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Case study of electric and DHW energy communities in a Mediterranean district

X. Masip [a,b,*], Enrique Fuster-Palop [a,b], C. Prades-Gil [a,b], Joan D. Viana-Fons [a,b], Jorge Payá [a], Emilio Navarro-Peris [a]

[a] Instituto Universitario de Ingeniería Energética, València, España, Universitat Politècnica de València, Spain
[b] ImpactE, C/ Joan Verdeguer N16, València, 46024, Spain

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ABSTRACT

Energy communities can play a key role to move towxards a low-carbon and decentralized energy system with higher penetration of renewable energies, offering new opportunities for citizens to actively participate in the energy transition. However, the term energy community is practically exclusively addressed in literature as photovoltaic systems shared by several users to cover their electricity needs. The present work describes the georeferenced modelling and assessment of potential domestic hot water energy communities based on heat pumps and photovoltaic energy communities in 150 residential buildings in a representative Mediterranean city. The main objective is to widen the concept of energy communities and to quantify their potential. The aggregated economic and emission savings of domestic hot water in the district can reach up to 85% and 73% respectively for heat pumps, and 22% and 23% respectively with photovoltaic systems. The analysis shows that domestic hot water energy communities should be prioritized if the objective of the decision-maker is to reduce the CO_2 emissions. However, photovoltaics energy communities reach higher economic savings. Combining the two energy communities could help reach the *Fit for 55 package* objectives for 2030, with emission savings up to 56%. The results show that 80% of emission savings can be achieved by acting only on 35% of the buildings.

1. Introduction

The challenge of climate change requires moving towards a low-carbon economy. This transformation (or better called revolution) is one of the biggest challenges for the humanity.

Cities are currently responsible for 72% of the Global Warming Emissions (GWE) [1], despite occupying only 3% of the territory. Moreover, the demand for energy is expected to increase with the population growth. The European Union (EU) settled a long-term strategy by promoting both Renewable Energy Sources (RES) and energy efficiency to reach a 80–95% GWE reduction by 2050 [2]. Furthermore, with the *Fit for 55 package* the objective for 2030 was reviewed to reach a reduction of 55% [3]. Regarding the residential sector, whose energy consumption and GWE emissions currently account for 40% and 36% [4], the EU settled a GWE reduction objective of 90% by 2050 [2]. This reduction has to be achieved through a combination of policy measures: near zero energy buildings (NZEB), the refurbishment of the old buildings, the replacement of the fossil fuels, the introduction of RES, and also by means of waste energy recovery. Energy communities (ECs) have recently emerged giving the opportunity to citizens to help in the transition towards a low-carbon economy [5]. These communities are collective actions participated totally o partly by citizens, public and private entities around a renewable energy (RE) project [5]. The energy system is totally centralized, and ECs constitute a radical change contributing to a decentralized system and promoting people empowerment.

Some cases of ECs appeared in the 80s and 90s in the Netherlands, motivated against nuclear energy [6]. However, the concept has recently gained a considerable attention given a growth in social responsibility and collaborative entrepreneurship [6]. For example, the Valencian Community Government recently decided to launch the strategy "*One Local Energy Community in each of the Valencian Community municipalities for 2030*" [7] and the city of València has the strategy "100 EC *for 2030*" [8], both refer to photovoltaics (PV). The first Italian Oil Free Zone initiative in Pinerolo area is described in Ref. [9]. The two very different EC were presented in Ref. [10], first in India as a solar station for charging 50–60 lanterns and the other in Scotland as the first

* Corresponding author. Instituto Universitario de Ingeniería Energética, València, España, Universitat Politècnica de València, Spain.
E-mail address: xmasip@iie.upv.es (X. Masip).

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Nomenclature

Abbreviations

AB	Apartment Block
CEC	Citizen Energy Community
DHW	Domestic Hot Water
EC	Energy Community
EU	European Union
GWE	Global warming emissions
HP	Heat Pump
HPWH	Heat Pump Water Heater
HR	Heat Recovery
KPI	Key Performance Indicators
MFH	Multifamily House
NZEB	Near zero energy buildings
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
REC	Renewable Energy Community
SHP	Subcooled Heat Pump
SPF	Seasonal Performance Factor
TC	Terraced House

Parameters used in thermal equations

A	Heat exchange area
C_p	Fluid specific heat
C_{pf}	Fluid specific heat
Qloss	Thermal power loss
k	Fluid thermal conductivity
L_{cond}	Conductor length
m	Fluid mass
Qcond	Energy from the condensedr
Q_{fuel}	Energy from fuel
Q_{fluid}	Energy from fluid
$Q_{Exhaust}$	Energy from exhaust gas
T	Temperature of the fluid
Tenv	Ambient temperature
T_h	Upper input temperature
T_{in}	Monitoring temperature
T_{set}	Setpoint temperature
U	Thermal transmittance
η_{boiler}	Boiler efficiency
$\eta_{combustion}$	Combustion efficiency

Parameters used in PV equations

A	Available rooftop area
B_0	Beam irradiance on the horizontal plane
B_{POA}	Beam irradiance on the plane of the array
D_0	Diffuse irradiance on the horizontal plane
$D_{POA,h}$	Diffuse irradiance on the plane of the array
DNI	Direct normal irradiance
fb	Beam shadow factor
G_0	Global irradiance on the horizontal plane
G_{POA}	Global irradiance on the plane of the array
NOCT	Nominal operating cell temperature
PR	Performance ratio
R_{POA}	Reflected irradiance on the plane of the array
SVF	Sky view factor
α	Azimuthal angle step of the skyline
$\beta_{buildings}(\alpha)$	Skyline profile of surrounding buildings
γ	Power temperature coefficient of the module
η_{deg}	Module degradation rate
$\eta_{PV,STC}$	Efficiency of the module at standard test conditions
η_{soil}	Soiling losses
θ_s	Angle between the direction of the sun rays and the normal to the surface
θ_{zs}	Sun zenith angle
ρ	Albedo coefficient

Units

c€	Euro cent
hr	Hour
m	linear metre
min	Minute
m^2	Squared metre
m^3	Cubic metre
MW_p	Megawatt peak
MWh	Megawatt hour
M€	Millions of euros
K	kelvin
kg	kilogram
kJ	kilojoule
kPa	kilopascal
kW	kilowatt
kWh	kilowatt hour
kW_p	kilowatt peak
k€	Thousand euros
L	liter
°C	Celsius Degree
tCO_2	Ton of carbon dioxide
W	Watt
W_p	Watt peak
€	Euro

urban EC owned wind turbine. The implementation of biogas co-operatives in Northern Italy has also been explored [11]. The specific target of the Scottish Government in 2011 of '500 MW of community and locally owned RE by 2020' resulted in many initiatives of community owned RES introduced in Ref. [12].

All the cases which are recently appearing in different regions globally confirm that EC are being developed to contribute towards the revolution of a low-carbon economy and a decentralized system. Furthermore, they are recognized under the EU policy (under RED II [13] and IEMD [14]). These EU directives support the development of the EC, in which citizens have the right to produce, consume, store and sell RE self-generated individually or under a Renewable Energy Community (REC) (in REDII) or Citizen Energy Community (CEC) (in IEMD). As [15] states, both directives place the citizen at the heart of the energy markets as an active player. However, despite being a very topical subject, ECs has received little attention in literature. There are very few papers referring to this topic (1579 document results in Scopus) and the most relevant studies mainly refer to the social innovation. Therefore, technical studies are scarce and yet necessary to demonstrate the great global potential of EC for a distributed energy transition. Moreover, most of the initiatives found in literature are related only to PV collective actions.

As stated by the EU, energy communities can include PV production, energy storage, energy retrofitting of buildings, electric mobility, etc. The present work aims to contribute to the literature with the objective of covering a wider spectrum of energy communities, not only limited to PV, and applied in a European district of the Mediterranean. PV production and DHW production are the collective actions which are compared. DHW represents on average 18.9% of the final energy consumption. Lighting, together with electric appliances represents 31.7%

[16]. Both are non-negligible portions of the energy usage and they are steadily increasing [17]. Among other technologies, Heat Pumps (HPs) play a key role for low-carbon heating [18]. This technology, supported by the development of PV ECs would provide the possibility to partially cover the DHW necessities with on-site RE, hereby contributing to the peak demand reduction [19] and to the self-empowerment of the consumers [20]. In addition, this combination can be considered as an alternative for solar-assisted heat pumps since PV ECs promoted and subsidized by local public administrations as well a growing penetration in the domestic sector of both PV and HP is expected [21]. Nevertheless, some significant barriers to be faced are the lack of business models and detailed information for citizens and stakeholders [22]. There are other interesting alternatives, such as geothermal energy and biomass, however this study focuses on electric-based solutions due to a growing electrification of the residential sector and a decrease of the non-renewable sources in the electric mix [23].

