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Energy Self-Sufficiency Urban Module (ESSUM): GIS-LCA-based multi-criteria methodology to analyze the urban potential of solar energy generation and its environmental implications

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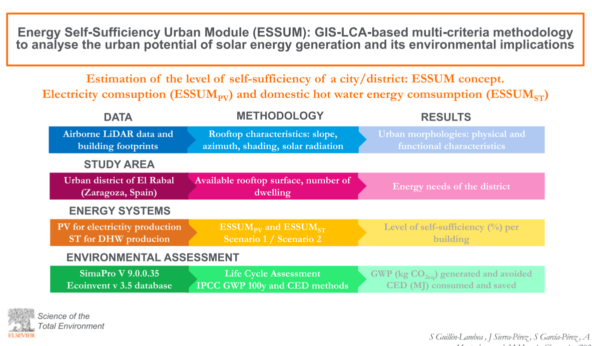
HIGHLIGHTS

- Proposed method determines the solar energy self-sufficiency of cities considering the environmental implications.
- Characterization of building rooftops is performed with LiDAR and Cadastral data.
- Energy systems potential at urban level have been related to their environmental implication of manufacturing.
- Self-production capacity of urban environments can be assessed through energy potential of physical characterization.

GRAPHICAL ABSTRACT



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ABSTRACT

The concentration of the population in cities has turned them into sources of environmental pollution, however, cities have a great potential for generating clean energy through renewable sources such as a responsible use of solar energy that reaches its rooftops. This work proposes a methodology to estimate the level of energy self-sufficiency in urban areas, particularly in a district of the city of Zaragoza (Spain). First, the Energy Self-Sufficiency Urban Module concept (ESSUM) is defined, then the self-sufficiency capacity of the city or district is determined using Geographical Information Systems (GIS), Light Detection and Ranging (LiDAR) point clouds and cadastral data. Secondly, the environmental implications of the implementation of these modules in the rooftops of the city using the LCA methodology are calculated. The results obtained show that total self-sufficiency of Domestic Hot Water (DHW) can be achieved using 21 % of available rooftop area, meanwhile the rest of rooftop area, dedicated to photovoltaic (PV), can reach 20 % of electricity self-sufficiency, supposing a final balance of a reduction in CO_2 emissions of 12,695.4 t CO_{2eq}/y and energy savings of 372,468.5 GJ/y. This corresponds to a scenario where full self-sufficiency of DHW was prioritized, with the remaining roof area dedicated to PV installation. In addition, other scenarios have been analyzed, such as the implementation of the energy systems separately.

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1. Introduction

Cities are frequently considered the engine of economic prosperity and social progress (Habitat, 2013), but they are particularly vulnerable to the future demand of food, energy and water (EEA, 2019; European Environment Agency, 2015; European Union, 2020). Approximately, 68 % of the world population is projected to live in urban areas by 2050 (World Urban. Prospect. 2018 Revis., 2019). Therefore, it is essential to apply Sustainable Development (United Nations (UN) General Assembly, 2015) strategies at urban level in order to become clean energy but more accessible and closer. In this regard, local renewable energy production is considered as a key facilitator of energy production systems in highly populated cities.

Mainly in the last decade, innumerable research efforts have focused on proposing scientific methods to evaluate the potential of cities in terms of food and energy production and rainwater harvesting (FEW systems), as well as in proposing renewable generation systems for their proximity production. Most of the research on the FEW systems is concentrated on the global, transboundary and national scales, with less focus on the urban scale (Zhang et al., 2019).

Cities are places of distribution, consumption and, to a lesser extent, production (Artioli et al., 2017). With respect to the last, several studies have proposed different approaches where they explore the self-productive possibilities, understood as the generation of products by the cities for self-sufficiency in resources. On the one hand, the Roof Mosaic framework approach analyses the technical feasibility and environmental implications of producing food and energy, and harvesting rainwater on rooftops through different combinations at different scales (Toboso-Chavero et al., 2019). On the other hand, Urban Cells approach is a computational model using a modular approach to create an interconnected urban infrastructure, including the energy, building, and transportation sectors (Perera et al., 2021). In this regard, some studies have proposed different indicators for the Urban FEW nexus, clustering them into four main distinct groups. According to Arthur et al. (2019), the representativity of these indicators in published studies of Urban FEW nexus are: measuring resource fluxes (52 %); quantifying environmental impacts (13 %), efficiency aspects (29 %) and others (5 %) The indicators used in previous studies are mainly concentrate on the input and outflow of FEW in the system paying less attention to other scales, such as efficient use of resources, flow pattern of the resources and the environmental impact associated with the production and consumption of resources (Arthur et al., 2019).

Through these approaches, the capacity of cities to self-produce and to be self-sufficient on their own resources is addressed, following the non-novel concept of hyper-proximity cities (The 15 minutes-city), recently recovered by Moreno et al. (2021). The 15-Minutes Cuty rides on the concept of “chrono-urbanism” witch outlines that the quality of urban life is inversely proportional to the amount of the time inverted in transportation, more so though the use of automobiles (Moreno et al., 2021). The necessary transformation does not go through a radical renewal, but rather by making the necessary adaptations that allow their implementation. For that, the use of underutilized areas in compact cities, such as rooftops, to produce clean energy might increase urban self-sufficiency and revitalize social economic activity. In this regard, Jurasz et al. (2020) investigated the potential of rooftop photovoltaics systems to cover the electricity consumption of a medium-size city in Poland finding the systems insufficient to ensure the city's energy self-sufficiency.

In this research, a further step has been included, since a self-sufficiency indicator is defined according to the morphology and compactness of the city (the shape of its roofs and the number of inhabitants). In addition, the definition of the new Energy Self-Sufficiency Urban Module (ESSUM concept), allows to evaluate through a multi-criteria methodology based on GIS-LCA the energy self-sufficiency of cities and the associated environmental implications. The results could be used as input to define district networks and also assist in the implementation of future energy communities. For this purpose, the installation in the rooftop of the city buildings of photovoltaic (PV) systems for electricity generation and solar thermal (ST) systems for domestic hot water (DHW) production has been considered.

Moreover, as a novelty, an analysis of the environmental results as a function of urban morphology is included. The environmental results vary, in some cases substantially, depending on the urban morphology, therefore disaggregating the results according to this physical characterization could open new lines of research with the aim of turning our cities into clean and environmentally friendly places. From the methodology point of view, this study proposes the development of an integrated approach that can be used to improve the retrofitting and planning of cities from the perspective of energy self-sufficiency.

The results presented in this research work can help public authorities and stakeholders to develop new regulations in cities that help protect the environment and boost the fight against climate change.

2. Materials and methods

This research has developed a new concept, the ESSUM module, which is defined as the physical module that is able to provide the needs of a home user in terms of electricity and energy consumption for DHW production.

ESSUM considers electricity consumption and domestic hot water energy consumption as currently the most relevant energy demands, however, it could be extended to other energy needs. The concept is based on a modular approach with the objective of assessing and analyzing the energy needs of a home user in a residential context on an urban scale and according to the specific morphology of the city under study.

To produce the necessary energy for a home user, the installation of photovoltaic systems on the roofs of the city's buildings for electricity generation ($ESSSUM_{PV}$) and ST systems for DHW production ($ESSSUM_{ST}$) have been considered.

ESSUM makes it possible to relate the self-sufficiency potential in a building-to-building scale. In this way, it will be possible to identify where there is a surplus or a need, and to establish synergies/symbiosis between buildings or a group of buildings in close proximity.

In addition, the environmental implications of the installation of the ESSUM module have been assessed: the environmental impacts caused by the installation of the solar energy generation systems and the impacts avoided by the reduction in conventional energy consumption.

The case of study selected is the city of Zaragoza (Spain), focused in the urban district of El Rabal. Zaragoza receives a daily solar irradiation of 3300–3400 J/m^2 (López Martín et al., 2007). The urban district was selected for two main reasons, firstly because the district has the second highest percentage of the population (78,325 inhabitants in 2018), and the fourth highest percentage in terms of surface area (8.38 km^2) of the urban districts of Zaragoza according to the city council information (Zaragoza City Council, 2016). The second reason is the heterogeneity of its urban morphologies, from historic areas to recent suburban residential ones. That is significant in the development of this method because of the importance of the physical aspect of buildings in terms of height, number of dwellings per building or compactness of the city (Montealegre et al., 2022). Fig. 1 shows the district location.

