers to promoting photovoltaic self-consumption among medium-long-term measures. The final objective of the implementation of these measures within this Strategy is to increase the comfort of vulnerable consumers, especially concerning shared self-consumption and the possibility of management of the installations by third parties, which would enable end users to benefit from savings in their energy bills without having to get involved in the specific tasks of project management.

Among the proposals in the Strategy, the most significant specifications are given for consumer protection, emergency measures to avoid supply cut-offs, and the Electricity and Thermal Social rate. To receive it, one must have contracted the voluntary price for the small consumer, which means being in the regulated market and meeting specific requirements associated with income or the type of family unit. The aid ranges from a 25% discount for vulnerable consumers to a 40% discount for severely vulnerable consumers. Exceptionally, until June 30, 2024, these discounts were increased to 65% for vulnerable consumers and 80% for severely vulnerable consumers, according to Royal Decree-law 18/2022 [41] and its extension in Royal Decree-law 8/2023.

Regarding the electricity social rate, from the very beginning, it was considered that this aid should be paid within the electricity market itself, falling on the vertically integrated companies, i.e. those that not only sell energy but also produce and distribute it. The amounts collected go to the regulated retailers who apply the discounts. In this way, their loss of income is compensated. The details of this method of financing have always been controversial, as evidenced by the successive appeals lodged by the companies, which have led to three changes in the system in eight years. First, from 2014 to 2016 (Royal Decree-Law 216/2014), the companies that, in addition to trading energy, also produce and distribute assumed this cost. However, the mechanism was declared unconstitutional, making it necessary to return the amounts they had paid and change the system. From 2016 to 2022 (Royal Decree-Law 7/2016) [42], only the retailers had to assume this cost depending on the number of customers they had. This was particularly disadvantageous for retailers focused on domestic customers, as they had many contracts but with small supplies. On the other hand, it benefited those working with large customers.

Once again, some retailers lodged an appeal against this model, and it was admitted, so now this financing model cannot be applied because it discriminates against them. A new financing model was therefore necessary. From April 2022 (Royal Decree-Law 10/2022) [43], the cost of the social bonus must be paid by all the actors in the electricity sector (generation, transmission, distribution, and commercialization companies). In the specific case of the retailers, the amount must be paid according to the number of customers of the company. Bagnoli et al. [12] state that this financing scheme seems unlikely without involving any public funds, and they suggest two options. One is that the policy could have had a fiscal cost, probably in terms of foregone fiscal revenues through lower tax rates. The other possibility is that other consumers could have financed the policy through cross-subsidies.

Spanish REC framework

Spain introduced the concept of shared self-consumption in Royal Decrees 244/2019 [44] and 23/2020 [45] after eliminating the controversial self-generation legal framework, which discouraged self-consumption by setting very restrictive and economically detrimental conditions for such installations. The Royal Decree 244/2019 introduced a compensation mechanism for prosumers with installed power until 100 kWp, establishing an offset price for self-consumption surpluses supplied to the national grid. In 2020, the Royal Decree 23/2020 introduced the concept of REC into Spanish regulation. This regulation established that REC members should be within 500 metres of the generation point, and the generated power should be allocated employing coefficients fixed in time. This limited distance was later increased to 2000 metres with the Royal Decree 20/2022 [46].

Data and context of the selected citizens

In this context, we propose the implementation of a public REC as a long-term solution to address energy poverty among vulnerable consumers. We aim to compare this alternative with the subsidies to determine its suitability in the medium to long term, particularly for cases where institutional support is needed beyond one-time emergency assistance. To investigate the feasibility and effectiveness of our proposal, we conducted a case study focusing on a simulated shared self-consumption system involving 50 vulnerable households in Valencia, Spain. The prevalence of energy poverty in the city is a significant concern, with 23.1% of households, amounting to more than 85,000 households, experiencing this issue, as indicated by the energy poverty map of Valencia [47]. Approximately 10,000 face Social Isolation and Loneliness (SIL) among these households, as determined through surveys and data from the city council's social services [48].

Table 1
Reference cost for PV systems.
Source: [53].

Power range	Reference cost
P <= 10 kWp	1.600 €/kWp
10 kWp < P <= 20 kWp	(1.800 – 20 * P) €/kWp
20 kWp < P <= 50 kWp	(1.566 – 8,33 * P) €/kWp
50 kWp < P <= 500 kWp	(1.178 – 0,556 * P) €/kWp

In the city of Valencia, any household has the potential to participate in an energy community, highlighting the inclusive nature of our proposed REC. Moreover, Valencia has shown a remarkable commitment to achieving climate-related objectives, exemplified by its designation as the European Green Capital for 2024. Additionally, the European Union has chosen the city to participate in the "One Hundred Smart and Climate Neutral Cities by 2030" mission, further underscoring its dedication to sustainable and environmentally friendly practices. By studying the implementation of a REC in the context of Valencia's energy poverty and commitment to sustainability, we aim to contribute to the broader understanding of effective strategies to address energy poverty and promote REC.

