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Renovation assessment of building districts: Case studies and implications to the positive energy districts definition

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A R T I C L E I N F O

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A B S T R A C T

As the built environment is among the main contributing sectors to climate change, it is needed to investigate new paradigms to push decarbonization efforts towards the ambitious objectives defined internationally. It is a shared understanding that shifting the perspective from the single building to the district perspective is required to fully take into consideration the complexity of all interactions undergoing within the built environment, thus the concept of Positive Energy District emerged as a district with annual net zero energy import and net zero CO_2 emission working towards an annual local surplus production of renewable energy. In this framework, this paper explores the investigation of the potential for achieving the level of Positive Energy District in a group of non-residential buildings in Balaguer, Catalonia, Spain. These buildings, occupying 8,825 m^2 in the city centre, require significant refurbishment for improved energy performance. The analysis includes building energy modelling and simulation, renovation studies, several alternative balance calculations, and carbon emissions assessment. The paper also considers mobility and embodied energy and their impact on energy/carbon balances. The results show that Positive Energy Districts carbon and primary energy balances are not met with rooftop PV installations when retrofitting an existing district towards the Positive energy target but further significant PV areas (roughly + 50%) are required to meet merely the use stage balances: negative results are traced when mobility and embodied energy are computed. A formulation alternative to the simple mathematical balance to facilitate the diffusion of Positive Energy District as catalyst of urban decarbonisation could be needed, including context factors and alternative systems (e.g., rating systems).

1. Introduction

The building sector is one of the main contributors to the overall energy use and carbon impacts of anthropogenic origin at a global scale. In this perspective all the activities, boundaries, policy limits and guidelines for increasing energy efficiency and reducing carbon emissions that have been developed both at a global and continental scale can be read as efforts towards the limitation of the effects of climate change. In this domain, the current trend is pointing with increasingly higher frequency towards more devastating extreme events as well as an average significant worsening in most of global warming related climate variables.From this perspective, the focus in the building sector is generally being extended from the single building scale [12] with specific interest on building energy efficiency to a more general interest from research and policy agencies to the level of neighbourhoods [16,25], group of buildings [3] and cities [15,26,44].This is the case, at different levels, of the 100-climate neutral and smart cities program from the EU, the European Bauhaus initiative and the specific focus of legislation implementing the concept of energy communities (ur [40] This shift in perspective is needed to encompass the whole building energy infrastructure towards a generalized decarbonization effort, including the complex aspects of building interactions, energy flexibility, grid interaction and load matching [37]. Moreover, the urban scale allows to focus other crucial aspects: the urban planning [35], the involvement of stakeholders [14] throughout the whole life cycle of the neighbourhood from the design stage, social and environmental considerations thus ultimately aiming at a truly interdisciplinary and holistic design and management of a neighbourhood.

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Positive Energy Districts (PEDs) [6] embody all these aspects, aiming at raising the quality of life in European cities, contributing to the COP21 targets, and at enhancing European capacities and knowledge to become a global role model [39] As defined within the SETPLAN, PEDs are defined as a "district with annual net zero energy import and net zero CO_2 emission working towards an annual local surplus production of renewable energy."PEDs are seen as lighthouse areas which could help driving the transition towards a low carbon future in the urban areas, aiming at partially covering the energy requirements of the nearby areas at pushing towards the development of truly climate neutral cities [13]. This is to be achieved through renewable energy systems embedded in urban and regional energy systems, high energy efficiency levels throughout the energy systems and grid, energy flexibility solutions (e.g., peak shaving, load shifting, energy storage [10], demand response and reduced curtailment and district level self-consumption of renewable energy systems (RES), use of advanced materials and low-embodied carbon materials, smart energy grids, advancement energy management and user interaction / ICT (Ohene et al., 2022) as well as with the interactions among buildings in terms peer-to-peer exchanges of electricity.PEDs are the focus of several *trans*-national and international initiatives aimed at the establishment of PEDs as a core element within the current building sector landscape, such as PED JPI Urban Europe [39], IEA EBC Annex 83 – Positive Energy Districts [22,23], EERA / Smart grids [18], PED EU NET Cost Action [17].

A significant number of challenges arise, however, from this concept, including the technical feasibility of achieving a positive balance in specific urban areas, the need for capacity-building and training throughout all the stakeholders up to the building owners and occupants and the cities' representatives, societal challenges and citizen participation, the improvement of the actual regulatory framework, the need for replication potential assessment and the creation of appropriately tailored business models and solutions towards the achievement of true PEDs.Another specific aspect only partially addressed so far is the difference of difficulty in the implementation of these solutions in a newly built districts or in an existing neighbourhood [21], especially from the technical and regulatory perspective: most of the built environment in the EU was built before the advent of energy efficiency legislation thus making the application of retrofitting solutions a priority conflicting often with historical centres legislation and policies.Lastly, another issue which is often overlooked is the actual assessment of all direct and indirect carbon emissions (this is usually tied more frequently to the operation stage) relating to the definition of PED and the possibility of achieving it, which is still today a matter of wide discussion and not fully agreed upon at the international level. The paper investigates these topics, with a specific focus on the retrofitting of existing districts into PEDs, the definition of PED and the assessment of direct and indirect carbon emissions related to the process.

1.1. State of the art

The definition of PED is in general terms agreed upon as per the already mentioned, from the 3.2 Framework SETPLAN (Koutra et al., 2023a) as a "district with annual net zero energy import and net zero CO_2 emission working towards an annual local surplus production of renewable energy".

Further practical PED definitions include the following three formulations [1]:

- PED autonomous—a district with clear geographical boundaries that is completely self-sufficient energy wise, meaning that the energy demand is covered by internally generated renewable energy. The district is thus not allowed to import any energy from the external electricity grid or district heating/gas network. The export of excess renewable energy is, however, allowed.
- PED dynamic—a district with clear geographical boundaries that has an annual on-site renewable energy generation that is higher than its annual energy demand. The district can openly interact with other PEDs as well as the external electricity grid and district heating/gas network.
- PED virtual—a district that allows the implementation of renewable energy systems and energy storage outside its geographical boundaries. The combined annual energy generation of the virtual renewable energy systems and the on-site renewable energy systems must, however, be greater than the annual energy demand of the district.

The definition is also shifted into other shapes, including different iterations of the geographical/urbanistic concepts of neighbourhoods, community, settlement, district, block and different references to the typology of balance to be calculated (Net, Low, Positive) and to the metric used (Carbon, Exergy, Energy).

[8] mentions that in the past years, the most common formulations and definitions used have Positive Energy District, Zero Emission Neighbourhood, Low Carbon District, Nearly Zero Energy Districts, Low Carbon Neighbourhood, Net Zero Energy Neighbourhood, and Net Zero Energy District.

Other definitions can be found in Table 1a and Table 1b, not limited to PED but also including comparable concepts.

Table 1b shows a summary of the main qualitative features of the definitions in Table 1a.

Other approaches available in literature include in general terms also other balance terms which require further calculations besides the energy uses required by the buildings, including e.g., the energy used for mobility and embodied energy within building materials ([32]).

However, reaching these targets with a generally inefficient building stock, as it is the case generally in Europe, is not a trivial task: guaranteeing high energy performances of the districts' buildings is thus of paramount importance. Therefore, whereas Positive Energy Districts are the focus in existing urban areas, they require building stock deep retrofitting. Building density significantly affects the performance of a district as does the possibility to install appropriately PV or other RES based systems, as in the case of historical buildings/areas. In [9], authors analyse quantitatively several PED case-studies and the impact retrofitting has on prices and technical feasibility of the projects. The study reports findings that the PED feasibility depends on the retrofitting and that retrofitting is most valuable when performed in colder countries. The study also suggests that retrofitting improves energy flexibility and grid interaction while reducing carbon emissions. In [4], authors propose a simulation scenario for densification of existing areas for low-density urban areas. A double density scenario is considered whereas each existing detached house is replaced with two houses of equal living area on the same land lot. It was found that the two new houses consumed overall 30% less energy than the existing house. It is mentioned that residential densification can significantly contribute toward retrofitting into positive energy districts. In [19], the PED model is presented as an opportunity for historic districts to limit the emissions they generate and mitigate energy poverty through extensive district renovation. A district in Lisbon is used as case study, highlighting potential for reduction of heating and cooling requirements up to 84% and 19% respectively and generating up to 64 GWh/year from PV.