There is scarce literature at a district level regarding combined systems of HP assisted by PV (HP + PV) for DHW [24]. The studies carried out for individual PV + HP systems agree on their positive environmental and techno-economic impact, especially the latter is expected to be reduced with new business schemes based on HP in district heating networks [25]. The replacement of facilities for district heating by HP + PV systems was also studied, concluding that the equivalent electricity consumption of heating of HP + PV system represented 30% of the consumption of an air source heat pump, 19% of a gas boiler and 12% of an electric boiler [26]. In a small scale, considering the energy needs of a single user or building, there is more literature on HP + PV systems. Experimental studies have shown that the emissions of a household can be reduced by 82% in comparison with a gas boiler system [27]. Another experimental application to provide DHW in a hotel, achieved energy reductions in the energy consumption of up to 69.94% [28]. Niccolò Aste et al. reduced by 83% the primary energy requirements in Italy by means of a ground water heat pump powered with a PV system [29]. A holistic-approach assessing HP + PV systems under 8 different scenarios with different load profiles concluded that PV contributes to decrease the total cost of ownership of HPs [30]. The operation costs of HP + PV systems can reach up to 30% in cold climates compared with a boiler, and this rate can further increase using thermal energy storage [31].

However, the impact of the previous studies is always limited to particular users. There is no existence to the authors knowledge on studies addressing the impact of HP ECs as well as HP + PV ECs. This would facilitate the decision-taking for stakeholders, citizens and reduce the social barriers of these systems.

This present study aims to explore and quantify at a district level, either both communities individually (DHW EC and PV EC) or their combination (HP + PV EC).

The main novelties of the present work are.

- Widen the concept of ECs by including DHW ECs and a combination with PV ECs.
- Environmental and economic assessment provided by DHW EC, PV EC and HP + PV EC at a district level.
- Method and criteria to prioritize the assessed energy communities (PV or DHW) depending on the emission or operation cost savings.

2. Materials and method

This section describes in detail the methodology and simulation procedure. The first subsection (2.1. Analysis area) introduces a preliminary analysis of the selected district. The subsequent subsections

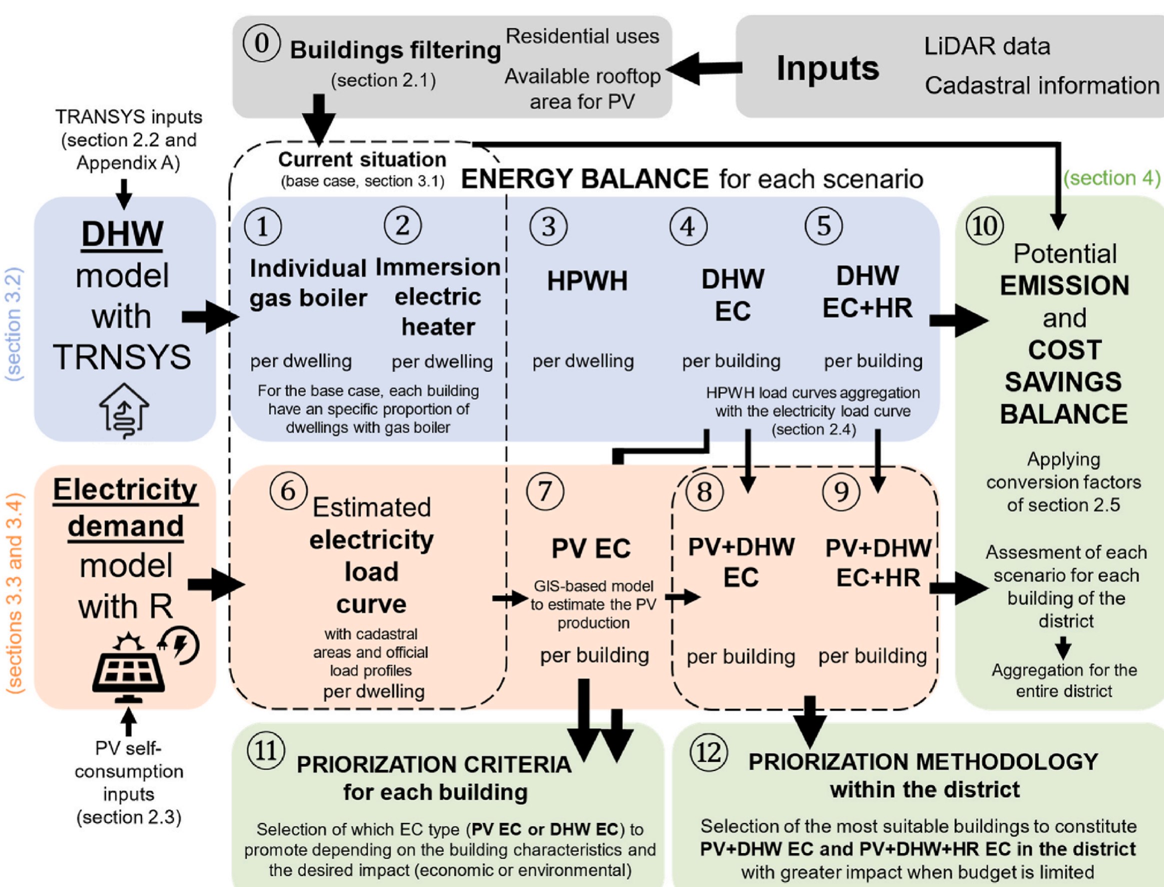

Fig. 1. Methodology to assess DHW and PV ECs.

(2.2. DHW analysis method, onwards) introduce the methodology and model assumptions for the different ECs.

The main steps of the study are summarized in Fig. 1. The starting point (0) is a descriptive analysis of the district and the filtering of the residential buildings in the district. The second step consists of the simulation of a base case scenario which represents the current state of the district, assuming that a ratio of dwellings from each building is equipped with immersion electric heaters and the rest with individual gas boilers, and without PV facilities (1–2,6). The economic and environmental impacts this scenario is compared independently with each individual numbered scenario in Fig. 1.

On the one side, the following scenarios for the DHW are analyzed employing the TRNSYS software: Heat Pump Water Heater (HPWH) for each dwelling (3), DHW EC for each building (4), and DHW with heat recovery (DHW EC + HR) for each building (5).

On the other side, the PV analysis includes the estimation of the electricity demand (6), and the PV EC estimated for each building (7). The study continues aggregating the DHW and PV alternatives under a combined alternative for the district buildings (8–9). Finally, the economic and environmental impacts of each independent scenario are compared against the base case (10).

Additionally, a prioritization methodology is developed to select between the DHW ECs and PV ECs (11) according to economical or environmental factors (12).

2.1. Analysis area

The present work aims to demonstrate the potential of ECs in urban areas at a district level under EU warmer climate conditions. The city of València has been selected for the study, considering its climate typical of the EU warmer climate, hereby extending the outreach of the results. The district of *'Illa Perduda'* in the city of València (Spain) has been selected for the study. Fig. 2 shows an aerial view of the neighborhood, as well as the location of València in Europe.

The *Illa Perduda* district is mainly a residential area. As shown Fig. 3a and b, there are 164 buildings and 6388 properties with a total area of 568,971 m^2, among which 150 are residential buildings and 4194 properties are dwellings (65.7%) with a total area of 428,083 m^2 (76.7%). The other dominant destination of the plots are for parking and storage (27.9%) or for commercial use (5.8%). The district was mainly built between the 60s and 70s, when 108 of the buildings were built, which represents almost 66% of the current buildings, as illustrated in Fig. 4a. Fig. 4b shows that most buildings contain between 10 and 30 dwellings, with an average of 17 dwellings per building. The highest number of dwellings per buildings is 210 whereas the lowest value is 6. According to the Tabula EU project, the typologies of buildings found in this neighborhood correspond with to 'Multifamily house (MFH)' (1) and mainly with 'Apartment block' (AB) (149) with none 'Single family house' (SFH) and 'Terraced house' (TH) [32].

According to the last census of the city of València, there is an average of 2.39 inhabitants per dwelling in the neighborhood of *Illa Perduda*. This average value for the whole city is 2.41, 2.5 for Spain [33], and 2.3 for Europe [34]. Considering these values, a representative rate of 2.3 inhabitants per dwelling has been considered in the present study.

2.2. DHW analysis method

In order to quantify the potential energy and emissions savings, a base case was first defined, including the most common buildings and technologies of the district. *TRNSYS* software was used for the dynamic simulations and *DHWcalc* for the generation of the different draw-off profiles.

According to recent literature, the DHW production is ensured in 28.6% of the dwellings with an immersion electric heater and in 70.1% with a gas boiler (the rest has solar thermal collectors) [16]. For this reason, two energy simulation models have been developed for the gas boiler and immersion electric heater.

Three energy production alternatives for the current scenario have been analyzed.

a. Heat Pump Water Heater (HPWH). This is an individual and more efficient renewable technology for DHW production, which can replace in a plug&play way the technologies of the base case.
b. DHW EC. This case is representative of an EC solution, as a collective DHW production system with HP technology.
c. DHW EC + HR. EC solution including heat recovery with a booster HP.

The individual DHW energy systems (for 1 dwelling) have been simulated only for the average dwelling. Afterwards, the results are extrapolated for the total number of dwellings of the neighborhood. This applies for the base case and HPWH case, in which the 100% dwellings have been assumed to change their current DHW production system by the HPWH. On the contrary, for the EC cases, the analysis is performed building per building. The EC is a single, centralized solution for all the dwellings of the same building. Hereby, each building will have its own

Fig. 2. Aerial view of the Illa Perduda district in València.