The ESSUM methodology follows the next steps which are deeply described in the following sections (Fig. 2):

1. Determine the self-sufficiency needs of an inhabitant in terms of electricity and domestic hot water energy (DHW) consumption. Individual needs depend on several parameters, such as city, country, climate conditions, and social behavior among others.
2. Data collection: LiDAR, cadastral data/building footprint data and ancillary data.
3. GIS data processing. Selecting suitable rooftop areas, and calculation of PV and ST panels surface.
4. Definition of the required energy systems. Definition of the PV system and calculation of the annual electricity production in the city under

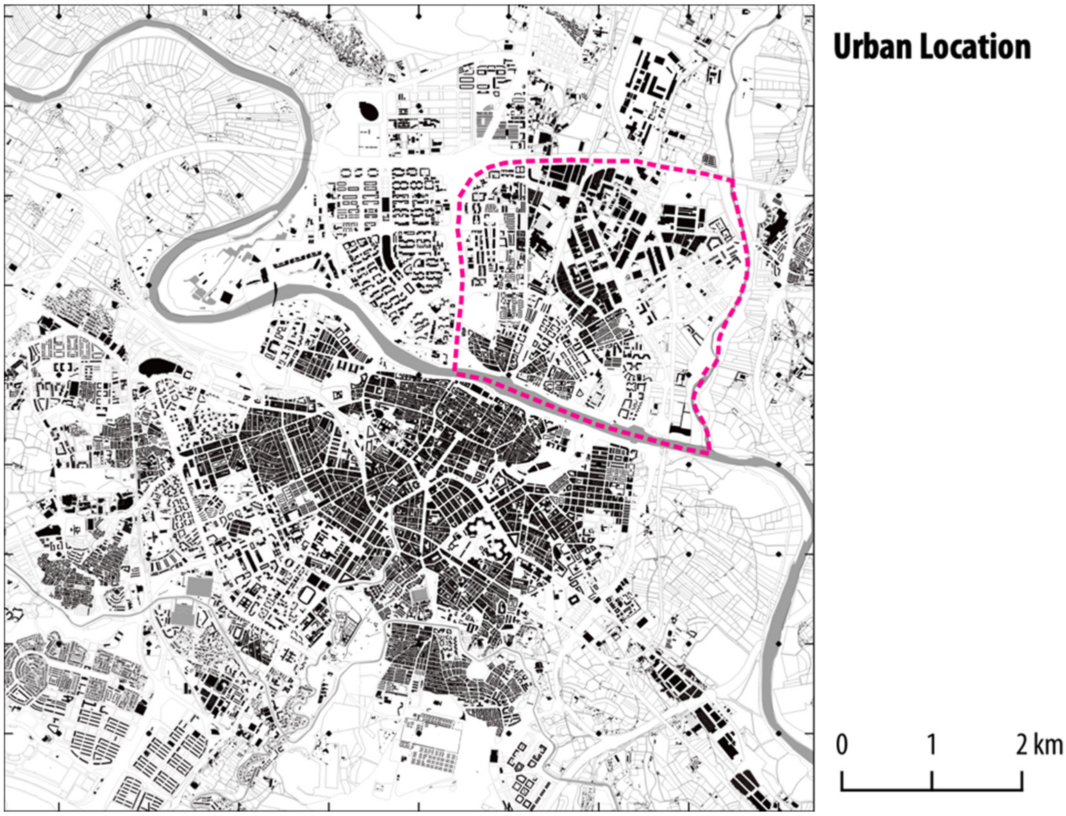


Fig. 1. District location in the city of Zaragoza (41.648801039355654, −0.8888275356806574).
Source: own elaboration from Spanish Cadastre dataset.

study using ArcGIS and establishment of the technical requirements of the ST to cover the DHW energy consumption.

5. ESSUM calculation of the total self-sufficiency module for solar energy systems at building-by-building level ($ESSUM_{PV}$ and $ESSUM_{ST}$ modules) and ESSUM energy and environmental assessment using LCA methodology.

Although there are numerous studies of the LCA of rooftop PV systems as well as domestic hot water systems, such as Piroozfar et al. (2016) or Spreafico and Russo (2020), this research includes a novelty and therefore a new advance as it has combined information on roof properties obtained from LiDAR point clouds and cadastral data. This new methodology constitutes an advance since the data obtained through a Geographic Information System (GIS) provide more realistic, objective and robust results compared to other studies that are based on theoretical and very casuistic estimates. The proposed methodology can be transferable to other urban environments in Spain, or even to other European countries and North America where LiDAR point clouds and cadastral data are available to characterize the roofs of buildings.

2.1. Energy self-sufficiency needs

First, it was necessary to define the self-sufficiency needs for an inhabitant in the selected case of study in terms of household energy, in this case: electricity consumption and DHW energy consumption.

Domestic consumption represents approximately 25 % of the total electricity consumption in Spain (IDAE, 2011). The energy consumed by dwelling varies greatly depending on the size and type of home, its location, and the number of occupants. The average electricity consumption by dwelling in Spain is growing in recent years according to the Institute for Diversification and Energy Saving (IDAE and Departamento de Planificación y Estudios, 2019) from 2477 kWh per dwelling in 2000 to 3788 kWh per dwelling in 2017. In contrast, the average occupancy per dwelling in Spain has risen from 2.30 inhabitants per dwelling in 2000 to 2.52 in 2017 (IDAE and Departamento de Planificación y Estudios, 2019).

Heating energy consumption is the most important in Spanish homes, accounting for 43.1 % of the energy consumption in the residential sector; however heating systems in Spain are mostly powered by natural gas, oil derivatives and renewable energy. The structure of household electricity consumption by type of equipment, data year 2017, (IDAE and Departamento de Planificación y Estudios, 2019) is: homes appliances 57 %, heating 7 %, cooling 2 %, ACS 8 %, kitchen 14 % and lighting 12 %. Therefore, the highest electricity consumption in Spanish homes is due to household appliances. This fact shows that, although the energy saving requirements in buildings achieve reductions in heating and cooling energy consumptions, the total electrical consumption of existing buildings will not decrease significantly because these standards do not affect the consumption of household appliances. Thus, the electricity consumption of Spanish households is fundamentally based on electronic appliances and devices directly related to the increasing comfort level of developed countries. However, the monthly variation is important, January has the highest electricity consumption in Spain and the lowest in April with 11 % and 7 % of the total electricity consumption, respectively. Dimensioning the PV system with annual values has the disadvantage that the months in which the electricity consumption is highest, that coincide with the months of minimal insolation, the consumer must buy electricity from the grid, while the months when electricity consumption is the lowest, the electricity generated by the PV panels will be more important and the PV system will feed electricity back into the grid.

The energy consumed in Spanish households by the DHW system represents the 19.2 % of the total energy consumed (IDAE and Departamento de Planificación y Estudios, 2019) which was estimated in 1877 kWh per household and year (IDAE and Ministerio de Industria Energía y Turismo, 2012), which gives 745 kWh/y per inhabitant considering an average occupancy in Spain, 2.52 inhabitant per household.

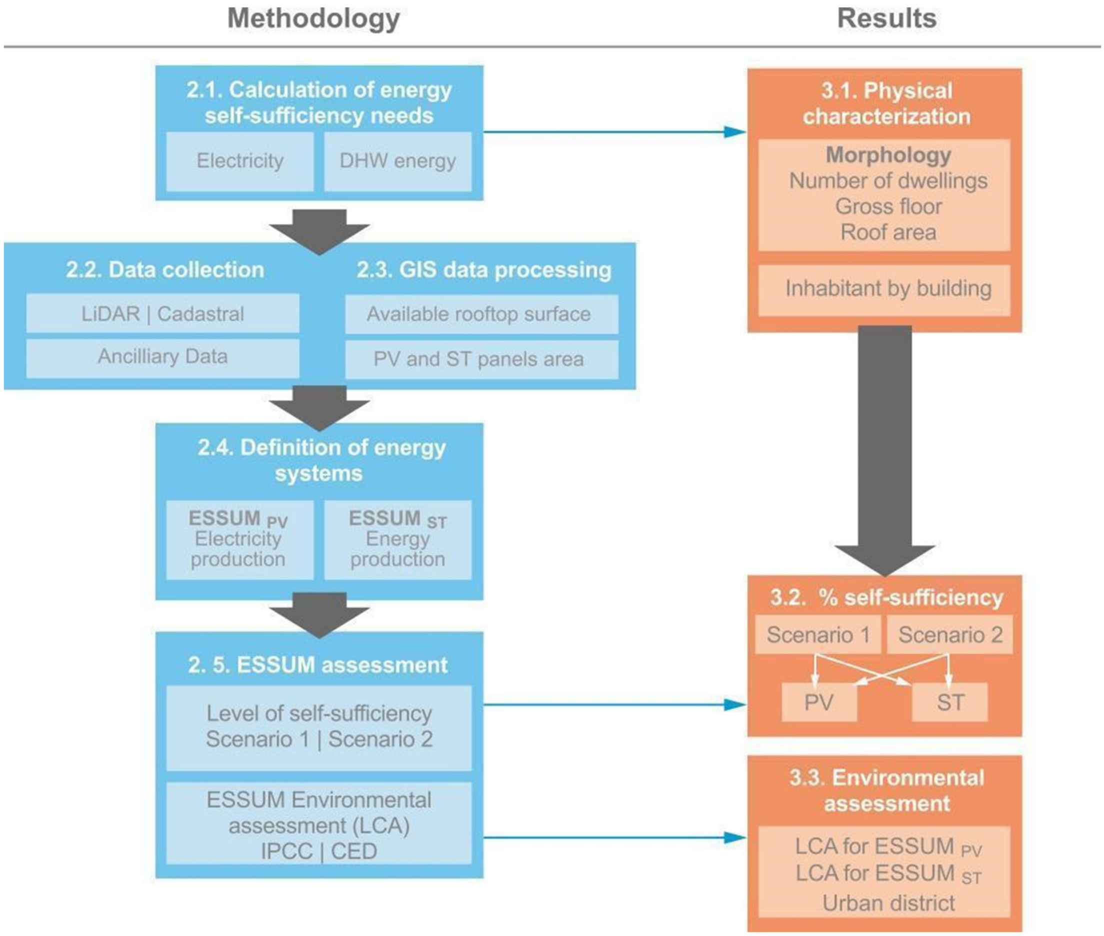


Fig. 2. Scheme for the methods used for the ESSUM calculation.

The 21.5 % of the DHW energy demand is covered by electricity, the 40.3 % by natural gas, 25.9 % by liquefied petroleum gas, 10.1 % by gasoil and 0.1 % by coal, only 1.7 % is covered by renewable energy (IDAE and Ministerio de Industria Energía y Turismo, 2012).