The focus on the environmental performances of said high performance districts is not, however, widespread and approached in literature, often only limited to the equivalent carbon emissions of the electricity and building energy use for heating and cooling. Although the district scale is a very intricate system of systems, and this complicates significantly the establishment of a quantitative approach in the environmental assessment, the focus should also include the possibility of being able to appropriately assess if carbon neutrality is achieved including also indirect [34] and (whenever applicable) life cycle carbon emission [11,42]. Failing in accounting for indirect emissions within PEDs definition and assessment might lead into a carbon balance which is very distant from being effectively close to reality. Some further

Table 1a
High performance districts and neighbourhood literature definitions.

Positive Energy Districts [39] are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability.
PED autonomous [1]—a district with clear geographical boundaries that is completely self-sufficient energy wise, meaning that the energy demand is covered by internally generated renewable energy. The district is thus not allowed to import any energy from the external electricity grid or district heating/gas network. The export of excess renewable energy is, however, allowed.
PED dynamic [1]—a district with clear geographical boundaries that has an annual on-site renewable energy generation that is higher than its annual energy demand. The district can openly interact with other PEDs as well as the external electricity grid and district heating/gas network.
PED virtual [1]—a district that allows the implementation of renewable energy systems and energy storage outside its geographical boundaries. The combined annual energy generation of the virtual renewable energy systems and the on-site renewable energy systems must, however, be greater than the annual energy demand of the district.
A net zero emission neighbourhood [27] aims to reduce and compensate its direct and indirect greenhouse gas (GHG) emissions towards zero over the analysis period, in line with a chosen ambition level.
Net Zero Energy Districts [43] requirements: Self-sufficiency / Sustainable energy region/ Carbon Neutrality and 100% renewable energy district heating/Carbon Neutrality/ Energy self-sufficiency up to a quota of 20% / carbon neutrality / 15% solar power on the consumptions
Positive Energy Community [29] PEC is seen as a single system with local supply, demand, and local energy management with the distribution/decentralization of the energy grids. The positive energy community explains that community-level energy analysis should account for the whole energy supply chain, such as production, storage, distribution, and end-us
A Sustainable Plus Energy Neighbourhood [36] is a highly energy efficient and energy flexible neighbourhood with a surplus of energy from renewable sources
A net zero energy community [2,33] is one that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy
A nearly zero energy district [2] is a delimited part of a city that "has a very high energy performance (…)", with the "nearly zero or very low amount of energy (…) covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.
Net-Zero Energy Districts (NZEDs) [28] are city districts in which the annual amount of CO2 emissions released is balanced by emissions removed from the atmosphere.
A Positive Energy Block (PEB) [7] is a compact area which over a year produces more energy than it consumes. It should include at least three mixed use buildings (>15.000 sqm) and needs to include local renewable energy production and measures to reduce its energy demand.

examples from literature on this specific issue are briefly summarized below. In [30], authors investigate through Life Cycle Assessment the environmental performances of a neighbourhood with a focus on GHG emissions based on a modular structure, accounting for buildings, mobility, open spaces, networks and on-site energy infrastructure. Results highlight that the largest share of emissions is due to the buildings with 52% of the total and mobility with 40%. Embodied carbon emissions account for up to 56% of the total. A similar scenario is proposed in [31] where with the same approach the study is extended to the district of Ydalir, a Zero energy Neighbourhood in Norway. In this case, mobility is the most impactful sector with 62% share of the total impacts of carbon emissions. The use of photovoltaics would allow for significantly reduced system-wide emissions.The perspective is also extended in [20] where authors investigate two alternative designs for the energy system of a large district in Canada, in the Okotoks area. Two alternatives, air-air heat pumps conventional systems and solar thermal/PV with seasonal ground storage, are compared with the second one resulting in lower environmental impacts in a life cycle assessment-based study. The approach suggests that among all the environmental indicators assessed some are more impacted by the operation stage and others by the embodied contributions.

1.2. Research gap and contribution of the paper

The state of the art has highlighted the availability of a range of PED definitions, considering a wide range of elements and energy uses/carbon emissions which would have a significant impact on the results. The achievement of the status of PED should also be investigated quantitatively considering the different iterations of the definitions available.

The environmental impacts of the renovation of existing districts into PED and the role of the embodied and indirect carbon emissions are also key topics which should be discussed and investigated quantitatively.

The paper describes the potential achievement of the PED level within an existing group of buildings in Balaguer, province of Lleida, Catalonia (Spain) in southern Europe. The buildings are all non-residential occupying an overall area of 8,825 m^2, need deep refurbishment to achieve high energy performances and are all located in the centre of the city, thus having several issues with displacing RES solutions in high quantity.

The paper proposes an analysis including energy modelling and calibration, analysis of retrofitting solutions to improve the performance of the buildings, PED balance calculations including different items and RES solutions. Direct and indirect carbon emissions are calculated through a life cycle perspective for retrofitting materials and energy use. Hypotheses on mobility use and its impact on PED calculations are also provided.

The contribution of the paper to the current body of knowledge lies in the development of further insights within the more appropriate formulation of the PED definition, the impact different definitions have on the achievement of the PED status, the assessment of the potential of renovation towards the achievement of the level of PED, the assessment of the impact of indirect carbon emissions for retrofitting existing districts into PEDs. The paper can contribute to stimulate the ongoing discussion on the topic of PED definition and, hopefully, to contribute towards orienting the quantitative definition of PED towards a wider range of highly impactful variables.

2. Methodology

In the following paragraphs, the main steps followed in the methodology will be discussed.

The methodological steps of the research can be summarised as follows:

1) On-site investigation of the district: the buildings were visited several times between 2020 and 2022, all necessary data about building envelope, energy systems, occupancy levels, internal loads, lighting and equipment, energy bills use were acquired.
2) District energy modelling and model calibration: this step was developed within Energy Plus environment, all the main data from step one is input to the modelling environment and a calibration procedure is performed on the main uncertain variables.
3) Renovation and energy efficiency: the main solutions for energy efficiency and energy generation are proposed and implemented in the calibrated model. The impact on energy use is calculated.
4) Environmental assessment: life cycle assessment is applied to the main renovation materials in order to compute a carbon footprint. Further considerations are performed for the main building components and mobility.
5) Road to PED: energy and carbon balances are calculated according to different calculations procedures and different strategies. Suggestions and lessons learned are drawn.

Fig. 1 reports a concept map of the connections between the different stages of the methodology.

In connection with the methodology proposed in Fig. 1 and to the aims of the paper discussed in paragraph 1.2 the paper proposes the following connections between research question and results proposed

Table 1b
Qualitative features of the PED definitions.

	Quantitative balance specification	District boundaries	Metric	Social aspects	Buildings interaction	Energy Flexibility	Mobility and ICT	Sustainability
Positive Energy Districts	Net zero greenhouse gas emissions/local regional suplus of generation from renewables	Areas or groups of connected buildings	Energy and Carbon	Yes	Yes	Yes	Yes	Yes
PED autonomous	Self sufficient	Geographical	Energy	–	Yes	–	–	–
PED dynamic	Generation higher than demand (grid interaction)	Geographical	Energy	–	Yes	–	–	–
PED virtual	Generation higher than demand (Grid + virtual interaction)	Geographical	Energy	–	Yes	–	–	–
Net Zero Emission Neighbourhood	Full compensation of carbon over the period	Geographical	Carbon	–	–	–	–	–
Net Zero Energy Districts	Self sufficieny up to different degrees	Geographical	Energy	–	–	–	–	–
Positive Energy Community	–	Geographical	Energy	–	Yes	Yes	–	–
Sustainable plus energy neighbourhood	Surplus of renewable generation	Geographical	Energy	–	Yes	Yes	–	–
Net zero energy community	Energy balance met	Geographical	Energy	–	Yes	Yes	Yes	–
Nearly zero energy district	Nearly zero / high performances	Geographical	Energy	–	–	–	–	–
Net-zero energy districts	Positive carbon balance	Geographical	Carbon	–	–	–	–	–
Positive Energy Block	Energy generation higher than consumption	Geographical It should include three mixed use buildings	Energy	–	–	–	–	–