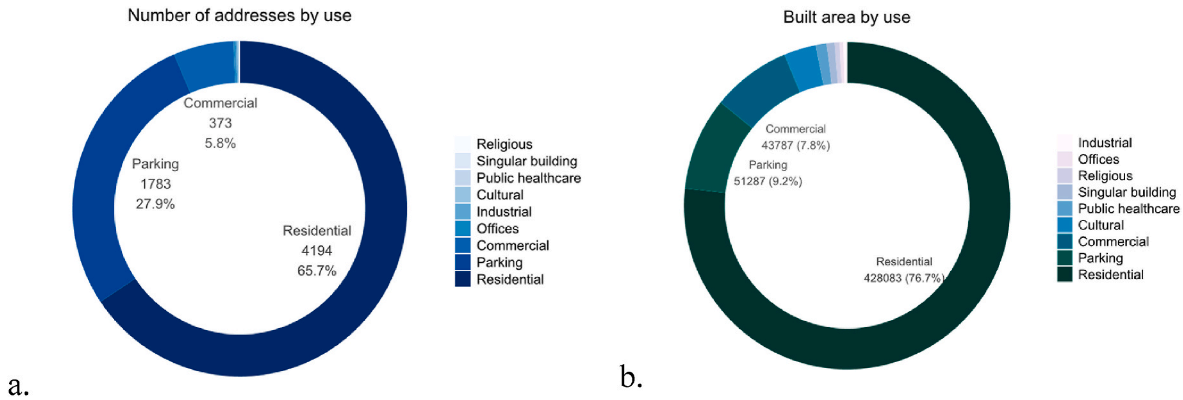

Fig. 3. Demographic data analysis of the Illa Perduda district.

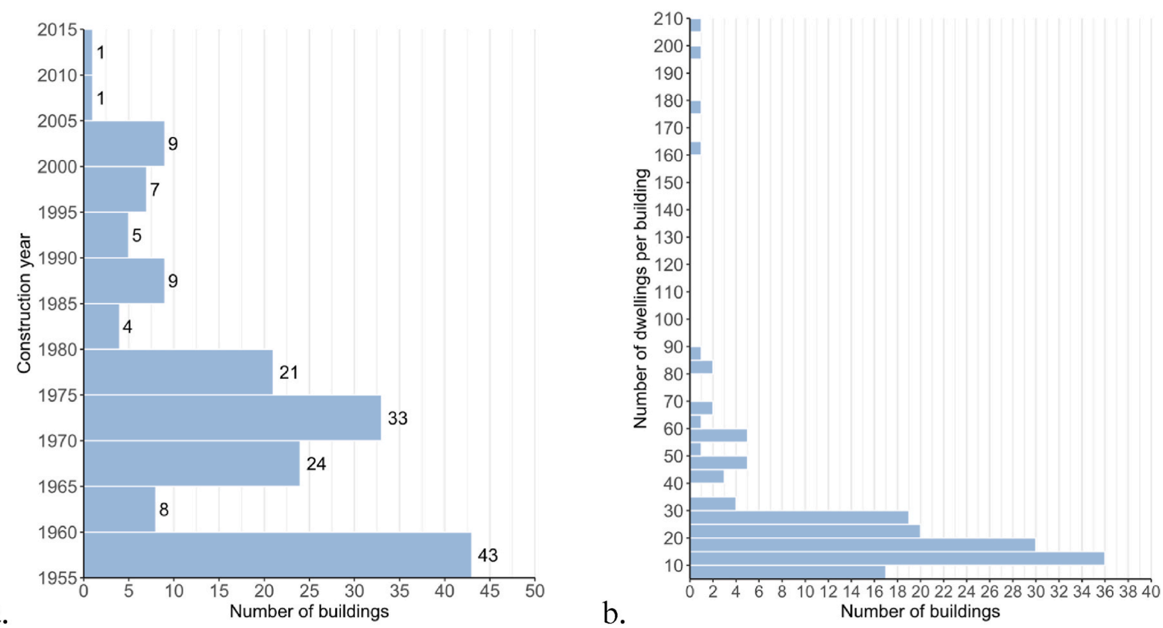

Fig. 4. Demographic data analysis over the study area of Illa Perduda.

DHW production system that will cover the total demand of the different dwellings.

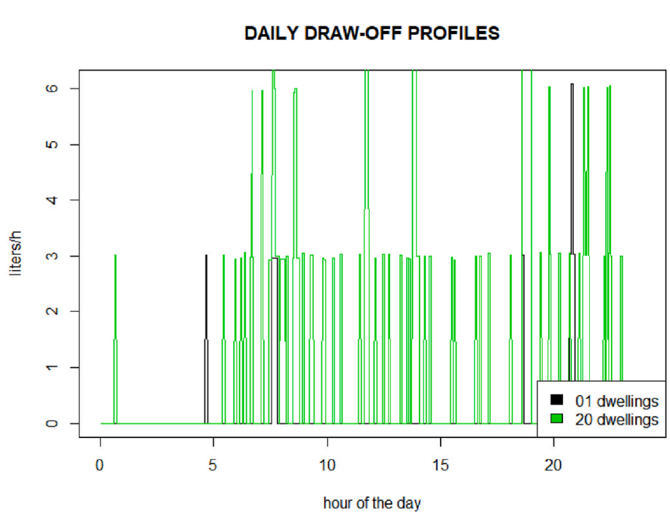

Fig. 5. Example draw-off profile for a random day for 1 and 20 dwellings.

For the DHW demand, the software *DHWcalc* was used to obtain the annual draw-off profiles with a 1-min step [35] (Fig. 5). The annual DHW consumption (l/year) has been obtained following published indications [36]. The detailed conditions of [37,38] have been employed as inputs for the different types of draw-off profiles in a dwelling (cleaning, shower, bath and cooking).

All the thermal models have been simulated with the dynamic energy systems simulation tool *'TRNSYS'* [39] and the main inputs for each of the models has been included in APPENDIX A. TRNSYS model. The dwelling cases have been built and validated over current commercially available systems from real manufacturers. A mean net water temperature has been assumed every month. The supply temperature to the user was considered as 45 °C and a tempering valve was added to the models. The insulation of the tank was considered according to the Spanish normative as 0.8 W/m^2 K.

Comfort Key Performance Indicators (KPIs) have been included in the models to understand the user comfort variations of each case. Discomfort restrictions have also been settled to guarantee the DHW comfort of the user in the EC cases. The discomfort is considered when the system is not capable of supplying the DHW to the user at 45 °C. The restrictions apply over.

a. Annual discomfort: a maximum of 0.5% hours a year of discomfort has been imposed.
b. Hourly discomfort: a maximum value of 30 min per year of discomfort for each different hour of the day has been assumed. This corresponds to a maximum of 5 s of discomfort per day for each hour of the day.

The limitation of the DHW analysis deals with a perfect stratification assumption in the stratified storage tank. It is known that it is broken with the inlet and outlet of the water, being solved by some manufacturers with the installation of components at the inlet/outlet to avoid it. According to this effect, the results from Immersion electric heater and HPWH should worsen in a real installation.

2.2.1. Immersion electric heater

This case has been modelled using a commercially available immersion electric heater and its annual consumption was validated according to the energy label certification and datasheet. The storage consists of water storage tank of 80 l with an aspect ratio of 2. The immersed electric heater has a nominal capacity of 1.5 kW and is located at one third of the height of the tank. The inlet to the tank from the net was considered at 5% of the height of the tank and the outlet to the mixing valve at 95%, as specified in the commercial model. The temperature sensor has been placed in the top node (considering 15 nodes) to maximize the energy performance, as demonstrated in Ref. [40].

In order to select the set-point water temperature production, different simulations have been carried out as shown in Table 1. The results indicate that the closer the set-point temperature is to the user supply temperature, the lower the annual energy consumption and the higher the annual discomfort. The case of 55 °C was finally selected as set-point water temperature to minimize the energy consumption while guaranteeing user comfort.

2.2.2. Gas boiler

The gas boiler case does not include a storage system. The water is heated instantaneously from the net to the set-point water production temperature. This case has been also modelled using a commercially available system and its annual consumption was validated according to the energy label certification and to the datasheet. The gas boiler is non-condensing, has 28 kW heating power and 92% energy efficiency.

Different cases have been simulated by changing the set-point water production temperatures. The results are presented in Table 2. As result of the instantaneous production, much more power input is needed compared to the cases with storage and the user comfort is much higher. The results show no variation since the production is instantaneous without storage.

2.2.3. Heat Pump Water Heater (HPWH)

The HPWH consists of a small air-source HP placed above the storage tank and with a wrap-around condenser coil in the storage tank. This case was also modelled taking as reference a commercially available system and was validated against the datasheet of the manufacturer. The HP water heater consists of an 80 l storage tank with an aspect ratio of 2 and the temperature sensor control in the top node of the tank. The air-source HP has 0.9 kW heating capacity and an immersion electric heater of 2 kW as auxiliary system. The condenser is wrapped-around the tank over almost the 25% of the height of the tank and the immersion electric heater is located at 10% of the height of the tank. The commercial model only allows the HP to work until 55 °C and the rest until 60 °C is achieved with the auxiliary immersion electric heater.