In the case of solar thermal energy to DHW production, the concept of self-sufficiency differs from that applied for the solar PV field. While for solar photovoltaic energy the concept of self-sufficiency means that the system is dimensioned to generate the same electrical energy that an inhabitant consumes throughout the year, in the case of solar thermal energy this definition cannot be applied because it would lead to oversized installations. Although the electrical energy produced by the photovoltaic system does not coincide in time with the profile of electrical consumption (greater production in summer than in winter), the over generation caused at some period can be dumped into the grid, making the definition of self-sufficiency meaningful in terms of environmental balance. However, dimensioning a system that provides the instantaneous demand for the DHW required throughout the year is not feasible due to the disproportionate size of the accumulation tank, making a new definition of self-sufficiency necessary in the case of DHW. The most common, therefore, is to combine the solar installation with a conventional heating system (gas, electric, etc.) so that the solar device solves a part of the energy consumption (solar fraction) and the rest uses the conventional system. According to the Spanish construction national standards (CTE), in his document HE4: Minimum solar contribution of sanitary hot water (Ministerio de Fomento, 2019), a minimum of 70 % of the energy used for DHW should be produced by renewable energy sources. Based on this restriction, in this research, a self-sufficient solar thermal system is defined as the system that can provide 70 % of the energy necessary to ensure the supply of DHW in the residential building.

Therefore, in this investigation the level of self-sufficiency has been defined as the annual the electricity to compensate the energy consumption of one inhabitant: 1503 kWh which is covered by the ESSUM electricity module ($ESSUM_{PV}$) and the energy to cover the 70 % of DHW thermal energy demand: 522 kWh which is produced by the ESSUM solar thermal module ($ESSUM_{ST}$). The selected value for yearly electricity consumption per person is similar to the value used for (Toboso-Chavero et al., 2019) when they developed their roof mosaic approach for residential use in Spain.

2.2. Data collection

The airborne LiDAR point clouds were captured by the National Plan of Aerial Orthophotography (PNOA) on 15/10/2016 and were downloaded in LAS format from the Directorate-General of the National Geographic Institute (IGN) of Spain. The point density was 1 point/m^2. The building data were provided in shapefile format as polygon geometries or footprints with several attributes, such as cadastral reference, gross floor area, year of construction and uses, among other attributes (Dirección General del Catastro, 2016; Mora-García et al., 2015). Moreover, ancillary data were used to classify buildings into 10 morphologies. The methodology and procedure is detailed in an article previously published by the authors (Montealegre et al., 2022).

2.3. GIS data processing

LiDAR data and building footprints were processed using GIS methods (Pieter Gagnon et al., 2016) in order to determine the rooftop physical characteristics (slope, azimuth and shading) and the global annual irradiance, at 1 m^2 spatial resolution.

The developed model (Montealegre et al., 2022) calculates, firstly the available rooftop surface for solar systems installation, secondly, a set of criteria was applied to calculate the solar panels area of photovoltaic modules and thermal solar systems deployment. Below is a summary of the main aspects of the aforementioned methodology.

1) Available rooftop surface. Building data from the Spanish cadastre were collected (number of dwellings and dwellings surface). After grouping the building footprint according to cadastral reference and building attributes, 1 m buffer was applied.
2) Panels area (PV and ST) which depends on the physical characteristics of the rooftop and the solar radiation it receives.

A digital surface model (DSM) in raster format with a 1-meter cell size was created using the first returns of the LiDAR dataset. This DSM was the topographic input used to derive the slope, azimuth, shading and global annual irradiance of the rooftops using ArcGIS (ESRI) software.

The rooftop slope determines the solar panels tilt angle. The optimum tilt angle for a PV panel oriented to the south at Zaragoza city is 37° (European Commission, 2019), then it is the panel tilt angle for flat roofs (≤15°) and equal to the rooftop slope for sloping roofs.

A rooftop has been considered suitable for solar system installation if the energy losses due to the tilt and azimuth are <20 % (Martín Ávila et al., 2016).

Shading analysis has been performed using the Hillshade tool of Spatial Analyst toolbox. The altitude and azimuth of the sun as input data were obtained in an hourly basis from SoDa (Solar Energy Services for Professionals, n.d.). The rooftops suitable for solar panels installation were those not affected by shadows in the central 4 h of the day throughout the year.

Reduction coefficients due to the self-shading and the free space needed for panels installation and maintenance. For sloped roof (>15°) the reduction coefficient applied was 0.95 and for flats roof the value obtained was 0.43 (Montealegre et al., 2022).

2.4. Definition of required energy systems

2.4.1. PV system definition and calculation of the annual electricity production

The annual electricity (E_e obtained in kWh) produced on each rooftop was calculated using the Eq. (1) (Wiginton et al., 2010):

$$E_e = I_G \cdot \eta_{PV} \cdot A_{PV} \cdot PR \tag{1}$$

where

I_G is the global annual irradiance in kWh/m^{2}y

η_{PV} is the PV panel efficiency

A_{PV} is the area of the installed PV panels in m^2

PR is the PV system performance ratio

Global solar irradiance is determined using the solar radiation analysis tools in ArcGIS which allow to map and analyze the effects of the sun over a geographic area for specific time periods based on methods from the hemispherical viewshed algorithm developed by Rich et al. (1994) and Fu and Rich (2002). Variation in slope and orientation, and shadows affecting the amount of insolation received at different locations are considered. The model considers climatic features such as atmospheric transmissivity and the proportion of diffuse radiation but does not include reflected radiation from the ground or other surfaces into its calculations (Mangiante et al., 2020).

Simulations were made using PVGIS web application, which is open access at https://joint-research-centre.ec.europa.eu/pvgis-online-tool_en (European Commission, 2019) to obtain the optimal angle for photovoltaic modules energy production for the city of Zaragoza which is 37°. An increasing coefficient of 1.18 was applied to the flat roofs for the values obtained with GIS as the panel will be placed at 37°.

The system performance ratio (PR) includes the losses in the system, the value obtained from PVGIS was 0.79 and 0.76 for flat and slopped roof respectively.

Nowadays the efficiency of the module varies between 14 % and 18 %, 16 % is a typical value for crystalline silicon modules (Martín Ávila et al., 2016), however the PV module market is enormously dynamic and the module efficiency announced by manufactures is increasing. A recent research (Wang and Barnett, 2019) provides a general and complete view of PV development, concluding that the high efficient PV modules already tested in laboratories could result in significant additional costs. After the analysis of technical specification from manufactures a multi-crystalline silicon module has been selected, the efficiency of the selected module is 17.5 %.

However, the area of PV panels necessary ($ESSUM_{PV}$) will vary depending on the punctual value of global annual irradiance received by each rooftop (calculated with ArcGIS).

2.4.2. DHW system technical requirements

Domestic solar water heating systems (DSWH) include a hot water storage since the consumption is not coupled with the solar irradiation daily profile, then thermal energy gathered by the collector field is stored in an insulated water tank. As solar irradiance could not permanently be enough to increase the water temperature up to 60 °C, an auxiliary boiler completes the plant; in Spain, typically this boiler burns natural gas. The DSWH can be divided into passive and active systems (Shukla et al., 2013). In Southern Europe, the first ones are widespread for single family houses where SDHW is generally supplied by thermosiphon systems which circulate the heat transfer fluid between collector and storage. These systems, robust, efficient and easy to build, consist of a solar collector with a capacity between 0.7 and 2.1 kW_{th} (between 1 and 3 m^2) and a hot water storage unit with a volume of usually 80 to 150 l for a family of four (Stryi-Hipp et al., 2012). Nowadays, there is a wide assortment of SDHW in the market, combining different types of collectors, storage, controllers, and hydraulic equipment. For multifamily houses, active systems and centralized accumulation are a common and an efficient choice (Mazarrón et al., 2016; Shukla et al., 2013), in this research, a centralized accumulation and an individual heat exchangers and conventional support system located at each dwelling has been selected. The system has a double circuit in which the fluid that flows through the collector is different from the one that flows through the storage tank.

For dimensioning a centralized system, the DHW consumption is the most relevant parameter, nevertheless recovering DHW consumption accurate data is a difficult task, the results are systems that often are either under or over dimensioned. The main impediments arise due to the fact that standard buildings are not equipped with meters to provide water flow and temperature, and because the difficulty in estimating highly variable parameters such as occupant's behavior (Evarts and Swan, 2013; O'Hegarty et al., 2014).

The CTE (Ministerio de Fomento (Gobierno de España), 2017) proposes a DHW consumption of a single occupant per day of 28 l (residential) at 60 °C. In addition, it imposes a coefficient that increases this amount depending on the number of rooms in a dwelling and another decreasing factor based on the number of dwellings in a multifamily building, which is based on not using all the systems at the same time (centralization factor which varies from 1 to 0.7).

The average area of a multifamily building in Spain is 86.5 m^2, being 140.2 m^2 for single family houses (Institute for Energy Diversification and Saving - IDAE, 2011). Considering the average occupation per dwelling (2.52 inhabitants), and the DHW daily demand per inhabitant 28 l/inhabitant, the total DHW consumption per building can be obtained. A system predesign has been done for several building sizes, from 2 inhabitants to 2000 inhabitants. The system predimensioning was checked using a free downloaded software CHEQ4 (https://cheq4.idae.es/) developed by the Institute for the Diversification and Saving of Energy (IDAE) and the Solar Association of the Thermal Industry (ASIT) Institute for Energy Diversification and Saving - IDAE and ASIT, 2013). CHEQ4 follows the requirements established in the Spanish standard HE4 "Minimum contribution of renewable energy to cover the demand for sanitary hot water" of the Technical Building Code published in Royal

Decree 732/2019 (Ministry of Development, 2019) and allows for defining a wide variety of solar installations by introducing a minimum number of project parameters, associated with each configuration of the system, and thus, obtaining the solar coverage fraction (SF) that the system provides.