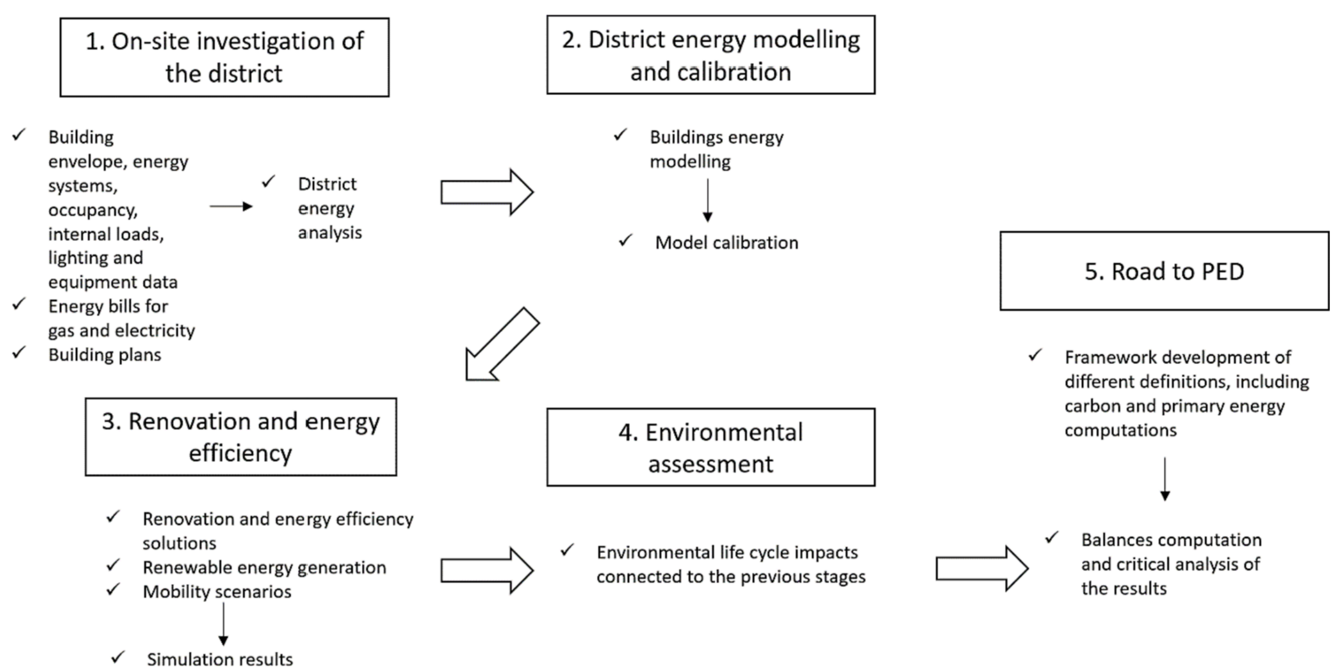

Fig. 1. Concept map of the methodology.

in the paper:

1. Development of further insights within the more appropriate formulation of the PED definition: The paper investigates energy uses and carbon contributors which are proven to be significant and comparable to the mere use stage of buildings which are often overlooked. It offers different formulations (eq.9–10-11) than the simplest ones and suggests alternative routes to the implementation of a strict mathematical balance which could prove challenging for the diffusion of PEDs,
2. Impact different definitions have on the achievement of the PED status: Tables 5 to 12 and Figs. 9 to 14 all quantitatively describe the detailed calculation of different kind of mathematical balances and how the different definitions impact the results of the PED status. Embodied energy and carbon are also proposed jointly with a simplified approach to the modelling of transportation consumption and carbon emissions proposed to further stress the need to integrate the existing PED definitions,
3. The assessment of the potential of renovation towards the achievement of the level of PED: The study discusses the technical feasibility

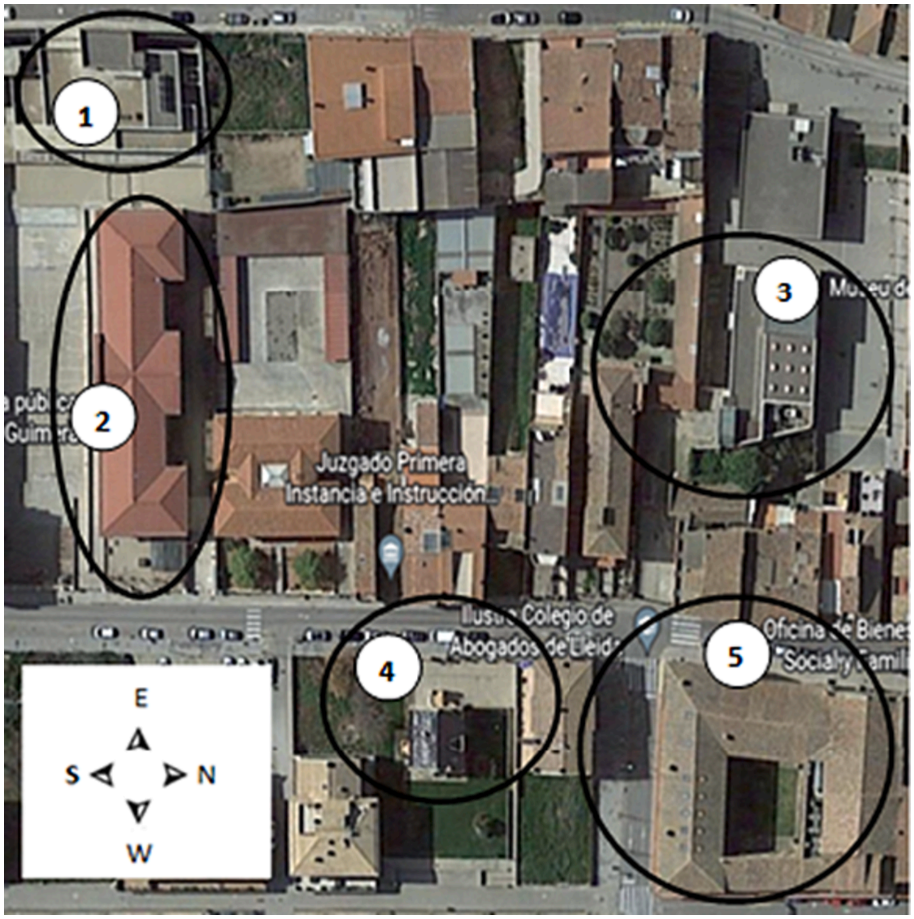

Fig. 2. Map of the Balaguer city centre. Monitored buildings: (1) Angel Guimerà Public School; (2) Xalet Montiu office building; (3) Servei Educatiu de la Noguera school; (4) Museu de la Noguera, museum; and (5) Library Margarida de Montferrat.

of the renovation of an existing district in the Mediterranean area to reach high energy performances to achieve a potential net – positive energy level. This is particularly useful as in the EU most of the existing built environment is in severe need for renovation and the number of new constructions is limited. Paragraph 3.2 discusses a redesign of the existing district quantitatively (Tables 7 – 8),

4. Assessment of the impact of indirect carbon emissions for retrofitting existing districts into PED: as mentioned in the paper, the embodied energy calculated (as in the case of carbon) refers to the impact of the renovation of the existing buildings. From this perspective, Tables 9 to 12 can allow for a quantitative benchmark of similar districts or buildings when it comes to the determination of a carbon footprint of renovation actions in similar contexts.

2.1. Case study description and on-site investigation

The district case-study investigated is found in Balaguer, a city of around 15,000 inhabitants, in the province of Lleida, in Catalunya (Spain). An aerial view of the buildings investigated is reported below in Fig. 2. The whole district covers around 8,825 m^2 of public buildings with different use destination. All buildings from an energy perspective can benefit from energy efficiency actions: although envelopes are characterized by high thermal mass insulation is missing in most cases, often single pane windows and low efficiency energy systems are available and low – efficiency lighting is also found in the buildings.

The buildings included in the district are briefly described in the following:

1) Angel Guimerà Public School, 1,800 m^2. The school operates mainly during the day, with limited occupancy in the afternoon and about one month of inactivity in August. The envelope consists of materials consistent with the building's construction period (solid brick and plaster) and single-glazed windows. The energy system for heating is based on gas heating. Cooling is provided by single split systems in most areas of the buildings, while some zones are not conditioned.
2) Xalet Montiu, 461.44 m^2. The Xalet is a historic building, typical of modernist architecture. It is a three-level building that operates mainly between 9:00 am and 8:00 pm with an interval from 1:00 pm to 4:00 pm. The envelope is composed of solid brick and plaster, with single-glazed windows, several split air conditioner systems are available to complement the existing radiator heat-based delivery. Cooling is based upon split single systems. The conditioned area is about 445.33 m^2.
3) Servei Educatiu de la Noguera, 1,093 m^2. The school operates mainly during the day, with limited occupancy in the afternoon and about one month of inactivity in August. The envelope is composed of solid brick and plaster and double-glazed windows. Heating is based on a gas burner with radiators delivery system. Cooling is based on –multi-split air systems. The conditioned area is about 692 m^2.
4) Museu de la Noguera, 1,496 m^2. The museum operates at different hours during the week. The envelope is composed of brick, polystyrene, clay, plaster and double-glazed windows. The energy system is based on gas for heating and the distribution is performed within an air system. Cooling uses an air system based on a chiller with low efficiencies. The conditioned area is about 948 m^2.
5) Biblioteca Margarida de Montferrat, 3,975 m^2. The library is operating with variable schedules during the week (average × hours a

Fig. 3. Main façades of the buildings. (a) Àngel Guimerà Public School, (b) Xalet Montiu, (c) Servei Educatiu de la Noguera, (d) Museu ee la Noguera, and (e) Biblioteca Margarida de Montferrat.