Table 3 includes the main KPIs when changing the set-point water production temperature. The results show high discomfort rates for set-point production temperatures close to the supply temperature of the user. The energy consumption highly increases, and the annual discomfort drops for 60 °C, since the auxiliary immersion electric heater acts. Finally, the case of 55 °C as set-point water temperature production was also selected.

2.2.4. DHW EC

The HP is shown in Fig. 6 and Fig. 7 and consists of a water-to-water subcooled heat pump with R290 (Propane) as natural refrigerant. The HP works with optimal subcooling and thus takes advantage of the high temperature lift in the DHW application. More details on the subcooled HP can be found in Ref. [38]. The HP is connected to a variable-volume storage tank that consists of a fully mixed tank in which the inner volume varies depending on the HP unit performance and user demand. This tank only has one inlet from the SHP and one outlet to the user. More details and a proposal of implementation of this tank in a real system can be found in Ref. [40] .

Contrarily to the other cases, the EC case presents the risk of legionella [41]. To comply with the corresponding normative, the set-point water production temperature of the system has been settled to 64 °C to maintain a minimum temperature of 60 °C in the tank. The user supply temperature remains at 45 °C, as in the other cases. The cases which do not comply with the comfort restrictions have been discarded. In the collective DHW production case, the circulation losses have to be taken in consideration. A 10% annual energy consumption reduction has been considered. To consider this reduction, two issues must be considered. First, that a new installation would be properly insulated. Second and last, the installation will take place separately in each building block, hereby with reduced energy losses since the HP is supposed to be in the basement and connected to the current existing water distribution installation through the distribution chamber in the building.

The energy consumption of these systems depends critically on the proper sizing of the HP and the tank. A parametric analysis has been

Table 1
Main KPIs for the immersion electric heater under different set-point water production temperatures.

Set-point production temperature	°C	45	50	55	60
Annual energy consumption	kWh/year	1157.62	1307.53	1399.62	1473.01
Working hours	hours/year	2778.30	3138.07	3359.10	3535.23
SPFuser	–	0.90	0.89	0.87	0.86
Annual discomfort	%	92%	38%	22%	15%

Table 2
Main KPIs for the gas boiler under different set-point water production temperatures.

Set-point prod. Temperature	°C	45	50	55	60
Annual energy consumption	kWh/year	1535.78	1535.78	1535.78	1535.78
Working hours	hours/year	183.10	183.10	183.10	183.10
SPFuser	–	0.92	0.92	0.92	0.92
Annual discomfort	%	0.08%	0.08%	0.08%	0.08%

Table 3
Main KPIs for the HPWH under different set-point water production temperatures.

Set-point prod. Temperature	°C	45	50	55	60
Annual energy consumption	kWh/year	339.28	418.93	486.46	822.83
Working hours	hours/year	1314.78	1505.80	1626.32	1424.82
SPFuser	–	3.12	2.81	2.53	1.80
Annual discomfort	%	88%	31%	19%	12%

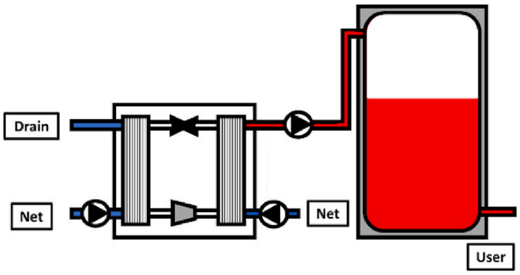

Fig. 6. Illustration of the HP installation with all its components.

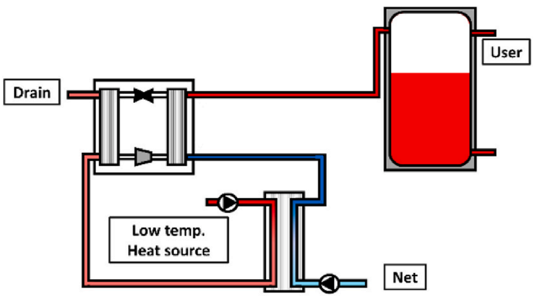

Fig. 7. Scheme of the booster HP installation with heat recovery.

performed for each building of the neighborhood to determine the HP and tank size corresponding to the minimum energy consumption that complies with the comfort restrictions. This minimum energy consumption will be employed for the comparison. For a more detailed description the reader can refer to Ref. [40].

2.2.5. DHW EC + HR

This case consists of the same case as before but includes heat recovery. As shown in Fig. 8, a recuperator is introduced to take profit of a low temperature heat source at 20 °C. The recuperator is a braze plate heat exchanger which preheats the net water temperature before entering the condenser. As low temperature heat source, one option is using sewage water as demonstrated in Ref. [42].

The same conditions as for the previous case have been employed for the set-point temperature, user comfort restrictions and circulation losses. The procedure to obtain the annual energy consumption also needs of a priori sizing of the HP and tank. The size has been obtained separately for each building of the neighborhood, following the same procedure as for DHW EC case.

2.3. PV EC analysis method

In the present work, PV ECs are circumscribed at the building level, which means that each PV installation on the roof of a building supplies energy to all the dwellings and premises of the building, following the self-consumption with surpluses modality from the current Spanish regulation [43].

The GIS-based model is detailed in previous work from the authors [44,45] and has helped to assess on rooftops in urban areas the techno-economic potential of PV communities [46]. The model employs mainly as inputs cadastral maps, which provide the horizontal geometry of the buildings, and LiDAR data, which include the height of the entire district with a density between 0.5 and 4 points/m^2 [47]. The

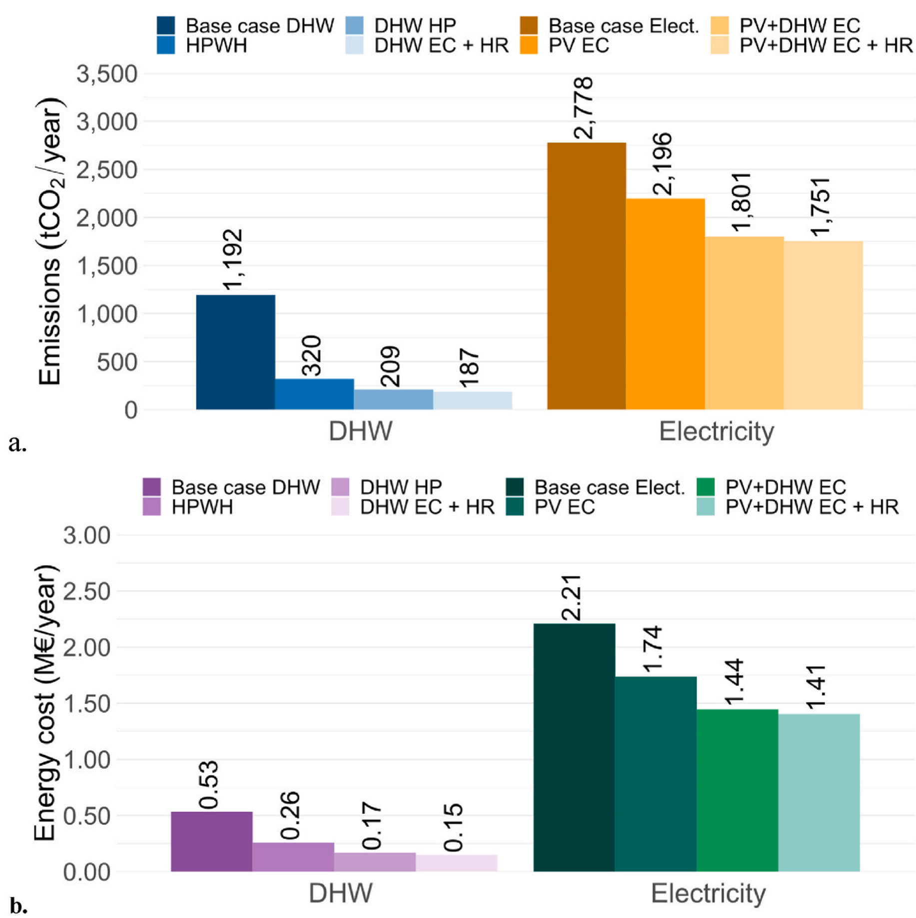

Fig. 8. Annual emissions (a) and energy cost (b) of the different cases.

combination of both the cadastral maps and LiDAR data has helped generate a 3D vector-based city model of prismatic buildings, whose level of detail is enough for multi-storey buildings according to Wang et al. [48]. The calculation of the shadows by the different buildings on the rooftops is described in Ref. [49].

The following spacing criteria suggested by the council technicians have been considered.

- The minimum available area without shadows is 7 m^2 to guarantee that the installations have enough space and enough installed power to guarantee a minimum energy supply to the building.
- The modules have a minimum distance of 1.5 m with respect to the rooftop walls in order to avoid shadows and have sufficient space for maintenance purposes.
- A minimum width of 1 m for the available area is required so the PV modules can fit.

The PV installed power in each rooftop is estimated using a typical ratio for horizontal surfaces between the installed PV peak power and the available rooftop area. The hourly in-plane global irradiation on tilted PV modules is obtained with a Typical Meteorological Year (TMY) climatic time series of València [50] and the Liu-Jordan equation [51], which is an isotropic irradiance model. The latter is combined with the skyline of surrounding buildings, obtained with the Viana-Fons et al. model [49], which reduces the diffuse irradiance component and cancels the direct component when sun is covered by the skyline of surrounding buildings. Additionally, a specific rate soiling losses for urban areas extracted from literature was assumed [52]. The equations to estimate the hourly PV production for each building are described in APPENDIX B. PV production model.