Flat collectors panels have been selected, in general, for the average conditions in Spain and for the production of domestic hot water. Flat collectors are sufficient to provide service in optimal conditions for a contribution of 50 to 80 % (IDAE, 2006). The panel performances of the selected collector are representative of a medium performance collector in the current market; they were obtained from manufacturers of thermal solar systems. The following relationships are proposed to determine the area of the solar collector (A_s) to accomplish self-sustainability for DHW, its value depends on the number of inhabitants in the building. Calculations have been done considering the solar radiation in the city of Zaragoza, the temperature of the tap water (annual average temperature of 13.3 °C) and the optimal solar collector tilt angle of 37°.

$$AS = V_{AC}/0.078 \cdot \quad \text{for } n_{inh} \geq 40 \tag{2}$$

$$AS = V_{AC}/0.070 \cdot \quad \text{for } 20 \leq n_{inh} < 40 \tag{3}$$

$$AS = V_{AC}/0.055 \cdot \quad \text{for } 2 \leq n_{inh} < 20 \tag{4}$$

where V_{AC} is the volume of water (m^3) in the central accumulation system and n_{inh} is the number of inhabitants in the multistorey building, which follows the Eq. (4)

$$V_{AC} = 0.028\ n_{in} \tag{5}$$

Rodríguez-Hidalgo et al. (2012) present a deep study to optimize the thermal storage tank making simulations with the monthly along-the-year calculation. They obtained an overproduction problem with the annual and monthly solar fraction values for V/A = 0.08 m. They found, from the economic point of view, that the optimal value of V/A should be the minimum given in CTE. Furthermore, CO_2 emission savings were also evaluated (natural gas is used as fuel in the DHW backup system) finding that the maximum saving happens for a V/A = 0.08 m, keeping constant for larger values of this parameter. Oversizing the storage tank volume above the value of 0.08 m for V/A, does not mean getting a significantly higher solar fraction (SF) for DHW consumption, neither to achieve better solar plant efficiency.

The proposed solar collector area and the accumulation volume obtained for all the cases guarantee a SF >0.7. The V_{AC}/A_S value should be lower when the number of inhabitants is minor to maintain the SF in acceptable values. The suggested system dimensioning accomplishes the Spanish standards, which establishes a recommended ratio between storage tank volume and collector field area (V_{AC}/A_S) between 0.05 m and 0.18 m, and the monthly SF cannot be higher than 110 % for a single month, neither can be 100 % for three consecutive months, the proposed module solar collector area guaranties that both requirements are accomplished.

The thermal solar module to reach DHW energy demands self-sufficiency ($ESSUM_{ST}$) has been established depending the building inhabitants as follows:

$$A_{S1} = 0.36\ n_{inh}\ \left(m^2\right) \cdot \text{for multistorey buildings where } n_{inh} \geq 40 \tag{6}$$

$$A_{S2} = 0.40\ n_{inh}\ \left(m^2\right) \cdot \text{for medium size buildings where } 20 \leq n_{inh} < 40 \tag{7}$$

$$A_{S3} = 0.51\ n_{inh}\ \left(m^2\right) \cdot \text{for small buildings where } 2 \leq n_{inh} < 20 \tag{8}$$

The thermal energy covered by the selected ST system DHW can be estimated with Eq. (9) obtaining 554 kWh/year per habitant, which covers slightly >70 % of the consumption per inhabitant in Spain.

$$D_{DHW} = V_{DHW} \cdot \rho \cdot Cp \cdot (T_{DHW} - T_C) \tag{9}$$

2.5. ESSUM assessment

The ESSUM assessment is focused in two approaches, the level of self-sufficiency of each building using solar energy, and in the energy and environmental implications of the substitution of current systems by the PV and SDHW systems.

2.5.1. Level of self-sufficiency

Once these data are known, different scenarios could be proposed depending on the case study. Although, a first scenario (scenario 1) has been proposed for all the case studies, that is, to analyze the level of self-sufficiency by energy system separately for each building. In this regard, the potential of each building based on this morphology, physical characteristics and location can be analyzed by each energy system. Based on these results, consequent scenarios with a combination of both energy systems can be proposed.

In this case study, due to the high self-sufficiency of DHW in the most of buildings, >100 %, the following scenario is proposed (scenario 2): 100 % self-sufficiency for DHW in each building, dedicating the remainder area for PV installation.

2.5.2. ESSUM environmental assessment by LCA methodology

On the basis of the self-sufficiency scenarios outlined above, the environmental implications derived from the implementation of the proposed energy systems have been calculated by means of the Life Cycle Assessment (LCA) methodology (International Organization for Standardization, 2006a). The life cycle impact assessment methods (LCIA) (International Organization for Standardization, 2006b) selected for this study are the IPCC 2013 GWP 100y (Intergovernmental Panel on Climate Change, 2014) to calculate the global warming potential (GWP) throughout a horizon of 100 years and the Cumulative Energy Demand (CED) which characterizes the direct and indirect energy use throughout the life cycle of a good, service or product (Huijbregts et al., 2010), providing primary energy from renewable and non-renewable sources separately. Thus, on the one hand, the GHG emissions avoided annual due to the installation of the self-sufficiency modules have been calculated and, on the other, the annual energy savings in terms of CED.

SimaPro V 9.0.0.35 (PRe Consultants, 2019) and the Ecoinvent v 3.6 database (Swiss Centre for Life Cycle Inventories, 2019) were used in this study to perform a complete LCA for each proposed solar systems.

Firstly, the annual environmental implications caused by the construction, installation and end-of-life of the $ESSUM_{PV}$ and $ESSUM_{ST}$ have been calculated (cradle to grave) and then compared with the environmental impact caused by the operation of the current systems. The avoided environmental impacts are calculated, and the implications are extended to the district under study, finally, the results are presented for evaluation at city scale (Table 1).

2.5.2.1. LCA for $ESSUM_{PV}$. The environmental impact of photovoltaic panels (PVs) is an extensively studied topic, generally assessed using the Life Cycle Analysis (LCA) methodology. To construct a robust and rigorous Life Cycle Inventory (LCI) is essential for LCA studies, and the availability of such data is frequently the greatest obstacle to conduct an LCA. There are numerous LCA studies over the last decades (Wong et al., 2016), however, the PV modules technologies, manufacturing processes have constantly been improved. Consequently, much of the PV LCA literature becomes outdated very rapidly.

Difficulties to select proper environmental values are then evident, in one hand due to the differences between the LCA scope, lifetime, functional

Table 1
LCA methodology.

Current situation (operation)	ESSUM deployment
Each person consumes 1503 kWh/y of electricity Electric energy production mix. for Spanish market 2020 (Red Eléctrica de España, 2021) 23.0 % nuclear, 22.2 % eolic 15.8 % combined cycle, 11.1 % cogeneration, 12.6 % hydraulic, 2 % coal, 6.1 % solar photovoltaic, 1.9 % solar thermal, 1.8 % others renewable, 3.5 % others.	$ESSUM_{PV}$: LCI for PV system. Calculation of PV area per person, depending on the rooftop characteristics (GIS) Lifetime for PV system 30 years Includes construction, installation, dismantling and disposal
Each person consumes 554 kWh/y for DHW production (slightly higher than 70 %) Operation mix of technologies for Spanish market (IDAE and Ministerio de Industria Energía y Turismo, 2012): 21.5 % electricity 40.3 % natural gas 25.9 % LGP 10.1 % gasoil 1.7 % renewable 0.1 % coal 0.4 % others	$ESSUM_{ST}$: LCI for ST system. ST collector area per person depending on the building type Lifetime for DHW system 30 years Includes construction, installation, dismantling and disposal

unit, etc. in the related literature and on the other hand due to the fast advancement of the technology. A PV system includes, besides PV modules, the balance of system components (BOS) which includes the structures for mounting the PV modules, inverters, electric installation and all the complementary equipment for PV system proper operation.

(Gerbinet et al., 2014) identify some gaps on the published studies, underlining among others, that few of them consider the end of life (EOL) and BOS are not always included. More recently, Stamford and Azapagic (2018), were also reporting that remain several important inadequacies in the existing literature and lack of transparency of the results.

Currently the Ecoinvent database is possibly one of the most complete and reliable (Ecoinvent, 2019). SimaPro provides complete processes for the manufacture of both photovoltaic and solar thermal systems. The LCI data for PV compiled into Ecoinvent database is based on the data presented by Jungbluth et al. (2012), which was investigated with 11 European and US photovoltaic companies for the reference year 2005 and it was implemented in the Ecoinvent database.

More updated data was compiled by The International Energy Agency (IEA) that published a report in 2015 (Frischknecht et al., 2015) containing a complete inventory for mono- and multi-crystalline silicon solar cells, PV modules production, partial data for the BOS, and the environmental impacts from these technologies. The LCI datasets presented in the report are describing the status in 2015 for crystalline Si.

The most recent publication found by the authors that presents a very complete and detailed LCI is the one developed by Stamford and Azapagic (2018). In their article, they estimate the environmental impacts of a PV system installed in Spain, the results of which vary between 47 and 52 gCO_{2eq}/KWh if the estimate is made with the 2005 Ecoinvent data or between 25 and 29 gCO_{2eq}/KWh if it is done with the 2015 data (ITRPV, 2015). The lowest value corresponds to mono-crystalline Si and the highest to multi-crystalline Si. In addition, they estimate a decrease in the impacts associated with the PV system between 8 and 34 % between 2015 and 2025, depending on the category.

With these precedents, Ecoinvent 3.6 (Ecoinvent, 2019) database has been used to estimate the impact assessment of the PV system (de Wild-Scholten et al., 2006; Jungbluth et al., 2012), the LCI data corresponds to 2005 PV market and then with the LCI proposed by Stamford and Azapagic (2018) as representative of the technological state in 2015 in order to validate the process. Finally, the LCI values have been modified with the forecasts of technological evolution of the PV systems according to the roadmap presented by ITRPV in 2021 (ITRPV, 2021).