Table 2
Calculated average U-values of the opaque and transparent envelope of all buildings.

Buildings	Area (m^2)	U Exterior fenestration average (W/m^2K)	Average Solar Heat Gain Coefficient (-)	U Opaque exterior wall average (W/m^2K)	U Opaque exterior floor average(W/m^2K)	U Opaque exterior roof average (W/m^2K)
ÀNGEL GUIMERÀ PUBLIC SCHOOL	1,800	5.8	0.80	1.2	3.7	5.1
XALET MONTIU	461	5.8	0.80	1.2	3.7	2.3
MUSEU DE LA NOGUERA	1,496	2.72	0.65	0.3	3.7	1.7
BIBLIOTECA MARGARIDA DE MONTFERRAT	3,975	2.72	0.65	1.5	3.7	0.8
SERVEI EDUCATIU DE LA NOGUERA	1,093	2.72	0.65	1.2	0.5	0.7

day). The envelope is composed of brick and plaster and double-glazed windows. The energy system for heating and cooling is based on radiators and split air conditioning systems respectively. The heated area is equal to the whole building walkable area.

An overview of the main thermal-physical properties and parameters of the envelope of all buildings is recapped in Table 2. The main façades of the buildings are presented in Fig. 3.

The approach to the energy audit of the existing buildings was performed including a phase of documental analysis about building plans and maps as well as the analysis of the available energy bills for electricity and gas use for each of the buildings within the district for three years (2017/2019). The on-site investigation has taken place within 2020 and 2021, with several visits in person to the buildings aimed at verifying some of the missing information regarding e.g. the quality of the envelope, the use of specific materials of insulation, the use of single/double pane windows, the key features, and characteristics of the heating, ventilation and air conditioning systems, the distribution and timings of the internal loads, the occupancy of the building, and the main control.

Table 3
Buildings main modelling assumptions.

Internal gains Buildings	Area (m^2)	Occupants	Lights (W/m^2)	Electric equipment (W/m^2)
Àngel Guimerà public school	1,800	241	9	0–14
Xalet Montiu	461	10	9	0–10
Museu de la Noguera	1,496	157	7–20	0–3
Biblioteca Margarida de Montferrat	3,975	381	10	3–5
Servei educatiu de la noguera	1,093	36	10	0–7

Table 4
Generation of all roof-installed PV systems within the district (Scenario R1).

	PV power [kW]
Xalet Montiu	8.75
Àngel Guimerà Public School	26.6
Servei Educatiu de la Noguera	6.3
Biblioteca Margarida de Montferrat	11.5
Museu de la Noguera	21

Table 5
Generation of all non-roof PV systems within the district (Scenario R2).

	PV power [kW]
PV installation A	58
PV installation B	30.8

Table 6
District electricity energy use (average monthly).

	Angel Guimera Public School- Servei Educatiu de la Noguera	Xalet Montiu	Museo de la Noguera	Biblioteca Margarida de Montferrat
Jan	7277	1085	3263	3511
Feb	7185	809	2703	2833
Mar	6033	598	2536	2354
Apr	6291	580	2142	2709
May	5811	336	1944	4473
Jun	3862	640	3257	6276
Jul	3884	660	7244	8933
Aug	1495	599	7349	9140
Sep	5042	446	3164,	7157
Oct	6171	522	2665,	4369
Nov	7167	824	2669	3361
Dec	5939	837	2881	3328

2.2. Modelling and re-design of the district

The buildings were modelled following the geometry of the existing district. Figs. 4-8 include screenshots of the models compared with the existing buildings. The model geometry was designed in Sketchup environment. Table 3 reports the main assumptions performed on modelling.

The building energy simulation performed was based on non-steady state calculations in Energy Plus environment. Air temperature and heat flows are computed through the heat balance method. All internal loads (lighting, people, appliances) are based on the data acquired from the on-site investigation. Also, energy systems use and schedules as well as information on occupancy are from the on-site polls. Natural ventilation and infiltration are modelled respectively as design flow rate and wind and stack infiltration, which through some well-known literature charge/discharge coefficients (Delmotte, 2021) allows for the assessment of the airflow through openings. Windows openings schedules are managed according to the feedback received. In particular, air infiltration is modelled as in the Equation (1):

$$Infiltration = I_{design}[A + B|T_{zone} - T_{odb}| + C(W) + D(W^2) \quad (1)$$

Where.

I_{design} is the expected average value for infiltration [1/h],

T_{zone} is the thermal zone air temperature [K]T_{odb} is the external dry bulb air temperature [K].

W is the wind speed [m^2].

As per the constants used for the modelling the typical constants from BLAST were used being respectively: 0.606, 0.03636, 0.1177, 0.

Natural ventilation is based on the following equations from the ASHRAE Handbook of fundamentals, describing respectively the stack (Equation (2)) and wind (Equation (4)) contribution to the

Table 7
District gas energy use (average monthly).

	Angel Guimera Public School- Servei Educatiu de la Noguera	Xalet Montiu	Museo de la Noguera	Biblioteca Margarida de Montferrat
Jan	70,951	10,824	35,154	46,188
Feb	65,855			41,233
Mar	45,763	7,480	14,160	24,271
Apr	31,825			12,397
May	6,974	4,608	4,605	2,765
Jun	0			0
Jul	0	513,71	0	0
Aug	3,404			0
Sep	1,829	10,427	100	0
Oct	14,007			2,174
Nov	50,875	16,894	10,312	12,547
Dec	66,803			27,026

Table 8
Electricity generation per PV plant installed.

	PV area [m^2]	Generation [kWh/y]
Xalet Montiu	50	11,540
Àngel Guimerà Public School	170	37,760
Servei Educatiu de la Noguera	74	8,729
Biblioteca Margarida de Montferrat	73	16,647
Museu de la Noguera	234	29,212
PV installation A	769	79,661
PV installation B	352	40,605

Table 9
Pre- and post- renovation electricity and gas use.

	Electricity Renovation	Existing district	Gas Renovation	Existing District
Jan	33,624	15,137	0	270,208
Feb	28,501	13,531	0	
Mar	20,343	11,522	0	135,898
Apr	18,422	11,723	0	
May	13,371	12,565	0	18,954
Jun	9,628	14,036	0	
Jul	14,168	20,721	0	3,918
Aug	14,333	18,583	0	
Sep	11,547	15,810	0	28,539
Oct	12,855	13,729	0	
Nov	18,620	14,022	0	184,459
Dec	24,119	12,987	0	

Table 10
Load Generation PED balances [kWh/y].

	E	C	Ee	Et	B
Be-S-M1-R1	284,922.04	−602,707.31	0	0	−317,785.27
Be-S-M1-R2	620,176.53	−602,707.31	0	0	17,469.22
Be-E-M1-R1	284,922.04	−602,707.31	−127,245.80	−2,431,347.95	−2,876,379.02
Be-E-M1-R2	620,176.53	−602,707.31	−295,115.78	−2,431,347.95	−2,708,994.52
Be-E-M2-R1	284,922.04	−602,707.31	−127,245.80	−1,073,319.75	−1,518,350.81
Be-E-M2-R2	620,176.53	−602,707.31	−295,115.78	−1,073,319.75	−1,350,966.31
Be-E-M3-R1	284,922.04	−602,707.31	−127,245.80	−277,105.85	−722,136.91
Be-E-M3-R2	620,176.53	−602,707.31	−295,115.78	−277,105.85	−554,752.41

Table 11
Load Generation PED balances [CO_{2eq}/y].