The electrical PV energy production is calculated considering the characteristics of a standard PV commercial model (Atersa A-395 M GS). The technical data includes the efficiency, the power temperature coefficient, and the yearly degradation rate. Additionally, other facility losses such as the wiring and inverter efficiency were considered with a common performance ratio [53].

The electrical demand is obtained assuming an hourly dimensionless load profile [54] and by multiplying it by the annual electricity demand of the building. The latter is obtained as the sum of the total area of dwellings and premises inside each building and applying a ratio of electricity consumption per constructed area. This ratio depends on the type of use of each premise, as specified by the cadaster.

The economic savings are obtained applying the current self-consumption regulation in Spain, which follows a net billing scheme [55]. Under this scheme, the surpluses are sold at a lower price than the energy bought to the grid for consumption. However the monthly economic surplus remuneration cannot be higher than the electricity bill of the billing period [43]. The equations to estimate the economic balance under the Spanish regulation are detailed in Ref. [56].

The simulations have been performed with an a hourly resolution for a lifetime of 25 years [57] and the assumptions of the PV model are given in Table 4.

In future work, the PV model will be improved to allow the sizing of the facilities considering the demand profiles to optimize their profitability. Likewise, electrical consumption will be estimated based on measured hourly profiles.

2.4. DHW + PV EC analysis method

To assess the combined HP + PV systems, the HP hourly load curve of each building has been aggregated to the hourly load curve of each PV EC. Prior to the aggregation, it is necessary to reduce the building load curve. In fact, the area/power density ratio of the residential premises also considers the electricity consumption to produce DHW satisfied with the immersion electric heater. The hourly consumption curve of the electric heater has been scaled up multiplying it by the number of

Table 4
Summary with the main inputs of the PV self-consumption model.

Parameter	Value	Units	Reference
Default module tilt angle	30.00	°	–
Default azimuth tilt angle	0.00	°	–
Soiling losses (η_{soil})	5.00	%	M. R. Maghami et al. [52]
Albedo coefficient (ρ)	0.2	–	P. Gilman et al. [58]
Efficiency of the module ($\eta_{PV,STC}$)	19.92	%	Atersa [59]
Power temperature coefficient of the module (γ)	−0.37	%/°C	Atersa [59]
Nominal Operating Cell Temperature (NOCT)	45.00	°C	Atersa [59]
Performance ratio (PR)	0.8784	–	A. M. Khalid et al. [53]
Ratio between rooftop area and PV power installed	10.00	m^2/W_p	Grupotech [60]
Module degradation rate (η_{deg})	8.00	%/year	Atersa [59]
Electrical demand per unit area (residential use)	34.05	kWh/ m^2·year	IDAE [16]
Surplus remuneration	0.046584	€/kWh	REE [61]
O&M costs	9.35	€/W_p·year	J.Chase [62]

dwellings of each building and the average ratio of dwellings in the Mediterranean area of Spain which have electric heater, which is defined as 28,6%, according to the SPAHOUSEC study [16]. Finally, the reduced building load curve has been aggregated to the hourly HP load curve, as a result of the DHW analysis for each building.

Lastly, the energetic, economic and emissions balance of each building is obtained applying the PV model described in section 2.3. PV EC analysis.

2.5. General considerations and analysis KPIs

This study focuses on the energy balance, as the main point to draw economic and environmental conclusions. The selected KPIs to analyze the results are the annual energy demand, the annual emissions in tons of CO_2 and the annual energy cost.

For the analysis, two different scenarios have been considered regarding the price of electricity. First, a conservative scenario has been considered with an average electricity cost from the last 4 years and an average emission rate from the last 4 months of the electricity mix. In this scenario, the averaged electricity cost for Spain is 14.7 c€/kWh, which is similar to the averaged electricity costs in 2020 of other Mediterranean countries [63]. The second scenario includes the averaged costs of the last five months of 2021, thus higher than in the previous scenario, and with a high energy emission rate, considering that the assessed alternatives substitute the natural gas thermal plants in the national energy mix. An emission rate of 0.201 tCO_2/MWh has been assumed for gas [64], with a cost of 0.067 €/kWh.

3. RESULTS and discussion

In this section, the main results are discussed. In first place, a detailed analysis is presented for the base case scenario of the district. In second place, an evaluation is performed for the different DHW alternatives compared to the *base case* and for the PV installation alternative. Finally, the priorization and combination of both alternatives is discussed.

Only the residential buildings have been selected for the study, with a total number of 150 buildings with 4194 dwellings (see section 2.1. Analysis areafor more details). However, regarding PV alternative only 129 buildings (1 MFH and 128 AB) are suitable for the installation of PV according to the criteria explained in section 2.3. PV EC analysis.

Fig. 8 includes the main results of this research work.

Fig. 8a includes the emissions savings whereas.

- Fig. 8b illustrates the economic savings.
- Both figures include the results for the base case of DHW and electricity and the alternatives for each case.
- The results of the DHW base case and their alternatives are separated from the electricity ones, whereas the alternatives that combine DHW and electricity appear together under the electricity bars.
- The legend above the figures includes the nomenclature which has been adopted for each alternative.

3.1. Base case

Fig. 8 shows the results of the current energy situation considering the DHW consumption (combining gas boiler and immersion electric heater use) and the electricity. The results indicate that the 150 residential buildings of the district are responsible for 1192 tCO_2 due to the DHW production, with an annual energy demand of 5516 MW h and an energy cost of around 533 k€/year. Regarding the electricity consumption, 2778 tCO_2 tCO_2 are emitted every year due to an electricity demand of 13.5 GW h, with an annual energy cost over 2 M€. Considering a high electricity scenario cost, the energy costs are around 700 k€/year due to the DHW production and more than 3.5 M€ for the electricity cost.

On average, each dwelling is responsible for 284 $kgCO_2$/year due to the DHW production and 662 $kgCO_2$/year due to the electricity consumption. The corresponding energy cost is of 126 €/year for DHW and almost 527 €/year for the electricity demand. This energy cost could reach more than 170 €/year for DHW and 820 €/year for electricity in periods of high energy prices (see Table 5).

Table 6 indicates the total annual energy consumption, emissions and energy costs for the district. The results show an absolute value of emissions of 3970 tCO_2/year and energy cost of 2,742,219 €/year regarding the electricity and DHW.

Considering that the DHW production energy systems are low-energy efficient and high CO_2 emitters and that there is no RES already implemented in the neighborhood, the energy, economic and emission savings potential are high.

3.2. DHW alternatives

In Fig. 8, the results are shown for the alternative DHW production systems. The HPWH, which is more energy-efficient but individual system, shows high energy savings. The results show potential savings up to 872 tCO_2 yearly (around 70%) and annual economic savings of almost 275 k€ (50%). For the EC case, the savings reach over 983 tCO_2 (82%) yearly and 365 k€ (70%) whereas the EC + HR cases reach more than 1000 tCO_2 (85%) and 386 k€ (73%). At this point, the energy savings could eventually even displace gas thermal power plants on the energy match, and thus the emissions savings could be higher. This evaluation of emission savings under scenario 2 lead to savings on the HPWH, DHW EC and DHW EC + HR case of 1208.21, 1319.40, 1347 tCO_2 respectively.

Both DHW EC cases show very similar results, although slightly better (around 6%) for the case with heat recovery. This is due to the high net water temperature of the city of València (warmer climate in Europe) which in summer is very near to the low temperature heat source of 20 °C considered in the HR case. The results of the individual case (HPWH) don't yield a high difference with the EC or collective cases, only around 10%. However, a high rate of discomfort of 20% (1752 h/year) will be experienced compared with a rate of only 0.5% (44 h/year) with the EC cases. Table 3 also shows that the HPWH almost has to double its energy consumption to reach a discomfort rate of 12%.

Moreover, the differences could be huge in terms of sustainability cost. Although they are not calculated in detail in the present study, they can be understood from the results presented in Table 7. If a total renovation was possible in the neighborhood, the HPWH total power installed would reach up to 3.8 MW with a total tank size of 335 m^3, with one installation per dwelling (total of 4194). The aggregated power installed for the EC case considering the one installed in each building will not reach 1.5 MW and 41 m^3, with one installation per building (total of 150). The differences in installed power reach over 60% and 85% difference for installed power and tank volume respectively.

For an average dwelling, the savings can reach almost 66 €/year for the HPWH and for the average building, the savings can reach 2430 €/year for the EC case and 2580 €/year for the EC + HR case. Under high price scenarios, the savings grow by a factor of 1.8. Although the economic analysis is not in the scope of the present work, the cost savings show a significant potential. In a 10-year period, the savings can reach 660 € for the HPWH, 24,300 € for the EC case and 25,800 € for the EC + HR case.

Table 5
Assessed scenarios of electricity cost and emission rates. Source [61]:

	Units	Scenario 1	Scenario 2
Emission rate	tCO_2/MWh	0.112	0.3961
Energy cost	€/kWh	0.147	0.265

Table 6
Evaluation of the current energy state of the *base case*, including total energy consumption, emissions and energy cost by energy source.