The study focuses on 50 households that can be classified as doubly vulnerable. These households primarily consist of elderly individuals who encounter challenges in meeting their energy expenses, maintaining adequate indoor temperatures, and experiencing Social Isolation and Loneliness (SIL). SIL is a serious public health risk that affects a significant portion of the older adult population, according to the USA National Academies of Sciences, Engineering, and Medicine (NASEM). The 2020 NASEM report also recommended using tailored community-based services to address SIL in older adults. However, there is a lack of evidence to identify the most effective interventions [49].

Moreover, elderly households are particularly vulnerable to energy poverty due to low annual income and higher electricity costs [50]. Based on the data provided by the families, we considered these households as severely vulnerable consumers. Therefore, it is considered a requirement that the savings obtained with the REC are at least equivalent to the 40% discount of the electricity subsidy for severely vulnerable consumers.

To simulate the self-consumption system, we gathered hourly electricity consumption data for the year 2021 from the 50 households mentioned above. The households have consumption levels below the average for Valencia during the same period, recorded as 2518 kWh/year per household. The consumption of the 50 households was acquired thanks to the participation of these households in the project "Energía social *y* confort en el hogar: retos mayores" (ESM) funded by the Innovation and Knowledge Management Department of the City Council of València and represents a sample of the elderly people in a vulnerable situation regarding SIL and energy poverty.

For simplicity, the PV system is assumed to be a centralized plant without specific roofs representing the installation points. A previous study indicated that photovoltaic roofs could be up to 64 kWp in public buildings and 92 kWp in commercial/industrial buildings in Valencia [51]. However, there are already PV installations in public buildings up to 100 kWp [52]. For this study, up to 100 kWp of PV, equivalent to 2 kWp per household, has been considered to capture the full range of rooftop installation potential. Nevertheless, the methodology is applicable to lower power constraints. We considered an azimuth of 0° degrees and a tilt angle of 40° degrees. The hourly capacity factors are generated with PVSyst [38]. The system yields 1622 kWh/kWp annually, which is scaled for the parametric sizing study from 1 to 100 kWp.

The investment depends on the size of the plant and its lifetime, so we have used the price scale in Table 1, provided by the regional government [53].

We assume 20 years of operation, inverters and other electronics are replaced after ten years, while PV panels last for the 20 years the study covers. Based on the benchmark, the price range considered for replacing inverters varies linearly between 737 € (for 1 kWp) and 7534 € (for 100 kWp). In addition, the operation and maintenance costs are calculated [54] as 20.60 €/kWp/yr. Since the government is not a profit-seeking stakeholder, the nominal discount rate is 2% to match expected long-term inflation.

Finally, we use the year 2021 to study this particular case as the demand data is from it. During 2021, the price of purchased electricity fluctuated between 0.077 and 0.270 €/kWh, including the commodity and grid charges, while the price of selling electricity fluctuated between 0.048 and 0.206 €/kWh [55–57]. Besides, the fixed part of the electricity price depends on the contracted power, which is 32.10 €/kW/year [56,57].

Results

In this section, we present a comprehensive analysis of the outcomes derived from the proposed integration of vulnerable households into a REC compared to the payment of the electricity social rate. The review is structured in three key subsections. First, in Section "Overall results", we address the main question of "Panel or check?" by demonstrating the economic advantages of integration into a REC, showing net savings for different photovoltaic (PV) capacities. Secondly, Section "Individualized results" delves into the distribution of savings for each household in different scenarios, providing information on the nuanced impacts of REC implementation. Finally, the Section "Analysis of savings distribution" examines histograms of relative savings in specific REC scenarios, unravelling the complexities of savings patterns across different installation capacities. Together, these subsections provide a detailed understanding of the economic implications and individualized benefits of the proposed REC integration.

Overall results

Addressing the main question "Panel or check?", the proposed integration of households into a REC, compared with the payment of the electricity social rate, proves economically advantageous in terms of public expenditure, securing net savings for all capacities up to a 75 kWp plant, as shown in Fig. 2 with the NPV for all PV capacities in 20 years. Three capacities stand out for a more detailed investigation; the first is 31 kWp, which results in the maximum NPV at 58,500 € and a simple payback time of 6.3 years. Next is 58 kWp, which is where the need for supplemental economic aid to secure savings of up to 40% of the electricity cost is eliminated, requiring no energy checks. Here, the NPV is 22,500 € with a simple payback time of 14.1 years. The third is 75 kWp, the maximum installation capacity possible using the current energy poverty budget. Installations above 75 kWp have a negative NPV.