	E_x	I_m	E_e	E_t	B
Bc-S-M1-R1	40,001.88	−84,617.63	0	0	−44,615.75
Bc-S-M1-R2	87,070.24	−84,617.63	0	0	2,452.61
Bc-E-M1-R1	40,001.88	−84,617.63	−21,110.09	−646,272.96	−711,998.80
Bc-E-M1-R2	87,070.24	−84,617.63	−30,494.04	−646,272.96	−674,314.40
Bc-E-M2-R1	40,001.88	−84,617.63	−21,110.09	−280,637.35	−346,363.19
Bc-E-M2-R2	87,070.24	−84,617.63	−30,494.04	−280,637.35	−308,678.78
Bc-E-M3-R1	40,001.88	−84,617.63	−21,110.09	−69,462.94	−135,188.78
Bc-E-M3-R2	87,070.24	−84,617.63	−30,494.04	−69,462.94	−97,504.37

Table 12
Import export PED balances [kWh/y].

	E_x	I_m	E_e	E_t	B
Be-S-M1-R1	48,396.07	−370,752.54	0	0	−322,356.46
Be-S-M1-R2	233,870.93	−227,166.56	0	0	6,704.37
Be-E-M1-R1	48,396.07	−370,752.54	−127,245.80	−2,431,347.95	−2,880,950.21
Be-E-M1-R2	233,870.93	−227,166.56	−295,115.78	−2,431,347.95	−2,719,759.36
Be-E-M2-R1	48,396.07	−370,752.54	−127,245.80	−1,073,319.75	−1,522,922.01
Be-E-M2-R2	233,870.93	−227,166.56	−295,115.78	−1,073,319.75	−1,361,731.16
Be-E-M3-R1	48,396.07	−370,752.54	−127,245.80	−277,105.85	−726,708.11
Be-E-M3-R2	233,870.93	−227,166.56	−295,115.78	−277,105.85	−565,517.26

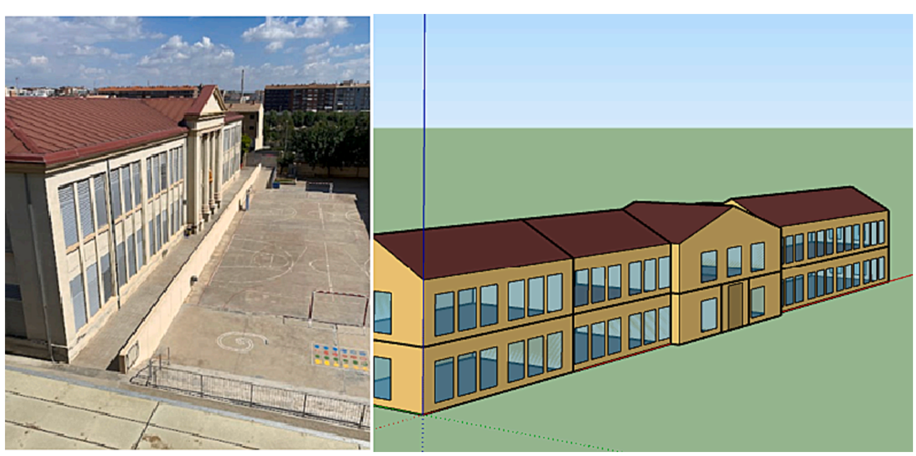

Fig. 4. Screenshots of the models: Àngel Guimerà Public School.

quantification of natural ventilation based airflow.

$$Q_w = C_w A W \quad (2)$$

where,
Q_w = Volumetric air flow rate driven by wind [m^3/s].
C_w = Opening effectiveness [dimensionless].
A = Opening area [m^2].
W = Local wind speed [m/s].
C_w is calculated as in Equation (3).

$$C_W = 0.55 - |A_e - D_w|180 \bullet 0.25 \quad (3)$$

Where:
A_e is the effective angle and.
D_w is the wind direction.
The stack effect is instead calculated as Qs in Equation (4).

$$Q_s = C_D A \sqrt{2g\Delta H \frac{|T_{zone} - T_{odb}|}{T_{zone}}} \quad (4)$$

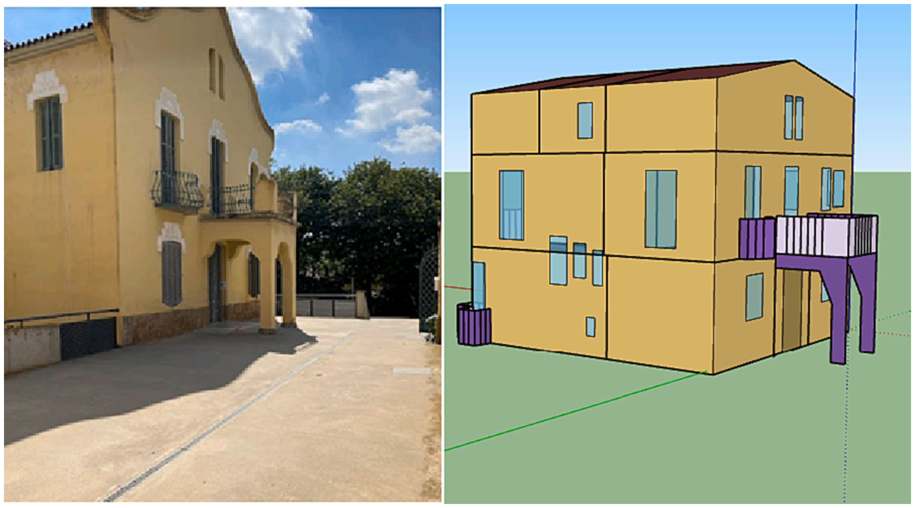

Fig. 5. Screenshots of the models: Xalet Montiu.

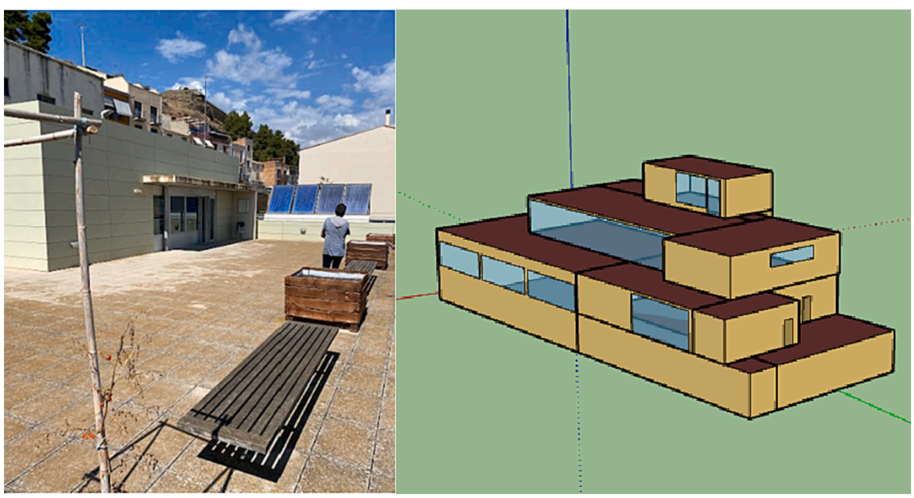

Fig. 6. Screenshots of the models: Servei Educatiu De La Noguera.

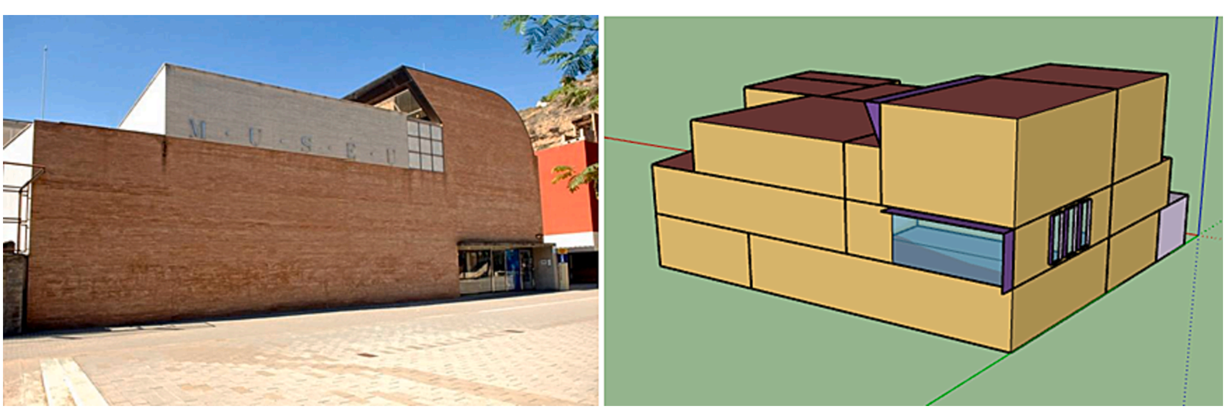

Fig. 7. Screenshots of the models: Museu De La Noguera.

where.

Q_s = Volumetric air flow rate due to stack effect [m^3/s].