	Energy consumption	Emissions	Energy cost
	MWh/year	tCO_2/year	€/year
Electricity	15,121	3063	2,439,968
Gas	4511.	907	302,250
TOTAL	–	3970	2,742,219

3.3. Electricity alternatives

The aggregated results of PV EC consider the 129 residential buildings with suitable rooftops, and the aggregated results for PV + DHW EC and PV + DHW EC + HR include the HP savings of those residential buildings without PV facilities, to provide the maximum RE potential of the district.

The aggregated available rooftop area that meets all the conditions (described in section 2.3. PV EC analysis method) is 54,637 m^2, which is only the 54.81% total rooftop area of the buildings according to the cadastral geometry. On average, each dwelling has 55.93% of the total rooftop area occupied by the PV modules (see Table 8).

Regarding the installed power, the district presents space enough to install up to 2.38 MW_p with PV facilities which have an average power of 18.4 kW_p. The interquartile range is between 5.7 kW_p and 21.06 kW_p, however there are a few buildings that reach 100 kW_p, which is the maximum value accepted by the Spanish regulation for the self-consumption modality. The mean PV power installed per dwelling is 0.57 kW_p, which is a reduced value caused by the small available area and the high density of the area. In other words, due to the lack of rooftop space, the PV facilities tend to be undersized in relation with the electricity demand. Consequently, there is a high energy demand compared to the PV production. The aggregated PV production potential is 3240.40 MW h/year and represents 23.89% of the estimated residential demand of the buildings with PV facilities (13,563.16 MW h/year). This rate decreases to 21.22% if all residential buildings are

Table 7
Values of aggregated power and tank volume requirement for a total DHW system renovation.

	Units	HPWH	DHW EC	DHW EC + HR
HP size	kW	3774.60	1480.13	1354.36
Tank size	l	335,520.00	40,116.80	42,406.90

Table 8
Statistical summary of the PV performance parameters of the assessed PV systems.

Parameter	Units	Min	1st Quartile	Median	Mean	3rd Quartile	Max
Useful area	%	13.66	46.45	58.60	55.93	65.97	89.57
Installed power	kW_p	0.94	5.71	10.56	18.43	21.06	100.00
Installed power per dwelling	kW_p/dwelling	0.06	0.38	0.48	0.57	0.68	1.45
Renewable fraction	%	2.44	15.91	20.45	21.62	26.60	38.22
Surpluses	%	0.00	0.00	0.09	3.29	2.58	26.45
Self-consumption	%	73.54	97.41	99.91	96.71	100.00	100.00
Economic savings	%	2.44	15.91	20.48	22.05	26.67	42.48
Emission savings	%	2.44	15.91	20.65	22.96	26.84	51.92

considered. 93.74% of the production is self-consumed and only 6.26% are surpluses. Due to their small frequency the renewable fraction follows a linear relationship with the PV installed power until 1 kW_p per dwelling. With higher values the growth rate decreases due to a greater presence of surpluses, as shown in Fig. 9. A similar trend is also perceived in the cost savings due to the differences between the surplus remuneration and electricity costs, as discussed hereafter.

The aggregated emission and cost savings due to the implementation of PV facilities is 582.30 tCO_2/year and 0.4722 M€/year, which mean a reduction of 20.96%, and 21.37% respectively compared to the current electricity consumption. These rates rise up to 22.37% and 22.84%, respectively, only considering the residential buildings with rooftop. Under this typology of buildings, the savings of not consuming electricity from the grid represent on average 98.14% compared to the remaining 1.86% from the surplus remuneration. The average economic saving per dwelling is 113.62 €/year, which represents around 22% of the electricity bill.

For the PV + DHW EC case, the aggregated electricity demand decreases 278.91 MW h/year (a reduction of 2.06%), which is on average a reduction of 2.16 MW h/year per building. In other words, including DHW communities reduces, averagely, the building energy demand an equivalent amount to the consumption of a small household of around 60 m^2. This demand reduction combined with an identical PV production and a very reduced change in the demand profile leads on average to an increase in the renewable fraction of 1.67%, and to an average increase in the surpluses of 8.40% in comparison with the PV EC case. The emission and cost reductions reach up to 977 tCO_2/year and 0.76 M€/year, which implies a reduction of 35.17% and 34.61% compared to the base case, respectively.

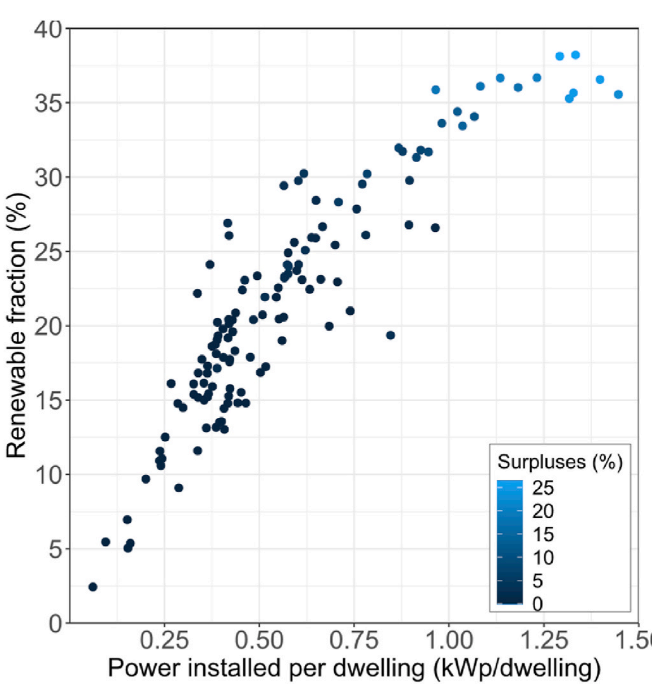

Fig. 9. Renewable fraction evolution with the installed power per building.

The demand reduction for the PV + DHW EC + HR case, implies an additional aggregated decrease of 126.82 MW h/year, which is on average 0.98 MW h/year per building. The HR savings, added to the PV + DHW EC savings, roughly reduce the electricity demand of a building to an equivalent consumption of a household (3.15 MW h/year). With this measure, the average renewable fraction experience minor variations compared with the PV + DHW EC case due to small differences in the load profiles of the HP systems. The emission and cost reduction compared with the base case reaches up to 1027 tCO_2/year and 0.80 M€/year, which implies a reduction of 36.98% and 36.41%, respectively.

3.4. *Combination of alternatives*

DHW and PV alternatives are never opposing solutions but always complementary. However, budgets in general (from citizens and from city-councils) are finite and it is important to prioritize strategies towards an energy transition. For this reason, the present section analyzes each alternative individually to prioritize them and then study them as combined solutions.

In general, 3 key issues arise from the results in Fig. 8. The first point is that the DHW alternatives achieve the highest relative impacts over PV regarding emissions and economic savings. Emission and economic savings for all DHW alternatives are over 70% and 50%, respectively, whereas PV emissions and economic savings range between 20 and 25%. The second point is that the DHW alternative always achieves higher absolute values of emission savings. Any of the alternatives of DHW achieves emissions savings over 870 tCO_2 with a maximum of 1011 tCO_2, while PV alternative reaches 582 tCO_2. The last point is that the absolute economic savings are always higher for PV alternative over DHW, although the emission savings are different: while DHW alternatives achieve economic savings between 270 and 380 k€, the absolute economic savings are almost 500 k€ for the PV alternative.

These results point out an important fact. If the objective of the decision-maker is to decide on energy-efficiency actuations based on their emission savings, the selected action will be the renovation of the DHW production system. However, if the decision-maker prioritizes the economic savings, the PV installation of the neighborhood should be clearly selected. To provide a more detailed approach, Fig. 10a illustrates the best possible action (among PV EC or DHW EC) in terms of emissions savings and Fig. 10b in terms of economic savings. The results show that the best action to reduce emissions is implementing DHW EC, whereas PV ECs are better to maximize the cost savings. This information is of interest for decision-makers, who could be the energy planning department of the city-council or the citizens as decision-makers of their own climate impact at a building level.

The potential PV installed power per dwelling is an interesting indicator to obtain a rule of thumb for technicians to decide which EC choice is more suitable. Fig. 11 relates the PV installed power per dwelling with the most suitable EC type depending on the objective. If the aim is to reduce the emissions, the most suitable buildings to promote PV EC are those with wide rooftop space compared with the

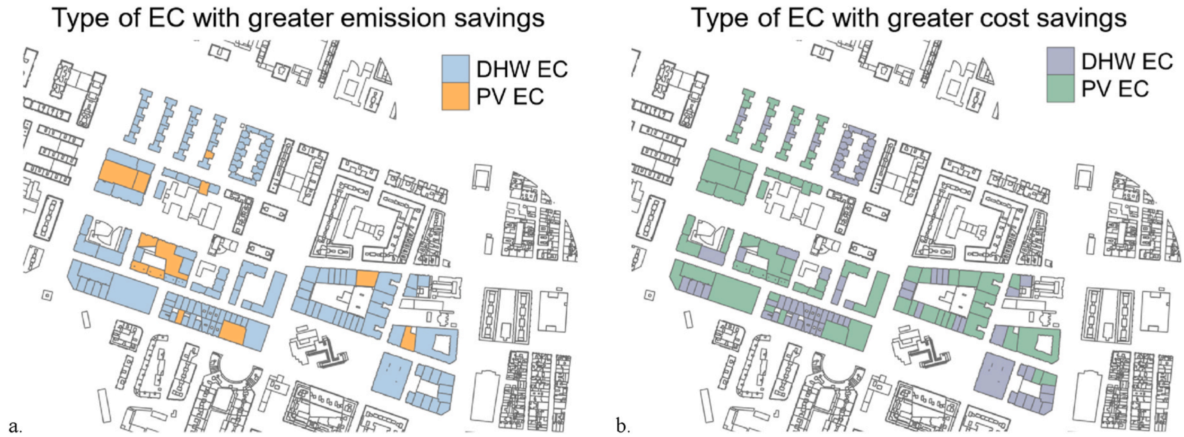

Fig. 10. Identification of best energy efficiency action (DHW EC or PV EC) to obtain. (a) Maximum emission savings and (b) Maximum economic savings.