Fig. 2 also depicts the cost of the energy checks solution (check) and the cost of the installation (panel) as a function of nominal power. For the baseline scenario (0 kWp), where there is no REC, the public expenditure after 20 years is 115,245 €. The annual public expenditure is 7048 €/year, or 141 € per household (on average). Since it is a condition that all households experience a minimum 40% reduction in their energy costs, aligning with the electricity social rate, the higher the installed PV capacity, the lower the annual public expenditure to support these households. With more savings from the REC, households need less financial support through checks. Beyond an installation of 58 kWp, households no longer require energy checks, and the cost of the REC in 20 years remains below cost only with checks in that period. At 75 kWp the cost of the installation reaches the cost without REC, i.e. the NPV reaches zero. It can also be seen that there is an elbow in the rate of cost reductions in checks at approximately 35 kWp, at which point 95% of the check costs have been reduced. This elbow is due to the saturation of self-sufficiency as the mismatch of supply and demand limits the greater economic potential of self-consumption.

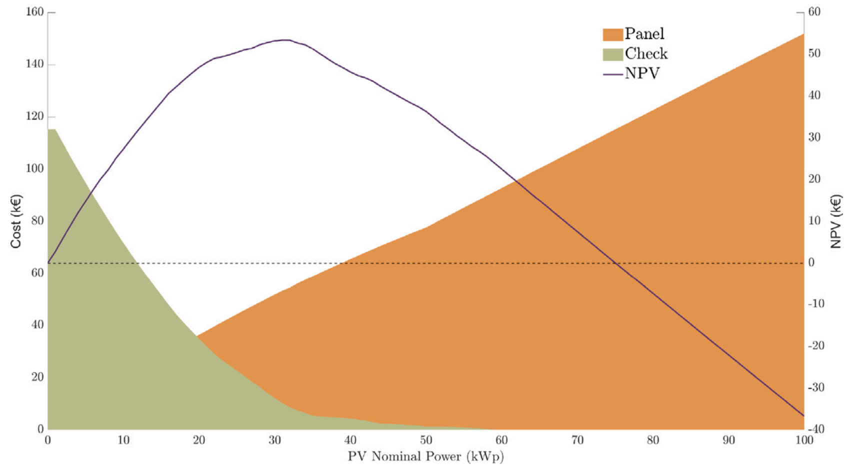

Fig. 2. Performance of the panel policy compared to check policy in 20 years.

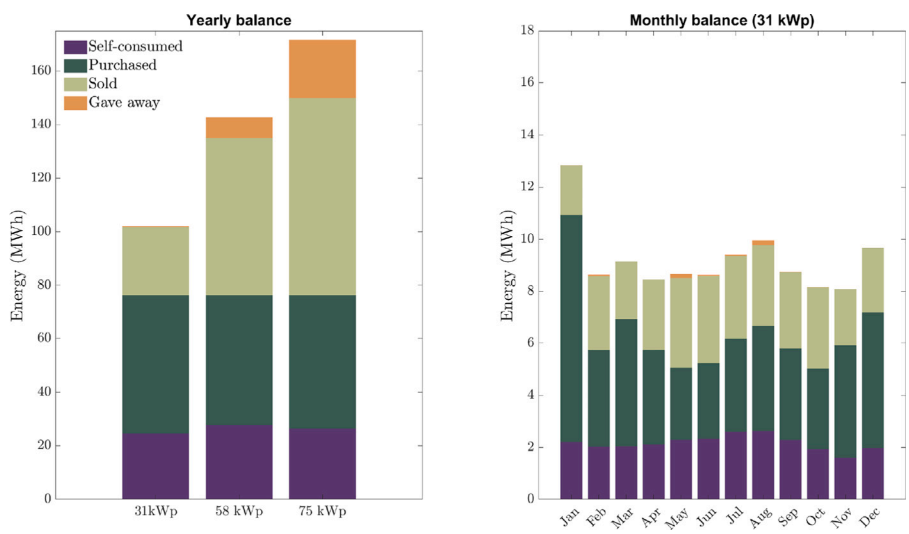

Fig. 3. Annual energy balance and monthly energy balance for 31 kWp.

Expanding on the earlier discussion, Figs. 3 and 4 provide more insights into how the energy system behaves with different PV system capacities. Transitioning from the 31 kWp to the 58 kWp scenario, there is an increase in self-consumption, less energy bought, and more available to share or sell. However, with the 75 kWp scenario, the energy sold and given away increases again, while self-consumption drops slightly. This slight reduction in self-consumption, in exchange for more energy sold and given away to the grid, results in greater savings. The monthly energy balance for the 58 kWp scenario shows differences throughout the year, with a significant increase in energy purchases in January and more energy left over to give away as the installation's power increases, especially during the hot season.

Individualized results

As explained in Section "Results", this study has hourly electricity consumption curves for the year 2021 for each of the fifty households. The least favoured profiles have consumption peaks in winter and dark hours when no generation exists (the seasonal profiles can be found in Appendix C).