C_D = Discharge coefficient for opening [dimensionless].

A = Opening area [m^2].

ΔH = Height from midpoint of lower opening to the neutral pressure level [m].

The discharge coefficient C_D is calculated as in Equation (5).

$$C_D = 0.40 + 0.0045|T_{zone} - T_{odb}| \quad (5)$$

The total ventilation rate calculated by the model is equal to the quadrature sum of the wind and stack air flow components as in Equation (6).

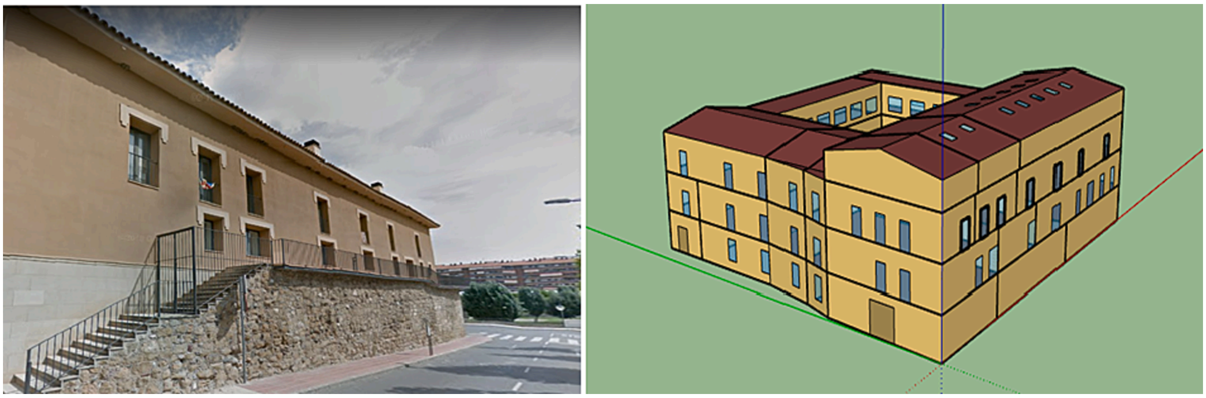

Fig. 8. Screenshots of the models: Biblioteca Margarida de Montferrat.

Fig. 9. Further PV installations planned (Scenario R2).

$$Q_{tot} = \sqrt{{Q_s}^2 + {Q_w}^2} \quad (6)$$

Energy systems are modelled as thermal ideal loads due to the complexity of the energy systems, the depth of the modelling and the large areas involved, with fixed efficiencies of the energy systems components.

All buildings are considered as connected to each other and able to exchange energy flows in terms of electricity between one another in a peer-to-peer approach. All generation surpluses from each building are first considered to cover the deficits in the other buildings, to feed the electricity storage after and only in the end to be fed to the grid. Assumptions on mobility fuel consumption and corresponding carbon equivalent emissions are based on the occupancy data from the building survey performed to model the energy modelling. Different scenarios are proposed including variable travelling distances within the urban area of Balaguer for all the occupants, as well as different percentage attribution of the travelling means chosen (public transport, car, walking) and taking in consideration the possibility of smart-working. In detail the three mobility scenarios investigated are:

- M1) 100% car driven mobility, long transportation route (from the district location to the farthest border of the city), twice/day all workdays.
- M2) 50% car driven mobility, 50% bus, average transportation route (half the scenario 1 distance), twice/day all workdays.
- M3) 20% car driven mobility, 50% bus, 30% walking, average transportation route (half the scenario 1 distance), twice/day three days a week.

Environmental impacts for the mobility scenarios are from [41].

The redesign of the existing district into PED is based on actions to improve the energy efficiency of the buildings and energy systems up to the actual legislative performance minimum requirements for the specific region within Spain.

The following technical solutions have been modelled and simulated for the district:

1. Coating external insulation (wall) (polystyrene, buildings: Xalet Montiu, Servei Educatiu de la Noguera, Àngel Guimerà Public School and Biblioteca Margarida de Montferrat).

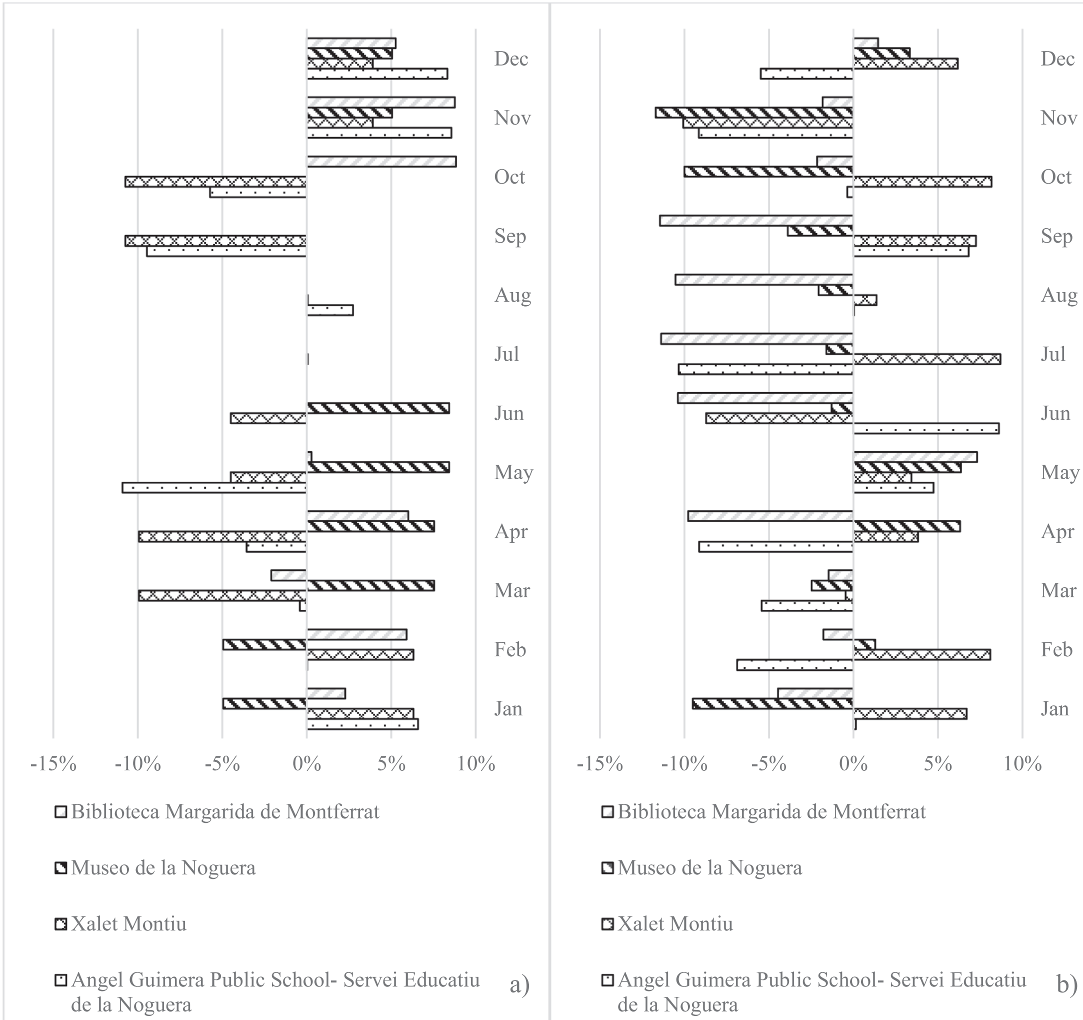

Fig. 10. Final error analysis in the electricity (a) and gas consumptions (b) for each building.

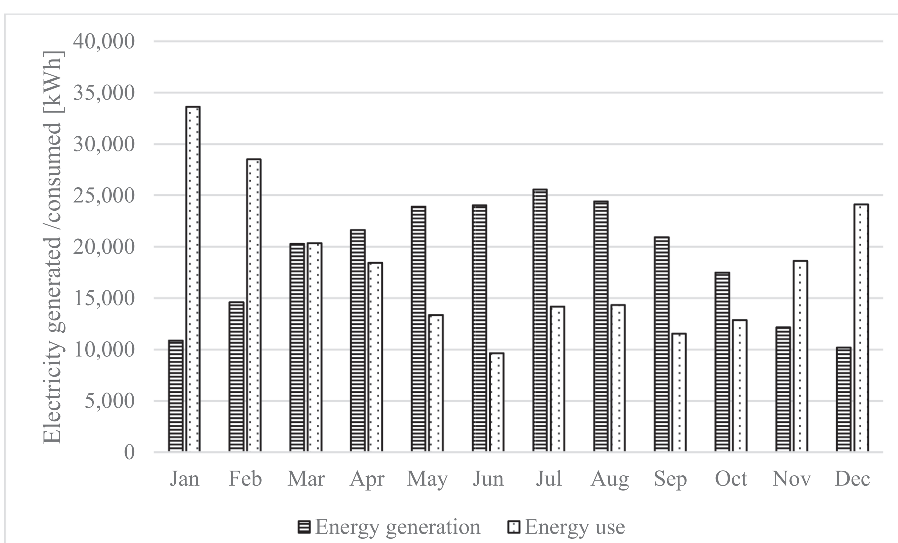

Fig. 11. Electricity use and generation for the overall Balaguer district.