This study follows a cradle-to-grave approach, including the production of energy systems, their transportation to the building site (330 km were assumed), their installation and finally their dismantling and disposal. For maintenance, the water to clean the PV modules is also included. In respect to the end of life, waste management scenarios (recycling, landfilling and incinerating) have been defined for raw materials, despite the lack of data on future recycling of PV systems. Steel, aluminum and copper are 100 % recycled, according to the Spanish recycling rates published by the Spanish Statistics National Institute ("INE, Instituto Nacional de estadística.," 2018). For the treatment of polyethylene, glass waste and plastic the existing process for the case of Spain in Ecoinvent 3.6 (Ecoinvent, 2019) has been used and modified accordingly, 80 % landfilling and 20 % incinerating. Electronic materials are 81.8 % recycled and the rest incinerated. Transport distances of the materials to a disposal or recycling facility were assumed to be 100 km.

The lifetime for PV system was considered 30 years except for the inverter which has a shorter useful life and was estimated to be 15 years.

As the current market share is about 95 % for the c-Si and about 5 % for thin-film technologies. ITRPV (2021), the multi-crystalline silicon cells have been selected to perform the LCA.

The additional technology improvements included for environmental impacts calculation of the PV system in 2020 modifying the LCI proposed by (Stamford and Azapagic, 2018) the following:

- The average utilization of poly-Si to produce silicon wafers was reduced to 12 g/m^2.
- Metallization pastes containing silver (Ag) and aluminum (Al) are the most process-critical in current c-Si cell technologies. Paste consumption has been reduced to 50 mg Ag per cell.
- The most massive non-cell material of a module is the front side glass. The thickness in front side glass has been reduced to 2.5 mm.

2.5.2.2. LCA for $ESSUM_{ST}$. Two Ecoinvent (Swiss Center for Life Cycle Inventories, 2018) process have been used for ST system calculations: 'solar collector system installation, Cu flat plate collector, multiple dwelling, hot water' for multifamily buildings' and 'solar collector system installation, Cu flat plate collector, one-family house, combined system' for single family houses. The data source was developed by Jungbluth (2007) in the year 2007. These processes have been adapted to the specificities of the current project, such as the electrical energy used (Spanish mix for electrical energy), transportation and the end-of-life (same values as for PV system). Moreover, the water storage tank volumes have been modified according to Eqs. (2), (3) and (4). Transport distances for equipment, were assumed 330 km, which represents the road distance between Barcelona port and Zaragoza. The lifetime for ST system was considered 30 years.

2.6. Limitations and assumptions

The electricity demand by building depends on the number of inhabitants, in this research an average of 2.51 inhabitants per dwelling have been considered. The same applies to the thermal energy required for the production of domestic hot water.

The values obtained for ESSUMPV module depends on the PV system efficiency. The value selected as representative at present is 17.5 %; however, this value is considered conservative since the evolution of photovoltaic technology has been and is expected to be significant in the coming years. The same applies to the performance of solar panels for hot water production, the performance of which is considered to be representative of current technology, although it is expected to improve in the future years.

An additional aspect to be solved is the structural verifications to confirm that the building meets the compulsory conditions to support the installation. In this research it has been supposed than the accumulation water tank will be placed in common areas (garages, machine room…) as it is not possible to verify the mechanical resistance of the rooftop with the available data.

Regarding LCA assessment, the lifetime for equipment was considered 30 years except for the inverter which was estimated to be 15 years.

Transport distances of all equipment to the installation site have been assumed to be 330 km and the distance of all materials to the landfill, incinerator or recycling plant to be 100 km.

3. Results and discussion

3.1. Physical characterization

The case study includes 1456 plots in an area of 8.38 km^2, where residential and industrial buildings coexist, as well as a great residential heterogeneity. In the neighborhood, single-family morphologies are mixed with other slab, originary and extension morphologies. This classification has been carried out manually, based both on the official municipal urban planning classification and on the observation of the fabric in situ (Fig. 3). Table 2 shows the relative weight of each urban morphology by number of dwellings, gross floor area and roof surface.

Table 2
Summary of the physical characterization of the case study in the neighborhood of El Rabal, Zaragoza (Spain).

Urban morphology	Number of plots	Number of dwellings	Gross floor area (m^2)	Roof area (m^2)
Single family	354	1953	163,541	29,254.04
Slab aligned	157	9481	1,415,185	95,006.07
Slab independent	119	8855	1,245,499	86,640.96
Slab not aligned	125	4061	342,498	37,980.35
Extension suburban	171	4577	479,165	42,032.15
Originary suburban	399	5720	624,702	73,211.65
Originary historic	103	955	95,976	9748.88
Industrial	17	41	26,656	16,980.16
Others	11	593	60,582	7876.72
Total	1456	36,236	4,453,804	398,730.98

3.2. ESSUM assessment: Calculation of % self-sufficiency

For the sizing of the energy production systems, it has been assumed that all dwellings are occupied. Based on the proposed scenarios, knowing the available roof area and the energy produced by PV and ST systems, data has been cleaned by identifying possible outliers in its distribution. The interquartile method was used, eliminating those data greater or <1.5 times the interquartile range. The results by scenario are the followings:

Scenario 1: In the case where the entire available rooftop area is used for the installation of PV systems, an average of 24 % of self-sufficiency is obtained (standard deviation of 17.7). The urban building by building distribution is represented in Fig. 4.

In the case where the entire available rooftop area is used for the installation of ST systems, an average of 497.8 % of self-sufficiency is obtained (standard deviation of 342.3). Fig. 5 shows the urban building-by-building distribution. Therefore, a high degree of self-sufficiency for DHW production can be achieved by installing ST systems on the unused areas of the case study rooftops.

Scenario 2, the available area is used to install ST systems until self-sufficiency is achieved. The remaining area (if there is still available surface) is completed with the installation of PV systems. Fig. 6 shows the results by urban distribution, giving a PV self-sufficiency of 19.7 % with a standard deviation of 17.4. In this case, included data should accomplish an interquartile method for both Scenario 1 and 2, then the number of data is smaller than in Fig. 4. The results show that by prioritizing the installation of ST systems, the decrease in PV self-sufficiency is small. Therefore, it could be the most appropriate strategy to maximize the self-sufficiency of all buildings in both PV and ST.

3.3. Environmental assessment

3.3.1. LCA for $ESSUM_{PV}$

The results are presented according to IEA (Frischknecht et al., 2016) for a functional unit (FU) of 1 kWh of electrical energy produced. Firstly, to obtain the values per kWh produced, the values are calculated for 1 m^2 of collector surface. The evolution of the technology in terms of the efficiency of the cells has also been considered; their efficiency varies from 14 % for 2005 to 17.5 % for 2020 (conservative value). The values obtained for $ESSUM_{PV}$ module, depending on the technological evolution of the PV systems, are presented in Table 3.

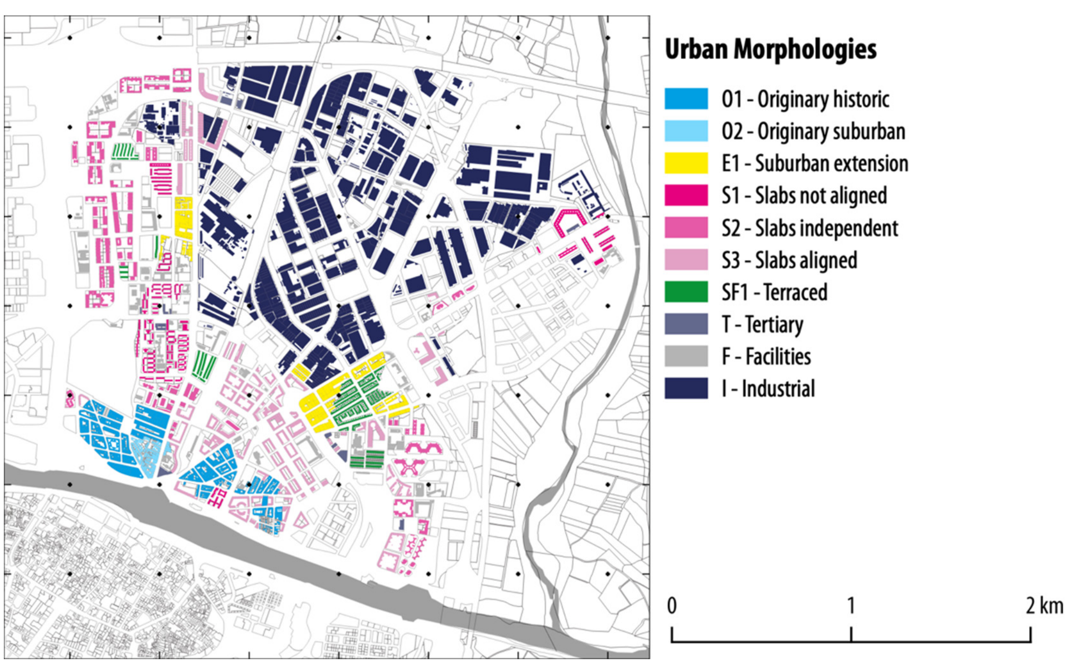
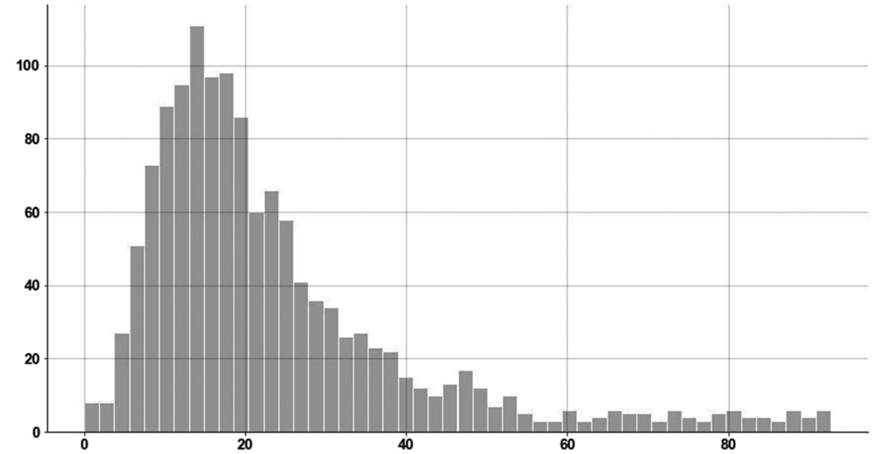


Fig. 3. Urban morphologies.



count	average	Standard deviation	min	Q1	Q2	Q3	Q4 (max)
1326	24.0	17.7	0.0	12.6	18.8	29.0	92.7

Fig. 4. PV self-sufficiency for scenario 1. (Histogram until 100).