The differences between the three scenarios in savings can be observed by analysing the relative economic savings for the fifty households with the REC compared to the current social electricity tariff. In the 31 kWp case, the average savings from the REC is 149 € per household on average, as compared to 141 € per household for the checks. While most households receive similar benefits, extreme cases can result in 182.4% REC support or as low as 34.2% compared to the energy checks. For the 58 kWp installation, where all households save at least 40% on electricity costs from the REC, the average household support increases to 232 €. In the scenario with an installation of 75 kWp the average household savings rises to 256 €. The relative savings for each household in the three scenarios can be found in Appendix C.

Analysis of savings distribution

To delve deeper into this analysis, Fig. 5 presents the relative savings histograms for the three scenarios. On the vertical axis, frequency represents the number of households for which the relative saving represented on the horizontal axis occurs. The horizontal axis represents the savings obtained with the REC compared to those obtained with the electricity social rate. A relative saving of 1 means the same savings are made with the electricity social rate as with self-consumption. A lower relative saving means less than 40% is saved with self-consumption, still needing an energy check, and vice versa.

Relative savings increase as power increases, at the same time the range is reduced. The 31 kWp installation shows the greatest range in household savings, with the least benefited households receiving 0.4

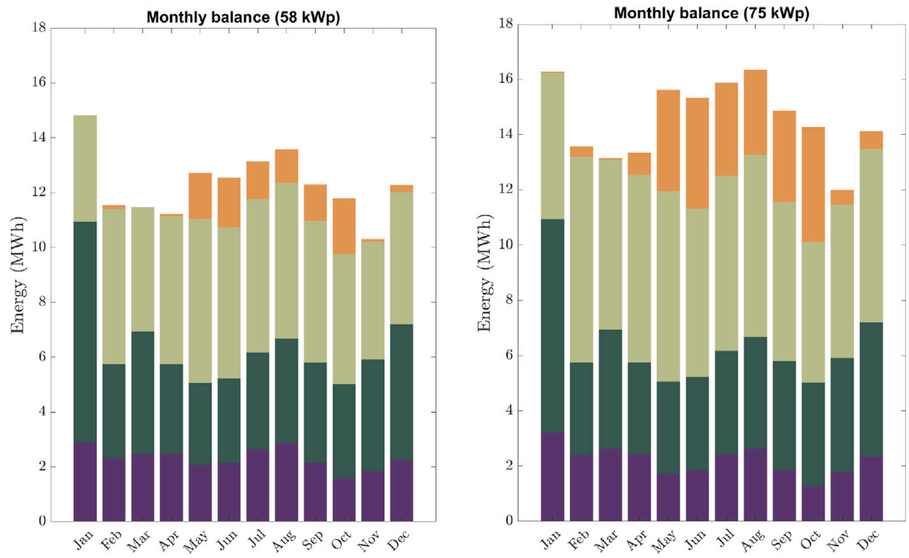

Fig. 4. Monthly energy balance for 58 kWp and 75 kWp.

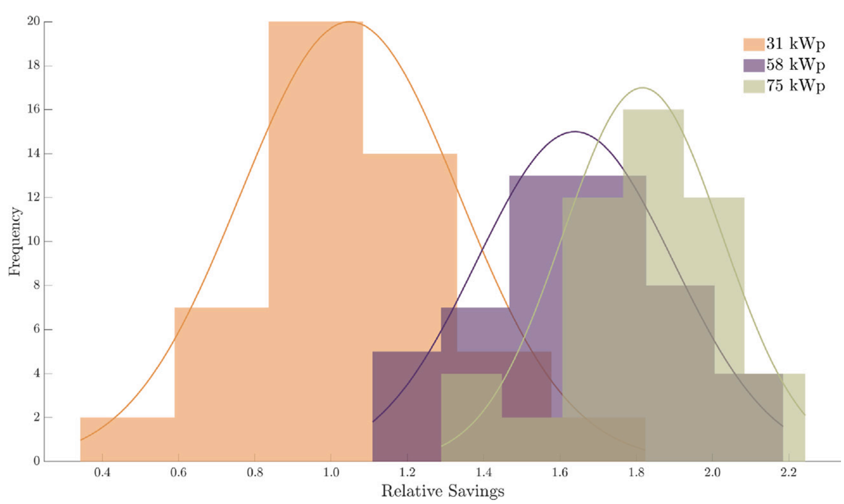

Fig. 5. Histograms of relative savings and frequency for three scenarios.

and the most benefited receiving 1.8, a range of 1.4. The range is narrower in the 58 kWp and 75 kWp cases, at 0.9 and 1.0, respectively. The 58 kWp scenario shows less difference in frequency between the most common savings, 1.6 and 1.8, and the rest. In addition, the distribution of the remaining household savings is more uniform. The 75 kWp scenario shows that the higher the power, the higher the savings for most households.

Fig. 6 shows the dispersion of the generated power allocated to each household to their annual energy demand. This graph shows a clear relationship between demand and allocated power by the energy community; therefore, the simulation model responds to the community's needs and does not arbitrarily favour some households over others.