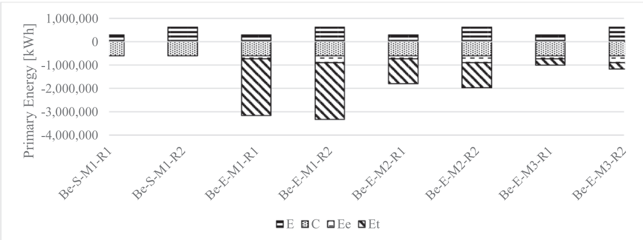

Fig. 12. District energy balance (Load generation).

2. Coating external insulation (roof) (polystyrene, buildings: Xalet Montiu, Servei Educatiu de la Noguera, Àngel Guimerà Public School, and Biblioteca Margarida De Montferrat).
3. Windows substitution (Up to 1.6 $W/m^2 \cdot K$, SHGC = 0,6 buildings: Àngel Guimerà Public School and Xalet Montiu)
4. Lighting bulbs and heating/cooling generator system substitution with commercial state of the art heat pumps (air or water based, according to the available distribution system, with COP and EER greater than 4.5).
5. Installation of photovoltaics generation systems on all available south, south-east and south-west surfaces (scenario R1) and on on-site close surfaces (e.g., covering of parking areas – scenario R2).
6. Use of a 250 kWh (Scenario R2) or 75 kWh (Scenario R1) electricity storage system (Whole district. This is based on the concept that an energy community could be structured with peer to peer energy flows connections).

The photovoltaics installation is planned for a total of 104 kW and a total area of 528 m^2 as per the following Table 4.

An explicative view of all the other PV generation solutions planned (Scenario R2) in close-by buildings is following in Fig. 9.

The environmental modelling of the district is based on the Life Cycle Assessment [24] methodology aimed at the calculation of a carbon footprint [5]. The scoping of the analysis is focused on the use stage and on the retrofitting of the existing district required to achieve the PED status. Thus, the boundaries of the analysis include energy use and carbon emissions due to heating/cooling and building use, lighting and plug loads. Also, mobility energy use and carbon emissions are included in the analysis as well as further embodied carbon and energy within the systems, components and materials that are substituted during the renovation stage. Data for the analysis are primary whenever possible, the use of secondary data from Spanish context was preferred and from EU and Ecoinvent sources was integrated whenever necessary.

2.3. *Road to PED: balances, scenarios, nomenclature*

The Positive Energy Districts definitions chosen include all energy uses occurring within the buildings, taking in consideration all exchanges with the grid and only the on-site generation, by means of photovoltaic systems integrated in the rooftop, electricity import and export from the grid.

The paper is using different formulations for the concept of positive energy district definition, including different balancing terms and with different assumptions for on – site generation, specifically tailored to the assessment of renovation of existing districts into PEDs.

Equation (7) is the **'simple PED balance'** which only computes generation and consumptions on-site.

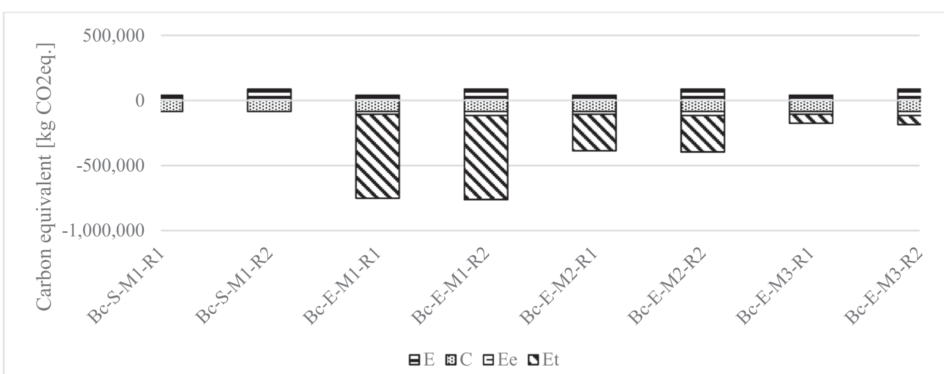

Fig. 13. District carbon balance (Load generation).

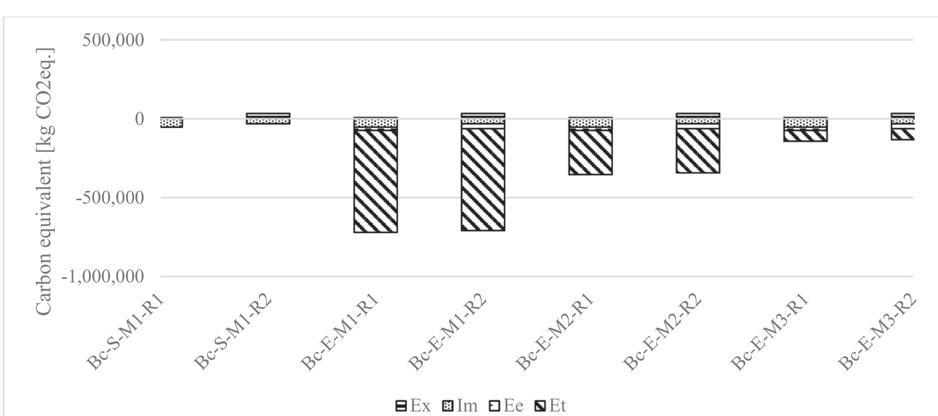

Fig. 14. District energy balance (import–export).

$$B = \sum_{i=1}^{n} E_i \times w_i - \sum_{i=1}^{n} C_i \times w_i \tag{7}$$

where B refers to the PED balance results; i refers to the generic energy carrier being used within the district area; E_i is the energy generated on-site by means of renewable energy sources; C_i is the energy use on-site per energy carrier; and W_i is a weighting/conversion factor (e.g., from final energy to primary energy/carbon equivalent).

Equation (8), instead, is the **'extended PED balance'** which also computes the annual energy/carbon for mobility and the annualized contribution for embodied energy/carbon.

$$B = \sum_{i=1}^{n} E_i \times w_i - \sum_{i=1}^{n} C_i \times w_i - E_e - E_t \tag{8}$$

where E_e is the annualized negative contribution due to embodied energy/carbon; and E_t is the annual negative contribution due to primary energy/carbon equivalent generated by transportation.

These two calculation options are based on the Load – Generation energy balances from previous applications within the Net zero energy buildings framework [38] having as fundamental assumption the non-interactivity between generation and loads (i.e. all generation is fed to the grid, all consumptions are covered by grid electricity import). Another option which is explored in the paper is connected with the Import-Export balance calculation, where a more accurate computation is performed with reference to the auto-consumption of on-site generation and import–export energy flows. Thus eq.1 can be re-formulated as in eq.9

$$B = \sum_{i=1}^{n} Ex_i \times w_i - \sum_{i=1}^{n} Im_i \times w_i \tag{9}$$

where Ex is the exported energy per energy carrier; and Im is the imported energy per energy carrier i.

The same line of thought is valid for Equation (8) which is now reformulated into Equation (10):

$$B = \sum_{i=1}^{n} E_{xi} \times w_i - \sum_{i=1}^{n} Im_i \times w_i - E_e - E_t \tag{10}$$

To summarise, the PED balances that will be discussed in the following arise from the combination of the following variables/calculation methodologies:

- Load – Generation / Import – Export balances
- Simple or Extended PED balance (S or E)
- Mobility scenarios M1, M2, M3
- Renewable generation scenarios alternatives R1 and R2
- Primary energy and carbon as primary metric (Be or Bc).

In the following, the nomenclature of the balances calculation will be based on these references e.g., Be-S-M1-R1 refers to the energy balance (Be), simple PED balance (S), mobility scenario M1, renewable energy systems scenario R1. Bc-E-M2-R2instead refers to a carbon balance (Bc), Extended PED balance formulation (E), mobility scenario M2 and renewable energy systems scenario R2.