Table 3 presents the values for an average global irradiance and an average area obtained with PVGIS (European Commission, 2019). However, the results presented in Section 3.3 are obtained for each rooftop solar irradiance received (GIS).

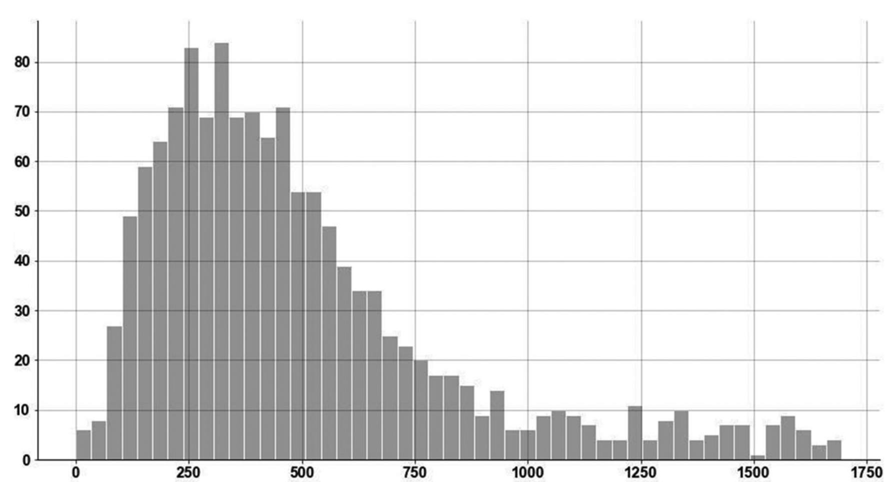
The Energy Payback Time (EPBT) of PV systems has been calculated according to Frischknecht et al. (2016) considering the evolution of the Spanish electricity mix. The conversion factors to the primary energy used are: 2.61 (2005), 2.37 (2015) and 2.24 (2020). The EPBT obtained is slightly higher than the proposed by Fraunhofer for southern Europe, its current estimation is around 1 for Southern Europe. (Fraunhofer Institute for Solar Energy Systems, 2020).

The Spanish electricity mix for the year 2020 has been used in SimaPro for the calculation of GHG emissions and the associated CED derived from the annual electricity consumption of one person. The values obtained are 0.169 $KgCO_{2eq}$/KWh and 2.24 MJ of primary energy/MJ of final energy.

3.3.2. LCA for $ESSUM_{ST}$

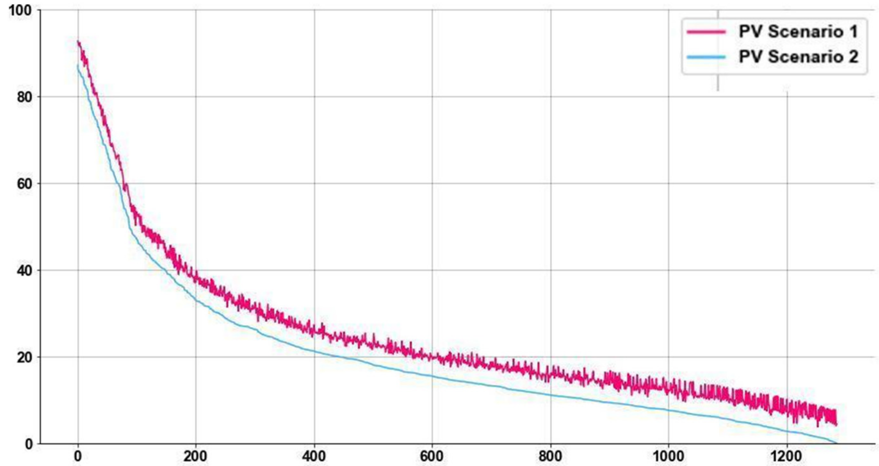
The values obtained for $ESSUM_{ST}$ module for the three scenarios and 1 kWh of energy produced are presented in Table 4.

The environmental impact assessment of ST systems is not as widely studied as that of PV systems, which are generally assessed using Life Cycle Assessment (LCA) methodology. Therefore, there are not as many publications comparing environmental performance with the technical progress of the technology. Ardente et al. (2005) published previously a detailed LCI for a solar thermal collector, including support and water tank for a family house installation in Italy. They obtained 4778 MJ/m^2 for embodied energy, which is 17.3 % higher than the value obtained in this research (3950 MJ/m^2), that corresponds to 302.33 $kgCO_{2eq}/m^2$, which is 14.6 % lower that the presented result (258 kg CO_2 eq/m^2). Gagliano et al. (2019) in a recent publication presented a LCI redrafted from Lamnatou et al. (2015) obtaining 189.35 kg CO_2 eq/m^2 for a flat plate collector system installed in Italy.



count	average	Standard deviation	min	Q1	Q2	Q3	Q4 (max)
1338	497.8	342.3	0.0	258.5	411.7	621.6	1693.5

Fig. 5. ST self-sufficiency for scenario 1 (Histogram until 2000).



	count	average	Standard deviation	min	Q1	Q2	Q3	Q4 (max)
PV SC1	1286	24.7	17.6	3.8	13.2	19.2	29.7	92.7
PV SC2	1286	19.7	17.4	0.1	8.2	14.4	24.7	87.1

Fig. 6. PV self-sufficiency for scenarios 1 and 2.

Table 3
$ESSUM_{PV}$ module environmental results.

	Ecoinvent data (2005)	Stamford et al. (2015)	ITRPV (2020)
kg CO_{2eq}/m^2y	9.73	5.63	**5.03**
kg CO_{2eq}/y	64.24[a]	34.70[a]	26.57[a]
g CO_{2eq}/KWh y	42.74[a]	23.09[a]	17.68[a]
CED (MJ/m^2y)	164.33	109.00	97.67
CED (MJ/y)	1084.60[a]	671.44[a]	515.68[a]
EPBT (years)	2.30[a]	1.57[a]	1.28[a]

[a] Calculated for average area of PV panel (6.60, 6.16 and 5.18 m^2, respectively).

The environmental impact caused by the annual energy consumption by person for DHW was calculated taking into account the operation mix for DHW technologies in Spain (IDAE and Ministerio de Industria Energía y Turismo, 2012), the conversion factor to final energy depending on the thermal installations (CENER, 2014) and the energy transition factors in Spain (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2014). Table 5 shows the conversion factors for final energy consumption (kWh) to emissions (in kg of CO_2) from the different sources and the conversion factors from final energy to primary energy.

3.3.3. Urban district environmental assessment

The results are presented depending on the urban morphologies to identify the influence of different physical aspects of buildings: height, number of dwellings per building and number of inhabitants. As in the previous section, the data have been cleaned according to the interquartile method, removing those that are excessively high or low in terms of ST or PV self-sufficiency results in both scenarios.

Table 4
$ESSUM_{ST}$ module environmental results.

Ecoinvent data (2007)	High multistorey building $n_{inh} \geq 40$	Medium size multistorey building $20 \leq n_{inh} < 40$	Family houses and small buildings $2 \leq n_{inh} < 20$
kg CO_{2eq}/m^2y	6.83	6.73	8.60
kg CO_{2eq}/y	2.46	2.69	4.39
g CO_{2eq}/KWh y	4.44	4.86	7.92
CED (MJ/m^2y)	106.66	105.00	131.66
CED (MJ/y)	38.4	42.00	67.15
EPBT (years)	0.45	0.49	0.79

Fig. 7 shows the Kg CO_2 -eq emitted for scenario 1 (the entire available area on each roof is installed with either PV or ST system) and Fig. 8 shows the emissions for scenario 2. The results are presented for the equipment (manufacturing, transportation, and end of life) which are considered as impact generated and during the use phase results are considered as impacts avoided.

For scenario1, the emissions caused by manufacturing, transportation, and end-of-life of the equipment due to the installation of PV panels for residential buildings are 27.8 % lower than those of ST panels, due to the fact that emissions per m^2 are lower for PV systems. The manufacturing phase account for 16.8 % of avoided emissions for PV system, while for ST this percentage drops to 2.3 %.

Nevertheless, the emissions avoided during the use phase more than compensate for those generated by the installation of the systems. The emissions avoided by the installation of ST systems are very significant, mainly due to the high emissions of the currently used technology mix, especially the use of NG for DHW production. The final balance indicates the implementation of ST instead of PV systems could reduce the annual CO_2 -eq emissions by almost 40,000 t.

In scenario 2 (Fig. 8), for the average for all urban morphologies, 21 % of the available rooftop area is occupied by ST systems achieving energy self-sufficiency for DHW production and the rest of the area is used for electric power generation with the installation of PV systems. The annual emissions are reduced by 12,695.4 tCO_2 -eq, which is 3.38 times lower than scenario 1 in case of only ST systems were installed.

Fig. 9 shows the CED for scenario 1 (the entire available area on each roof is installed with either PV or ST system).

Table 5
Conversion factors.