We were also interested in understanding what behaviours led to higher savings in some households versus others. Our initial hypothesis is that the most significant savings would occur in households with higher electricity consumption during peak price hours and with PV generation as they would self-consume in the most expensive hours. Peak hours in the Spanish electricity tariff system are from 10.00 to 13.00 and 18.00 to 21.00 on weekdays [58]. Fig. 7 shows how these variables relate and show linearity while the demand is not too high. However, increasing the demand does not imply higher savings once the energy demand surpasses 300 kWh in those hours. We interpret this shift to occur because the constraint in the relationship changes from demand to generated power. As a result, we have to purchase electricity from the grid to cover part of that demand during expensive hours.

Discussion and policy implications

The optimal installation approach varies, depending on whether the goal is to enhance overall efficiency or secure substantial household savings. If the focus is on economic optimization, not every household can attain savings comparable to those offered by the electricity social rate. Consequently, the REC falls short of entirely replacing checks. While increased installation power correlates with higher household savings, it may result in negative Net Present Values (NPV). An intermediate solution targets installations where all households achieve savings equivalent to the electricity social rate. However, this assumes that these households maintain their current consumption levels, overlooking the potential for increased consumption to enhance comfort.

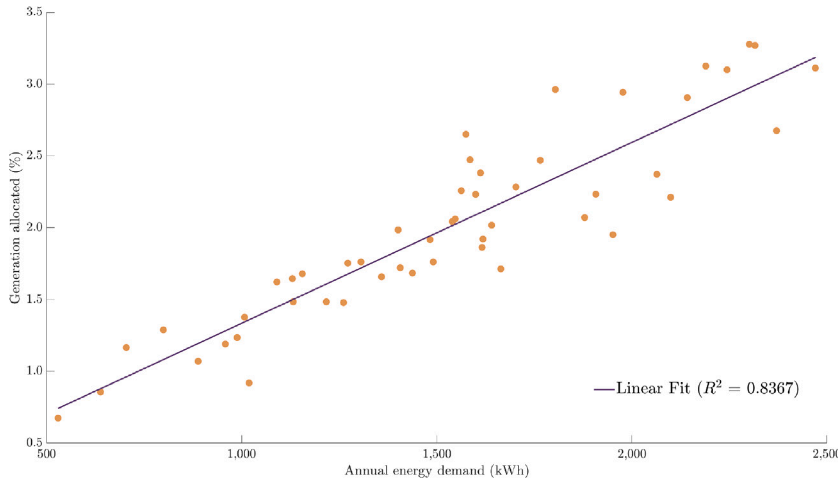

Fig. 6. Dispersion of allocated power generated depending on annual energy demand.

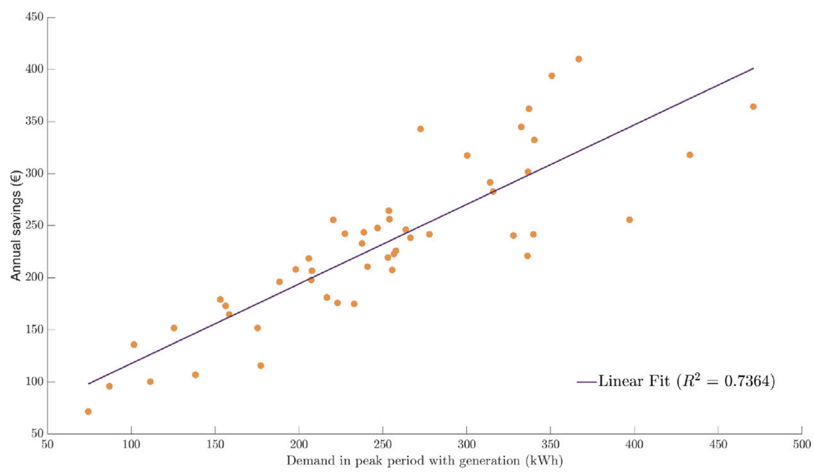

Fig. 7. Dispersion of economic savings depending on energy demand during peak hours with generation.

Notably, Bordón-Lesme et al. [59] suggest that, for low-income consumers, the rebound effect might occur, albeit to a lesser extent than for higher-income consumers.

Even if consumption does not rise, solving these households' issues remains uncertain. As highlighted by Bagnoli et al. [12] in the context of the electricity social rate, economic relief may not eradicate the rationing of electricity consumption. The REC offers an advantage over the social bonus by optimizing savings through a shift in consumption to the installation's peak energy generation hours. Besides, solar-powered RECs will be better suited to reduce energy poverty related to heat levels, especially in Mediterranean climates, as generation perfectly matches hours of the largest energy needs.

A uniform distribution proves suboptimal in addressing households' varying optimal powers and consumption profiles. Instead, establishing distribution coefficients, subject to annual review based on consumption variations, ensures a tailored approach for each household, as shown in Figs. 6 and 7.