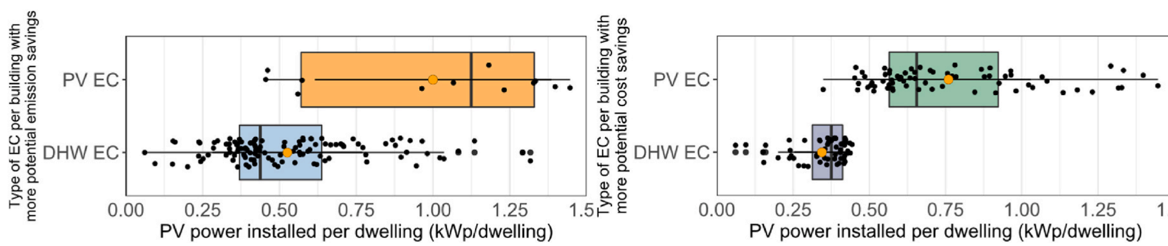

Fig. 11. Boxplots of the PV power installed per dwelling grouped by which EC type promote if the emission savings are prioritized (left) or cost savings are prioritized (right).

number of dwellings, with an installed power per dwelling near to 1.2 kW_p, which maximizes the emission savings. If the cost reduction is the priority, most of the buildings with reduced rooftop area achieve higher cost savings with DHW EC if the potential PV installed power per dwelling is under 0.45 kW_p, which means significant rooftop space limitations. The above-mentioned thresholds were obtained applying a logistic regression, providing an accuracy of 0.94 and 0.98 respectively.

Considering a combined scenario in which both, PV and DHW EC production cases are implemented together, the PV covers partially the DHW demand a part of the building electricity demand. The absolute value of emissions savings for the case of PV combined with the DHW EC solution is 2169 tCO_2/year and the annual energy cost saving is 1.29 M€, whereas the results for the PV combined with the DHW EC + HR solution are 2219 tCO_2/year and 1.33 M€/year. This implies emission savings of 54.6% and 55.9% respectively and energy cost savings of 47.3% and 48.8% respectively.

These values of emission reductions show that the DHW and PV energy-efficiency actions could reach very high emissions savings on the neighborhood, near to the EU emission reduction objective of *Fit for 55 package* for 2030. However, there is still a big gap to reach the emissions reduction objective of 90% settled by the EU for 2050. For this purpose, alternative solutions should be considered, such as buildings refurbishment, which is the objective of a future work.

Finally, Fig. 12 shows the relationship between the number of buildings in which the combined alternative option is allocated and the corresponding emission savings. The results show interesting findings. For instance, acting on 10% of the buildings of the neighborhood, 50% savings could be achieved. This value can increase up to 80% savings if acting on 35% of the buildings.

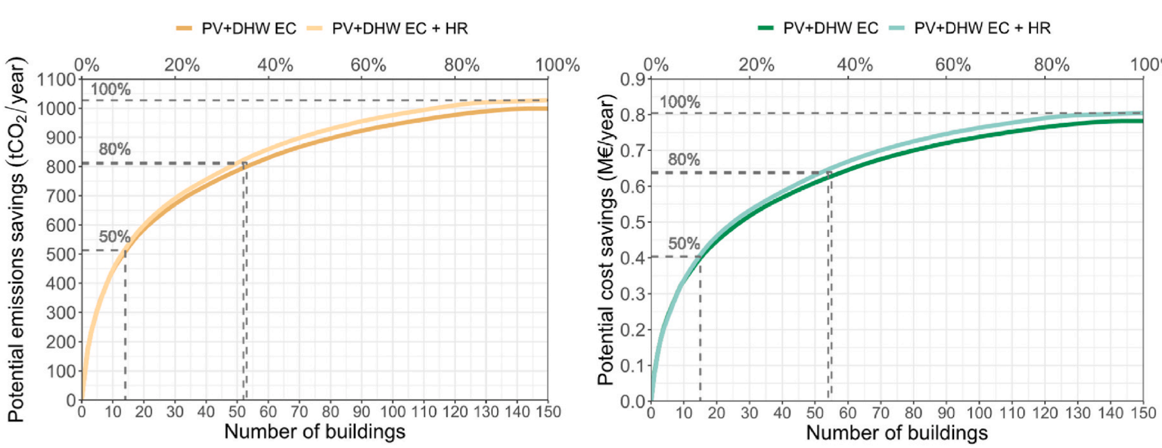

Fig. 12. Cumulative curve of potential emission savings over building in which the energy-efficiency actions take place.

4. Conclusions

To meet the sustainability objectives of the EU and develop Positive Energy Districts, a holistic and shared vision of energy must be performed. ECs are an interesting solution to decarbonize the residential sector, providing a positive impact in terms of cost reduction and citizen empowerment. However, a gap has been identified in the literature on ECs, since most of the publications refer to shared PV installations, leaving aside other alternatives.

The present work quantifies the potential emission and operation cost savings applying PV and DHW ECs in 150 residential buildings of a representative city of EU warm climates (València, Spain). The current energy consumption at building and district level was obtained for DHW and for general electrical uses, as well as the emissions and operating costs.

The current DHW emission and costs were compared with the DHW alternatives considering an individual HPWH, a DHW EC and a DHW EC with HR. The best results of emissions and economic savings were obtained for the DHW EC cases. Moreover, the DHW EC show 60% and 85% less power and tank volume needs compared with the individual solution of HPWH. The results show average annual savings of 66 € per dwelling for the HPWH, 2430 € for the DHW EC and 2580 € for the DHW EC + HR per building.

The current electricity consumption was also compared with a scenario with PV installations in each building with enough available rooftop area. Only 54.81% of the aggregated rooftop area of the district is suitable for PV systems, which leads to undersized facilities with an average of 0.57 kW_p per dwelling. The average renewable fraction is 21.62% and 93.74% of the energy produced is self-consumed. The average emission saving per building is 22.96% and this value can reach up to 51.91%. The aggregated results when installing only PV systems provide a reduction of the electricity bill of 22.84%.

From a decision-maker perspective, the decision to promote a DHW EC or PV EC depends on which type of savings are planned to be maximized. If the emissions are the priority, DHW EC provide in absolute the highest emission savings; when the economic savings are the objective PV EC would be more effective. To facilitate the decision process, an analysis building-to-building of the district has been included. The majority of buildings follow the previous general rule. The choice mainly depends on the availability of rooftop area. The results show that only those buildings with high rates of potential PV power installed per dwelling present higher emission savings with PV (over 1.2 kW_p/dwelling). This value is clearly lower when prioritizing cost savings, since only undersized PV facilities under 0.45 kW_p per dwelling would adopt DHW EC.

When combining both alternatives (DHW EC and PV EC), the emission savings could reach values up to 55% savings regarding the current emissions. This is the scenario settled for 2030 by the *Fit for 55 package* of the EU. However, extra energy-efficiency actions are required to reach the objective of 90% emissions reduction for 2050.

When promoting ECs in a district, selecting the buildings with the most impact in the district is an interesting solution when the budget or actions are limited. The results show that acting only in a third part of the residential buildings would reduce the emissions and costs up to 80%. The key factor when prioritizing buildings is the number of dwellings involved.

As future work, the buildings refurbishment scenario will be studied together with the DHW and PV alternatives. Finally, a more detailed analysis including investment costs and life-cycle analysis would also be of interest.

Credit author statement

X. Masip – Conceptualization, Method and Results, Writing, Enrique Fuster-Palop - Method and Results, Software, Writing, C. Prades-Gil - Software, Joan D. Viana-Fons - Software, Jorge Payá -Supervision, Emilio Navarro-Peris - Supervision.

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

The authors do not have permission to share data.

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Appendix. ATRNSYS model

The TRNSYS models used in this research work include the following main types.

For storage.