	DHW	GHG	CED renewable	CED non renewable	CED total
	% Energy consumption	$kgCO_2$/KWh	kWh R/kWh	kWh NR/kWh	kWh/kWh
Electricity[a]	21.5 %	0.169	0.473	1.767	2.24
GN	40.3 %	0.252	0.005	1.19	1.195
GLPG	25.9 %	0.254	0.003	1.201	1.204
Gasoil	10.1 %	0.311	0.003	1.179	1.182
Ren	1.7 %	0	0	0	0
Coal	0.1 %	0.472	0.002	1.082	1.084

[a] Electricity values calculated for mix 2020. Values from IDAE.

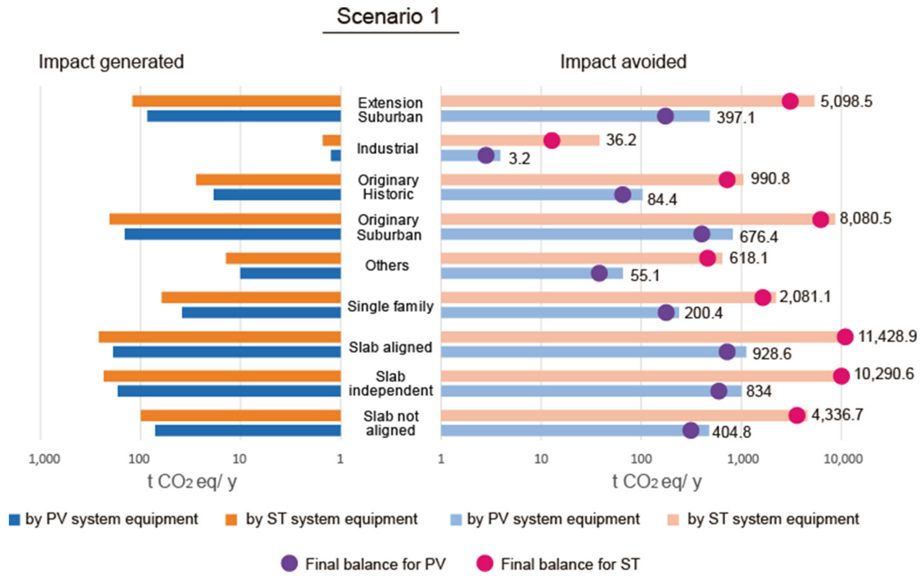


Fig. 7. Results for Scenario 1, annual GHG emissions (log scale).

For scenario1, the CED due to the manufacture, transport, and end of life of the PV equipment is 10.0 % lower than those of ST panels, because CED per m^2 are lower for PV systems, resulting in a reduction on energy demand of 1570.2 GJ/y.

However, for the use phase, it is much more interesting in environmental terms, the installation of ST systems, mainly due to the high nonrenewable energy demand of the currently used technology mix, especially the use of NG for DHW production. The final balance indicates that the implementation of ST systems could reduce the CED by 973,568.6 GJ/y which is 5 times the reductions that would be achieved when installing PV systems.

In scenario 2 (Fig. 10), the energy needed for the manufacture, transport, and end of life of the ST equipment are 3 times more than those of PV panels. The annual CED is reduced by 372,468.5 GJ/y, which is 2.6 times lower than scenario 1 in case only ST systems were installed.

Table 6 shows the GHG emissions per dwelling and disaggregated by urban morphology for scenario 2. It was considered interesting to compare the data on a relative basis (per dwelling) in order to discuss the avoided impacts according to the existing urban forms in the case study.

For ST systems, the results obtained are very similar since the sizing of the system depends on the number of dwellings and their average occupancy. However, for PV systems, the results strongly depend on the morphology, and for the case of industrial morphology the behavior is very different, due to its high production capacity (large available areas) and its low level of residential occupancy. For the residential morphologies, the balance obtained for ST system, is very similar among all urban morphologies per dwelling unit, being between 2.6 and 4.3 times greater than the impact avoided by the installation of PV systems. The residential morphologies with the highest environmental benefits are single-family houses, with the suburban extension having the lowest benefits.

The differences by dwelling unit, showed in Table 6, do not seem to indicate that it is convenient to prioritize some urban forms over others in the implementation of ESSUM. Despite this relative homogeneity, Fig. 11 shows the slight variations by urban form. In contrast to the more homogeneous slab morphologies, single-family housing forms tend to be more dispersed.

Table 7 shows the CED per dwelling disaggregated by urban morphology for scenario 2. CED results are in line with those obtained for GHG

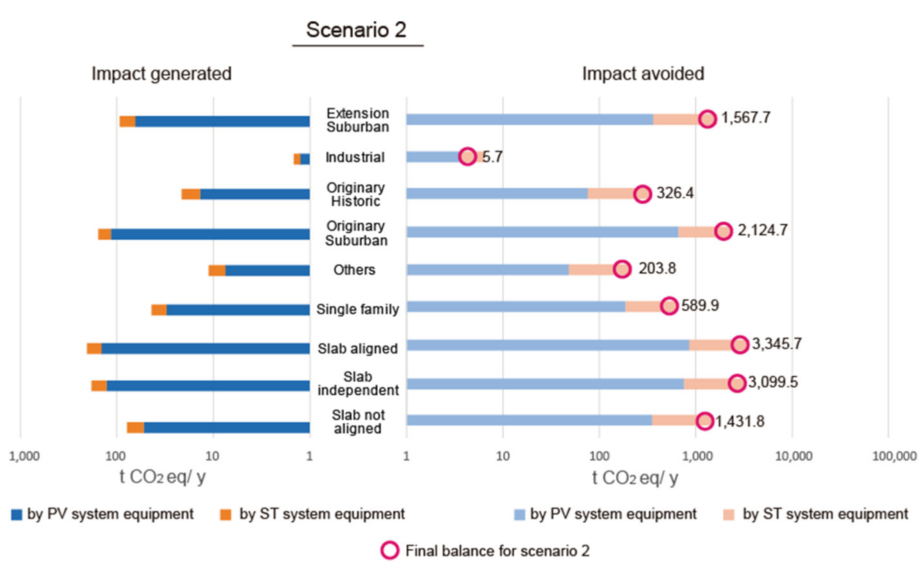


Fig. 8. Results for Scenario 2, annual GHG emissions (log scale).

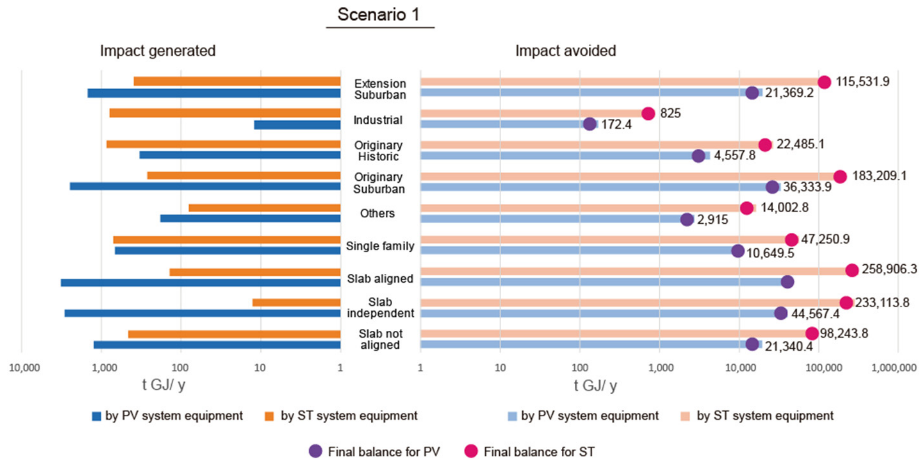


Fig. 9. Results for Scenario 1, annual CED (GJ/y) (log scale).

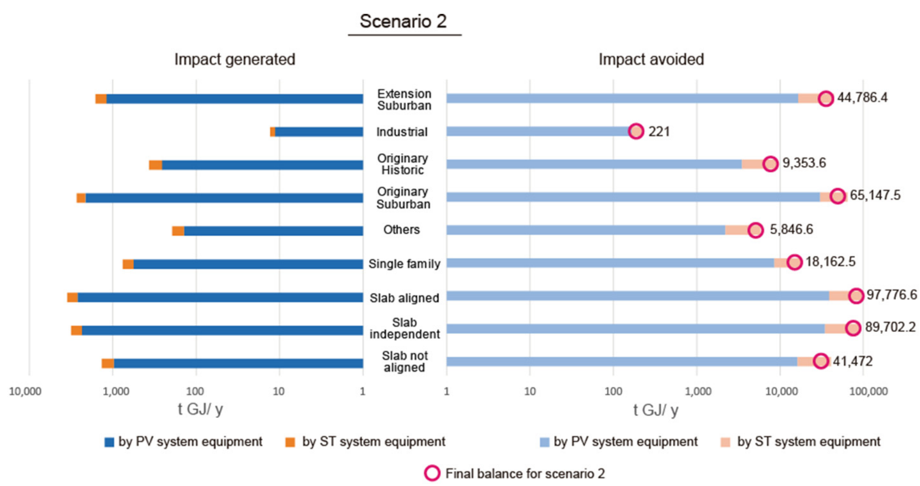


Fig. 10. Results for Scenario 2, annual CED (GJ/y) (log scale).

emissions. The balance obtained for ST system is very similar among all urban morphologies and is remarkable the unusual behavior of industrial forms. The residential morphologies with the highest avoided CED are single-family houses, with the suburban extension having the lowest avoided CED. Fig. 12 shows the diversity of distributions according to urban forms, the most homogeneous being the slap morphologies and the most dispersed the single-family ones.