Additionally, other boundary conditions influence this decision. While in a rural environment, there is typically more space for panel installation, in an urban environment, space tends to be scarcer, leading to the decision to use all available space for rooftop installation. In such cases, it may be more interesting to install the maximum allowed by available space, e.g., 100 kWp in the case study, even if it may not be economically advantageous. In this way, the plant would allow the growth of electricity demand by households, which is expected since they consume below average due to their low income. It would allow other users to join if there is excess electricity. Furthermore, in the worst case scenario, the plant sells electricity with very low emissions in its life cycle (approximately 40 g/kWh according to [60], which replaces electricity from the grid, which has higher emissions per unit of energy (approximately 200 g/kWh according to [61]).

Conclusions

Our study investigates a specific solution through a REC to alleviate energy poverty. Our results reinforce Primc et al.'s assertion [35] that while gaining access to renewable energy infrastructure demands a significant investment, this cost can be offset by the difference in annual social support provided. The REC, designed for long-term vulnerable consumers, emerges as a tangible solution that substitutes traditional energy checks and aligns with the objectives outlined in institutional guidelines.

The fifty households can be classified as doubly vulnerable. These households primarily consist of elderly individuals who encounter challenges in meeting their energy expenses, maintaining adequate indoor temperatures, and experiencing feelings of SIL. To simulate the self-consumption system, we gathered hourly electricity consumption data for the year 2021 from these fifty households, which have consumption levels below the average for Valencia during the same period.

The results show that participating in RECs is a better economic option for public institutions than paying energy subsidies. At the economically optimal sizing of 31 kWp, the cost of subsidizing energy would be reduced by 58,000 €. At 58 kWp, the need for additional support checks to top up undersupported households disappears, however at a lower NPV of 22,500 €. The largest possible system without incurring additional cost is 75 kWp, which on average increases the electricity cost reduction to 70%. These extra savings would not have been possible in the initial situation with the energy check. Nevertheless, the investment has a lower or equal cost for the public administration in the medium term.

Our results underscore that the REC surpasses the efficacy of traditional energy checks, marking a transition towards renewable energies that is not only fair but also inclusive. Seamless integration of renewable energy sources significantly contributes to alleviating energy poverty among vulnerable households, exceeding the impact of conventional energy checks. Crucial elements include optimal installation distribution, adaptation to variable consumption profiles, and consideration of specific boundary conditions.

CRediT authorship contribution statement

I. Aparisi-Cerdá: Writing – original draft, Visualization, Methodology, Data curation. **Á. Manso-Burgos:** Writing – original draft, Software, Methodology, Data curation. **D. Ribó-Pérez:** Writing – review & editing, Supervision, Conceptualization. **N. Sommerfeldt:** Writing – review & editing. **T. Gómez-Navarro:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

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Appendix A. Electricity billing

The cost of the purchased electricity from the grid (C^G) is the sum of the variable costs incurred during the year (C_t^V) and the contracted power cost (C^{POW}), Eq. (A.1). On the one hand, the variable costs are calculated hourly as the difference in the price of electricity purchased (C_t^{PUR}) and sold (C_t^{SELL}) to the grid, Eq. (A.2), where π is the price per kWh to sell or purchase electricity. On the other hand, the contracted power cost is the product between the contracted power (POW_j) and the price per contracted kilowatt (POW_j), Eq. (A.3).

Excess PV generation sales are capped, as the bill must be positive. Therefore, Eq. (A.4) determines that the price of electricity purchased (where π_t^{PUR} is the price per kWh of purchased electricity) must be equal to or higher than the price of electricity sold (where π_t^{SELL} is the price per kWh of sold electricity) in each billing period from b_0 to b_f. In the case of generating more surplus than the REC can sell in a given month, it will give it away to the grid for free.

$$C^G = \sum_{t=1}^{T} C_t^V + C^{POW} \tag{A.1}$$

$$C_t^V = C_t^{PUR} - C_t^{SELL} = \sum_{j=1}^{J} P_{j,t}^{PUR} \cdot \Delta t \cdot \pi_t^{PUR} - P_t^{SELL} \cdot \Delta t \cdot \pi_t^{SELL} \tag{A.2}$$

$$C^{POW} = \pi^{POW} \cdot \sum_{j=1}^{J} POW_j \tag{A.3}$$

$$\sum_{t=b_0}^{b_f} P_{j,t}^{PUR} \cdot \pi_t^{PUR} \geq \sum_{t=b_0}^{b_f} P_{j,t}^{SELL} \cdot \pi_t^{SELL} \tag{A.4}$$

Appendix B. Financial evaluation

We determine the economic performance of the REC through the Net Present Value (NPV). Eq. (B.1) defines REC's NPV of each year as the subtraction of operation and management (NPV^{OM}) and investment value (PV^{INV}) in that year to the value of the savings (NPV^{SAV}). Eqs. (B.2) to (B.4) define the NPV of saving, operation and management and investment every year, respectively (where SAV is the annual billing savings generated by the REC, d is the market discount rate and OM is the operation and maintenance annual expenses).