- Type 158. This type models a constant volume fluid-filled storage tank cylindrical shaped and vertical. The tank has two inlets and two outlets and it is modelled in different iso-thermal user specified nodes to gather stratification effect. The model considers environmental losses regarding top and bottom surface as well as cylindrical surface according to (Eq. (1)). The iso-thermal nodes can interact through them by conduction effects, as described in (Eq. (2). For specific information about the type consult TRNSYS Mathematical reference and consult Table A1 for the specific values used.

$$Q_{loss_i} = U_i \cdot A_i \cdot (T - T_{env}) \quad \text{(Eq. 1)}$$

$$Q_{cond_j} = k_j \cdot A_j \cdot \frac{(T_j - T_{j+1})}{L_{cond_j}} + k_{j-1} \cdot A_{j-1} \cdot \frac{(T_j - T_{j-1})}{L_{cond_{j-1}}} \quad \text{(Eq. 2)}$$

- Type 39. It is a variable-volume storage tank, with one inlet and one outlet that can have different circulation flows and thus have variable-volume in the storage tank. One of the outputs of this type is the level of water in the storage tank, in %, that is used in the controller. The tank is modelled as a *'fully-mixed variable mass of water storage tank'* and the following differential equations, extracted from TRNSY Mathematical reference, describe its energy behavior. For more detailed information consult TRNSYS Mathematical reference and consult Table A1 to check specific values used.

$$\frac{dM}{dt} = m_i - m_o \quad \text{(Eq. 3)}$$

$$C_{pf}\frac{d(M\,T)}{dt} = m_i C_p T_h - m_o C_p T - (UA)_t (T - T_{env}) \quad \text{(Eq. 4)}$$

- Type 60 d. Immersion electric heater. This type models a constant-volume storage tank that can have optional internal heat exchangers and internal heaters, 2 inlets and outlets and can have multiple internal nodes to model stratification. The model is very detailed, and it is recommended to check the TRNSYS mathematical reference. It includes an internal time step, a de-stratification modelling and insulation modelling.

DHW production system.

- Type 122. Gas boiler. This type models a fluid boiler with a capacity and energy efficiency user-specified. In case of higher capacity needed, the boiler will work under its maximum capacity. *'This model is based on ASHRAE's definition of boiler efficiencies as published in 2000 ASHRAE Systems and Equipment Handbook.'* The following equations describe the energy behavior of the type.

$$Q_{need} = m_{fluid} \cdot C_{p,fluid} \cdot (T_{set} - T_{in}) \quad \text{(Eq. 5)}$$

$$Q_{fuel} = \frac{Q_{fluid}}{\eta_{boiler}} \quad \text{(Eq. 6)}$$

$$Q_{Exhaust} = Q_{fuel} \cdot (1 - \eta_{combustion}) \quad \text{(Eq. 7)}$$

- Own developed type for the HPWH. This model is own-developed and acts as a black-box model, including the inputs for the HP type (inlet water temperature, air temperature and humidity ratio) and returns the output regarding the working point of the HP. Internally a HP map with an interpolation function is implemented.
- Own developed HP type for HP. This model is own-developed and acts as a black-box model, including the inputs for the HP type (inlet water temperature, air temperature and humidity ratio) and returns the output regarding the working point of the HP. Internally the correlations of the HP are included.

Other types.

- For weather, type 15–2. The type reads and interprets available weather data from TMY2 standardized files. The specific file used in this study is 'ES-Valencia-Airp-82840. tm2'.
- For the circulation pumps, type 742 from TESS library. This type models a circulation pump with matching inlet and outlet circulation flow. The model calculates the energy consumption based on user-specified pressure drop, fluid characteristics and efficiencies.
- For control, type 2. It is a differential controller that returns a control logical output (0 or 1) regarding the difference among an upper and lower temperature compared with user specified deadbands. In this work, the upper temperature corresponds with the set-point temperature of 60 °C, and the deadband considered is of 5 K. The specific values used are included in Table A3. For more detailed information consult TRNSYS Mathematical reference.

Table A.1
Storage units

	Electric heater	HPWH	DHW EC	Units
Type	60 d	158	39	–
User-specified inlet positions	2	2	2	–
Tank volume	80	80	–	l
Fluid specific heat	4.19	4.19	4.19	kJ/kg.K
Fluid density	1000	1000	1000	kg/m^3
Tank loss coefficient	0.8	0.8	0.8	W/m^2·K
Fluid thermal conductivity	0.6072	0.6072	0.6072	W/m·K
Auxiliary heater mode	2	2	0	–
Height of 1st aux. heater	1/3*h_tank	1/4*h_tank	–	string
Height of 1st thermostat	inlet_1	inlet_1	–	string
Maximum heating rate of element 1	750	900 (HPWH)	–	W
Height of heating element 2	1/3*h_tank	1/10*h_tank	–	string
Height of thermostat 2	inlet_1	inlet_1	–	string
Maximum heating rate of element 2	750	2000	–	W
Tank nodes	15	15	–	–

Table A.2
Weather unit

Weather file	ES-Valencia-Airp-82840.tm2

Table A.3
Control unit

	Individual	Collective	unit
Type	2 b	2 b	–
Upper input temperature Th	55	60	°C
Lower input temperature Tl	tank variable	tank variable	–
Monitoring temperature Tin	90	90	°C
Input control function	0	0	–
Upper dead band dT	5	5	°C
Lower dead band dT	0	0	°C

Table A.4
Reader for demand profile unit

	All	units
Type	9e	
Mode	6	–
Header Lines to Skip	1	–
No. of values to read	1	–
Time interval of data	1	min
Interpolate or not-1	−1	–
Multiplication factor-1	1	–
Addition factor-1	0	–
Average or instantaneous value-1	0	–

Table A.5
Gas boiler unit

	GB	units
Rated Capacity	28	kW
Fluid Specific Heat	4.19	kJ/kg·K
Minimum Turn-Down Ratio	0.2	–
Setpoint Temperature	60	C
Boiler Efficiency	0.92	–

Table A.6
Circulation pump unit

	DHW EC	units
Fluid specific heat	4.19	kJ/kg·K
Fluid density	1000	kg/m3
Motor heat loss fraction	0	–
Inlet fluid temperature	–	C
Inlet fluid flow rate	–	kg/hr
Overall pump efficiency	0.3	–
Motor efficiency	0.9	–
Pressure drop	–	kPa

Appendix. BPV production model

The hourly PV production model is based on the Liu-Jordan isotropic sky model [51] to estimate the hourly global irradiance on the plane of the array ($G_{POA,h}$). According to (Eq. (8). The $G_{POA,h}$ is the sum of direct ($B_{POA,h}$), diffuse ($D_{POA,h}$) and reflected ($R_{POA,h}$) components.

$$G_{POA,h} = B_{POA,h} + D_{POA,h} + R_{POA,h} = B_{0,h} \cdot \frac{\cos \theta_s}{\cos \theta_{zs}} \cdot f_b + D_{0,h} \cdot SVF + G_{0,h} \cdot \rho \cdot (1 - SVF) \quad \text{(Eq. 8)}$$

The TMY climatic file provides the hourly direct normal irradiance (DNI_h) and the diffuse horizontal irradiance ($D_{0,h}$). Both variables together the sun zenith angle (θ_{zs}), and the angle between the direction of the sun rays and the normal to the surface (θ_s) obtained with the sun trajectory equations defined by J.J. Michalsky [65], allow calculating the beam horizontal irradiance ($B_{0,h}$) global horizontal irradiance ($G_{0,h}$) through the (Eq. (9). The latter and a ground reflectance ratio (shown in Table x) are required to estimate the $R_{POA,h}$,

$$G_{0,h} = B_{0,h} + D_{0,h} = DNI_h \cdot \cos\theta_{zs} + D_{0,h} \quad \text{(Eq. 9)}$$

The shadows casted by nearby buildings are considered in the irradiance model by means of the beam shadow factor (fb) and the sky view factor (SVF). Both coefficients are determined by means of the 3D vector-based city model mentioned in section 2.3. PV EC analysis method, which provides the heigh of each building. Through geometric calculations a skyline profile ($\beta_{buildings}(\alpha)$) is generated from the calculation point of the rooftop under study. The latter represents for each azimuthal angle step (α), set in 5°, the elevation angle of the highest building or obstacle found within a radius of 200 m from the analyzed rooftop. The variable fb is a binary factor (0 or 1) which cancels the beam component when the sun's height is below the skyline vector. The SVF is a coefficient ranging between 0 and 1, which reduces the diffuse component according to the Oke's expression [66] ((Eq. (10)).

$$SVF = 1 - \int_0^{2\pi} \sin^2\beta_{buildings}(\alpha)d\omega = 1 - \sum_{i=1}^{N} \frac{\alpha}{2\pi}\sin^2\beta_{buildings}(\alpha)d\omega \quad \text{(Eq. 10)}$$

As last step, the hourly electricity production ($E_{AC,h}$) for each year (i) is obtained with (Eq. (11)) and (Eq. (12) [67] considering the $G_{POA,h}$, the available rooftop area (A), and the rest of variables described in Table 4. The hourly ambient temperature (Ta,h) is provided by the TMY climatic file.

$$E_{AC,h} = \left(PR \cdot \eta_{soil} \cdot \eta_{PV,h} \cdot A \cdot G_{POA,h}\right) \cdot \left(1 - \eta_{deg}\right)^i \quad \text{(Eq. 11)}$$

$$\eta_{PV,h} = \eta_{PV,STC} \cdot \left(1 + \gamma \cdot \left(T_{a,h} + \frac{NOCT - 20}{800} - 25\right)\right) \quad \text{(Eq. 12)}$$

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