Finally, the building-to-building approach has made it possible to disaggregate the results according to urban morphologies, which offers a new manner of characterizing the renewable energy resources available in cities. In addition, the results grouped by urban morphologies can be spatially represented on maps since all the information is geo-referenced. No published work has been found that analyzes the self-sufficiency potential of cities with results disaggregated by type of urban morphology.

Table 6
Annual GHG emissions by dwelling for Scenario 2 disaggregated by urban morphology.

Urban morphology	PV			ST		
	PV system equipment/ number dwellings [t $CO2_{eq}$/y dw]	Phase use (avoided) / number dwellings [t $CO2_{eq}$/y dw]	Balance/number dwellings [t $CO2_{eq}$/y dw]	ST system equipment/ number dwellings [t $CO2_{eq}$/y dw]	Phase use (avoided) /number dwellings [t $CO2_{eq}$/y dw]	Balance/number dwellings [t $CO2_{eq}$/y dw]
Extension suburban	14.16	−79.34	−65.19	6.35	−284.80	−278.45
Industrial	74.03	−445.71	−371.67	11.05	−284.80	−273.75
Originary Historic	15.23	−84.08	−68.86	7.83	−284.80	−276.97
Originary Suburban	20.45	−116.81	−96.36	6.88	−284.80	−277.92
Others	12.75	−82.02	−69.27	6.21	−284.80	−278.59
Single family	20.46	−125.40	−104.94	8.45	−284.80	−276.35
Slab aligned	15.58	−92.47	−76.89	6.21	−284.80	−278.59
Slab independent	14.48	−85.95	−71.47	6.20	−284.80	−278.60
Slab not aligned	13.03	−87.25	−74.22	6.25	−284.80	−278.55

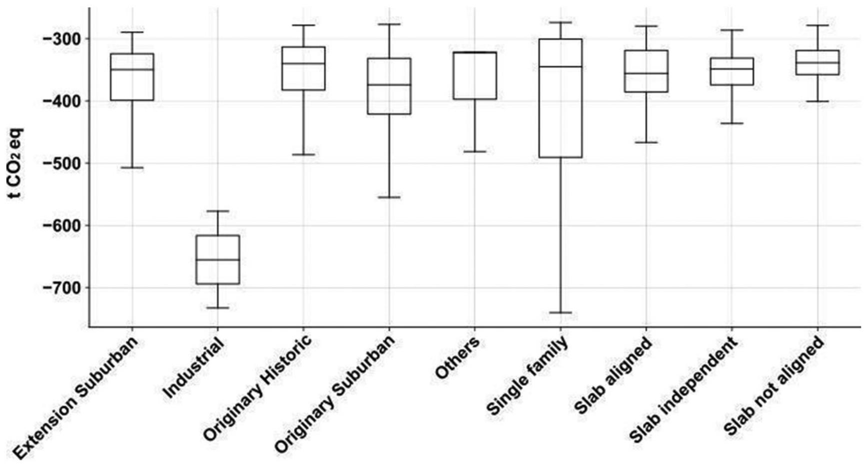


Fig. 11. Balance GHG emissions by dwelling for Scenario 2 disaggregated by urban morphology.

Table 7
Annual CED by dwelling for Scenario 2 disaggregated by urban morphology.

	PV			ST		
Urban morphology	PV system equipment/number dwellings [GJ/y·dw]	Phase use (avoided) /number dwellings [GJ/y·dw]	Balance/number dwellings [GJ/y·dw]	ST system equipment/number dwellings [GJ/y·dw]	Phase use (avoided) /number dwellings [GJ/y·dw]	Balance/number dwellings [GJ/y·dw]
Extension Suburban	0.27	−3.79	−3.51	0.10	−6.41	−6.31
Industrial	1.44	−21.27	−19.83	0.17	−6.41	−6.24
Originary Historic	0.30	−4.01	−3.72	0.12	−6.41	−6.29
Originary Suburban	0.40	−5.57	−5.18	0.11	−6.41	−6.30
Others	0.25	−3.91	−3.67	0.10	−6.41	−6.31
Single family	0.40	−5.98	−5.59	0.13	−6.41	−6.28
Slab aligned	0.30	−4.41	−4.11	0.10	−6.41	−6.31
Slab independent	0.28	−4.10	−3.82	0.10	−6.41	−6.31
Slab not aligned	0.25	−4.16	−3.91	0.10	−6.41	−6.31

4. Conclusions

A new Energy Self-Sufficiency Urban Module (ESSUM concept) is defined which determines the level of energy self-sufficiency of cities for electricity domestic consumption and DHW energy needs. In the case of study, an urban district in the city of Zaragoza (Spain), those values are 1503 kWh and 522 kWh respectively.

The urban district has been characterized by urban morphologies, and the number of dwellings and the occupancy building by building have been calculated.

Two scenarios have been defined to evaluate the level of self-sufficiency. For scenario 1, in which the entire available rooftop area is used for the installation of PV systems, an average of 24.7 % of self-sufficiency is obtained (electricity consumption). While if the entire

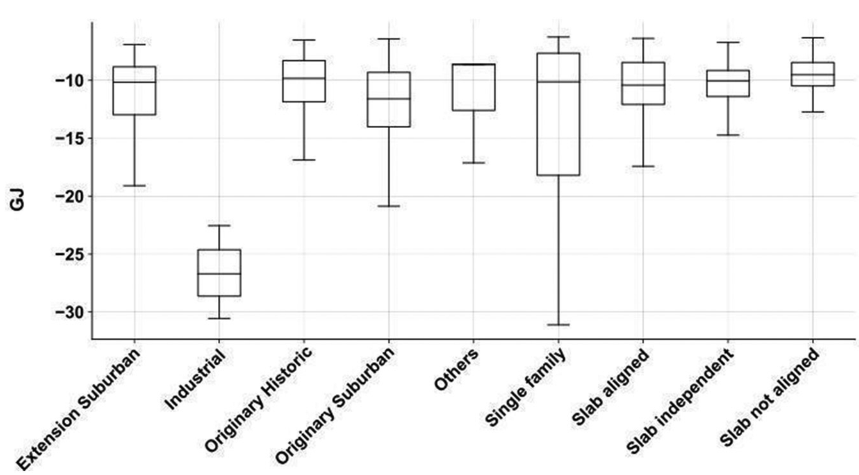


Fig. 12. Balance CED by dwelling for Scenario 2 disaggregated by urban morphology.

available surface area is used to install the ST system, an average of 497.8 % of self-sufficiency is achieved (DHW energy consumption). For scenario 2, self-sufficiency is achieved on 100 % of the district's rooftops in the production of DHW ($ESSUM_{ST}$), regardless of urban morphologies, with 21 % of the available rooftop area . In addition, if the rooftop area that is still available is dedicated to the installation of PV systems, 19.7 % of self-sufficiency in electricity consumption can be reached.

The environmental assessment for $ESSUM_{PV}$ (PV system for electricity production) and $ESSUM_{ST}$ (ST system for DHW production) has been evaluated depending on the technological evolution. The selected methods have been IPCC GWP 100y to calculate the GWP and the CED method. In the manufacturing, transport, and end of life phase, the $ESSUM_{PV}$ generates >26 $kgCO_{2eq}$/y and consumes >515 MJ/y, meanwhile the $ESSUM_{ST}$ provokes between 2.49 $kgCO_{2eq}$/y and 4.39 $kgCO_{2eq}$/y and consumes between 38.4 MJ/y and 67.15 MJ/y (depending on building size).

The implementation of scenario 2, would imply a reduction in CO_2 emissions of 12,695.4 t CO_{2eq}/y and energy savings of 372,468.5 GJ/y. The 790 t CO_{2eq}/y generated by the installation, transport, and end of life of the equipment are clearly offset by the 13,485.3 t CO_{2eq}/y avoided due to the use phase. In the case of the CED, the values amount to 14,453.5 GJ/y consumed by the equipment compared to the 386,922 GJ/y avoided in the use phase.

The results show that the most appropriate strategy from an environmental point of view could be to favor the installation of ST systems until self-sufficiency is achieved and to dedicate the rest of the available roof area to the installation of PV systems since the decrease in self-sufficiency in electricity consumption is very small (5 %).

For the urban district analyzed, the environmental results due to the implementation of ESSUM do not recommend prioritizing of some urban forms over others. However, there seems to be a greater diversity of environmental implications on the single-family fabrics. In any case, environmental implications should not be the only ones considered for prioritization during the design of public policies.

In this regard, based on the methodology and approach proposed in ESSUM, several possibilities open up for future research in how the energy generated in urban areas is consumed. On the one hand, aspects related to the energy efficiency of the building, the type of heating or cooling systems used and even the consumption pattern of the residents and the responsible use of energy could be incorporated. On the other hand, beyond the building, other challenges that the city will face in its energy transition could be addressed, such as the emergence and extensive use of electric mobility and the need for local and renewable energy generation. In the exploration of all these scenarios, in addition to considering the environmental implications, other relevant valuation aspects should be incorporated, such as costs or public acceptance.

Based on the results, the installation of PV on all roofs is able to cover an important part of the electrical energy needs, however, it does not even come close to the possibility of covering the self-sufficiency of the residential sector. Therefore, there is a need to improve the efficiency of PV panels or to develop new technologies based on renewable sources.

Finally, one of the lines identified is the scalability of the method. To this end, it would be necessary to work on a programming code that would allow us to reproduce this work in other areas, sharing the process through coding notebooks or other similar products.

CRediT authorship contribution statement

S. Guillén-Lambea: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **J. Sierra-Pérez:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **S. García-Pérez:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **A.L. Montealegre:** Methodology, Investigation, Data curation, Writing – review & editing. **M. Monzón-Chavarrías:** Methodology, Investigation, Data curation, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jorge Sierra-Perez reports financial support was provided by University of Zaragoza. Jorge Sierra Perez reports a relationship with University of Zaragoza that includes: employment.

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