The savings for the public entity that carries out the solar installation are due to not supporting the electricity bills in these households. The annual total save is the sum of the savings due to each household (SAV_j), Eq. (B.5). Meanwhile, we measure the annual savings produced in each household using Eq. (B.6) as the difference in the initial economic support and the support once the REC is established. The initial economic support is the annual cost of electricity purchased from the grid in the initial case multiplied by EC, the percentage of the bill covered by the energy check or electricity social rate. Ideally, once the REC is established, these households will not require more economic support to reduce their bills as with the social rate. However, we considered that if any household's savings fall short of achieving this minimum saving (if they do not achieve at least the same savings as in the initial case with the social rate), the public entity will cover the difference. This covering will be a direct bill reduction as it is currently done with the electricity social rate. Thus, we guarantee that the service offered by the public entity is at least as extensive as in the initial situation, implying a net reduction of the savings expected by the public administration. This covering is the subtractor in the equation Eq. (B.6).

$$NPV_n^{REC} = NPV_n^{SAV} - NPV_n^{OM} - NPV_n^{INV} \tag{B.1}$$

$$NPV_n^{SAV} = \frac{SAV}{d} \cdot \left[1 - \left(\frac{1}{1+d}\right)^n\right] \tag{B.2}$$

$$NPV_n^{OM} = \frac{OM}{d} \cdot \left[1 - \left(\frac{1}{1+d}\right)^n\right] \tag{B.3}$$

$$NPV_n^{INV} = NPV_{n-1}^{INV} + \frac{INV_n}{(1+d)^n} \tag{B.4}$$

$$SAV = \sum_{j=1}^{J} SAV_j \tag{B.5}$$

$$SAV_j = EC \cdot C_0^G - max(0, C_{REC}^G - (1 - EC) \cdot C_0^G) \tag{B.6}$$

Appendix C. Additional figures

See Figs. C.8–C.12.

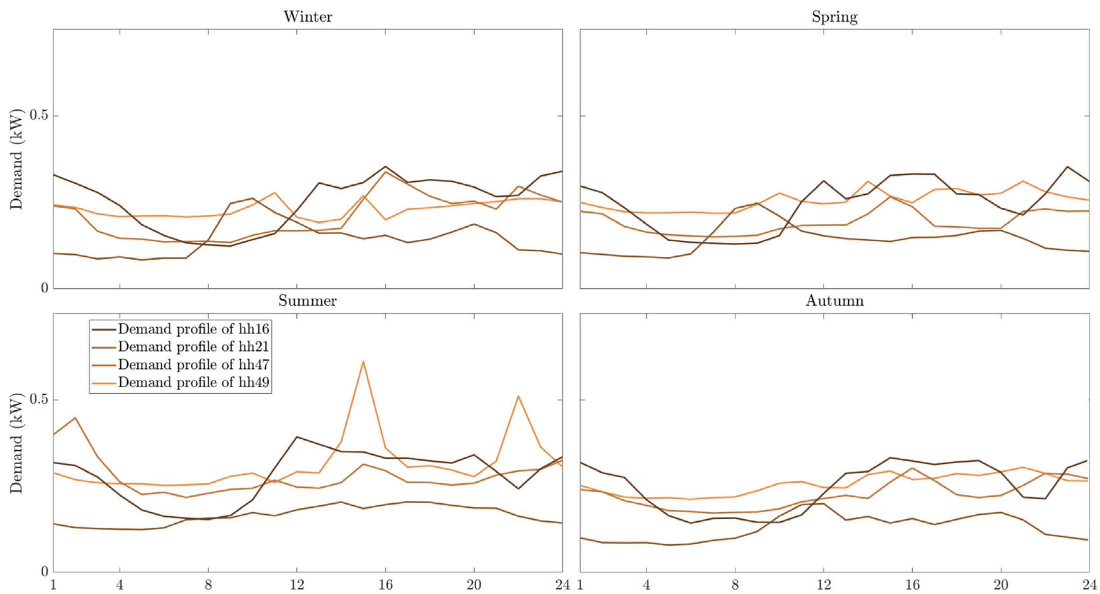

Fig. C.8. Demand profiles of the profiles most favoured by REC installation.

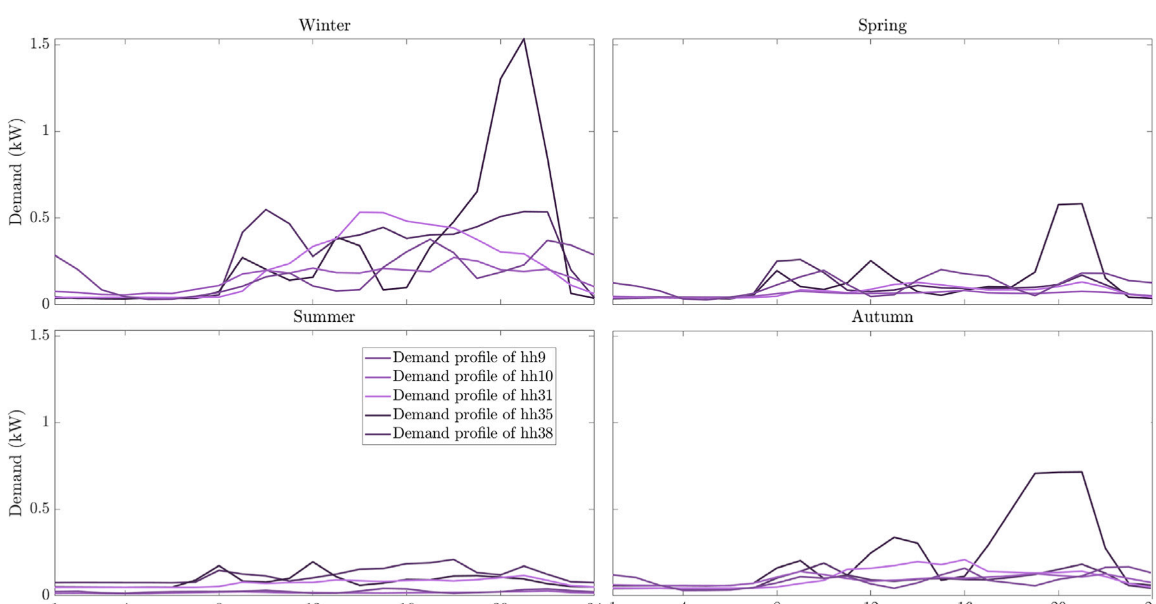

Fig. C.9. Demand profiles of the profiles least favoured by REC installation.

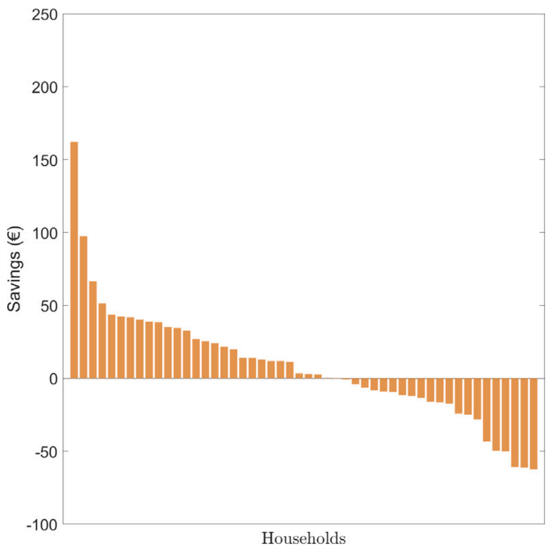

Fig. C.10. Relative savings for 31 kW.

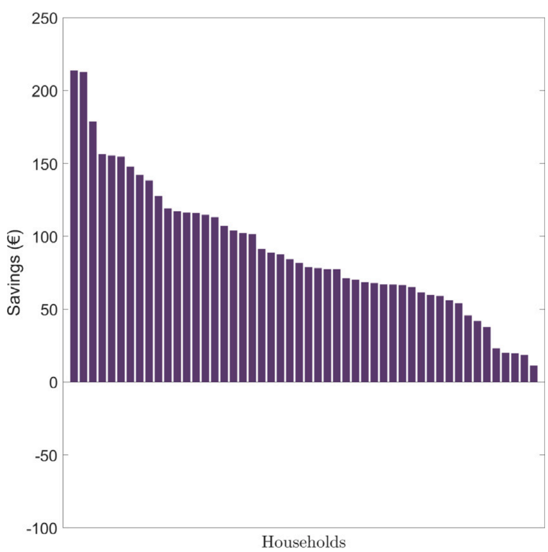

Fig. C.11. Relative savings for 58 kW.

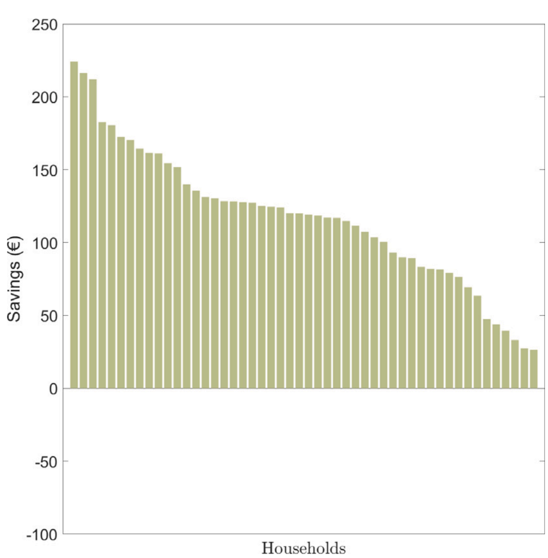

Fig. C.12. Relative savings for 75 kW.

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