3. Results

In this section all results regarding the previously mentioned methodological steps will be described.

The available monitored data are showed for the whole district with detail on the single building level in Table 6 and 7 for electricity and gas.

The electricity bills as well as the gas bills cover a two-year time span, the average of which was averaged for comparison with the simulation data. For the entire simulation year, the results are compared to the bills data for the periods considered for each of the buildings composing the district. The annual deviation reported is lower than ± 10%, validating the hypotheses advanced. Fig. 9a and Fig. 9b show the quantitative comparison between simulated and existing energy use, reported in percentages as variation from values reported in Fig. 10. Calibration was performed with regards to the uncertain parameters (thermal properties of some of the windows adopted and of some opaque structures, occupant behaviours and occupation levels of some thermal zones, lighting and manual operation of split systems), identified in a range of reasonable variation uncertainty. Simulations were run iteratively until a good fit was identified. The following parameters were modified in an iterative procedure only when uncertainty arose, with the corresponding variability range: occupants per thermal zone (±20% if compared to the suggestions of the buildings' owners and managers), schedules per thermal zone with reference to lights ignition per hour (±1-2 h of working time, according to the building and the suggestions of the building management), opening fraction of all windows, according to the window typology (from 0 to 1, variable during the year), schedules for windows opening (±1-2 h of activation, according to the building and the suggestions of the building management), U opaque exterior wall for Angel Guimera public school and Servei educatiu de la Noguera (average expected 1.15 W/(m2K), range of variation ± 10%), U exterior fenestration for Museu de la Noguera, Biblioteca Margarida de Montferrat and Servei educatiu de la Noguera (average expected 2.75 W/(m2K), range of variation for calibration ± 10%), manual operation of the split systems (±0.5 – 1.5°if compared to 20 °C for heating and 26 °C for the temperature setpoints).

The installation of photovoltaics on the roofs of the buildings as well as in the selected off-site areas showed in Fig. 9 will generate the following energy yield, as per in Table 8.

The strategy for electrification of the district, although causing an overall increase in use of electricity of around 25% compared to the existing one, has nullified gas expenses, due for domestic hot water and heating while also guaranteeing significant improvement in the performances of the buildings, clearly recognizable in the electricity requirements trends during summer being significant lower, due to a reduction in cooling requirements.

If overall generation and consumptions are concerned, Fig. 11 reports the monthly trend for electricity generation and consumption.

Although the overall generation is higher than consumption (overall generation is equal to 226,090.13 kWh while consumptions amount to 219,532.04 kWh) during the year examined, it is worth mentioning that some relevant deficits are traced for the winter months causing a significant import from the grid which is counterbalanced by a net export during summer.

In the following, instead, the results for all the PED balances are shown, organized with the pre-defined nomenclature and divided in different figures according to the metric and the equation used for calculating the balance. Figs. 12 and 13 show the results for all balances including load-generation calculations and energy as metric. The most relevant terms in the balance refer to the mobility in most cases but with different magnitudes, according to the scenario chosen. The balances show in most cases negative results in the extended formulation while in some cases positive results can be achieved, specifically in the simple PED ones.

Further modifying the metric into carbon in Fig. 11 does not significantly alter the results, already mentioned for the previous figure.

If the calculation is performed by computing import export balances (Figs. 14 and 15) the results tend to follow the previously discussed trend with very few scenarios actually achieving the positive target, with a much higher occurrence within the simplest calculations. Embodied energy and carbon in this case is aligned with the impacts caused by energy import from the grid with mobility potentially being the most impactful one.

Tables 10 and 11 recap all results for the load generation balances, while Tables 12 and 13 provide a synthetic view on the import – export results, with an in-depth numerical focus on all terms of the balance.

Within all the scenarios proposed the only solutions able to achieve a positive status are the simple PED balances in the case of larger generation capacity installed than the roof availability. Extended PED

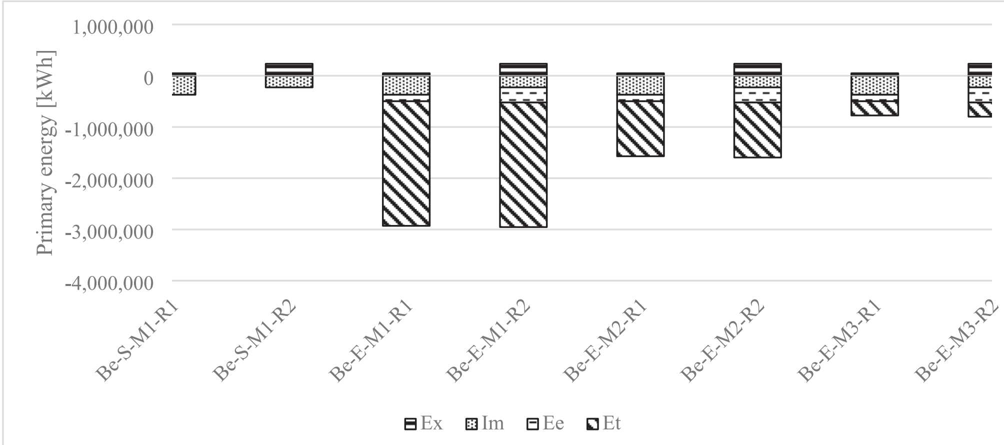

Fig. 15. District carbon balance (import export).

Table 13
Import-Export PED balances [CO_{2eq}/y].

	E	C	Ee	Et	B
Bc-S-M1-R1	6,794.61	−52,052.13	0	0	−45,257.52
Bc-S-M1-R2	32,834.52	−31,893.25	0	0	941.27
Bc-E-M1-R1	6,794.61	−52,052.13	−21,110.09	−646,272.96	−712,640.58
Bc-E-M1-R2	32,834.52	−31,893.25	−30,494.04	−646,272.96	−675,825.74
Bc-E-M2-R1	6,794.61	−52,052.13	−21,110.09	−280,637.35	−347,004.97
Bc-E-M2-R2	32,834.52	−31,893.25	−30,494.04	−280,637.35	−310,190.12
Bc-E-M3-R1	6,794.61	−52,052.13	−21,110.09	−69,462.94	−135,830.56
Bc-E-M3-R2	32,834.52	−31,893.25	−30,494.04	−69,462.94	−99,015.71

balances never actually achieve a positive level although the best results are found when combining larger renewable generation potential with limited mobility impacts.

4. Discussion

The definition of Positive Energy District is being developed under different umbrellas and policy discussion tables. While much can be argued with a focus on opportunities and expectations, a detailed technical analysis of the PED potential for the case study in Balaguer can lead to the following points:

- The city of Balaguer is representative for a large part of the Mediterranean area, especially for mid-to large cities with similar constructions and only structures with a moderate number of storeys. Results can therefore be extended to a large pool of countries with comparable conditions.
- The renovation of existing districts into higher energy performance levels is particularly effective in the case of low energy performance structures. The electrification of the whole district would lead to the removal of the requirements for heating and only a moderate increase in electricity use, also partially covered by the contemporary use of renewable energy generation and electricity storage devices. If only the average cost of the kWh of natural gas and electricity for Spain is considered, the implementation measures proposed would limit the expenses of the municipality for only the five buildings considered to around 10,000 Euro from 50,000 originally.
- Only one of the balances identifies a PED (two if also the corresponding carbon one is concerned). However, the simplest PED definition is not by any means easily attainable. In order to fulfil the PED balance for standard office buildings no more than 5 storeys high, using only the rooftop availability for PV allows the covering of only around the 50% of the overall demand. The situation worsens if mobility and embodied energy are included in the balance.
- The need for complexity and understanding the level of PED conflicts with the possibility of easily achieving the target and ultimately, therefore, with the potential for diffusion of all decarbonisation actions embedded in the concept of Positive Energy Districts. It is clear that achieving merely a use stage (generation vs consumption or import vs export) positive energy balance already is challenging, particularly so in several storey buildings e in densely populated centres making it necessary to search for further public areas not originally envisaged in the roof PV design. If also embodied energy/ carbon and mobility are included in the calculations the strict mathematical balance proposed will probably not converge towards zero or plus zero.
- Embodied energy is a term which needs to be carefully addressed when discussing energy performances of buildings and districts. Although its contribution at this stage is considered limited, it should be taken in consideration that the values reported are calculated only for the case of the renovation materials and referred to a year (by choosing appropriate life cycle lengths for all the renovation options introduced in the design). An alternative option could be to consider all the main materials included in the building construction which were omitted here since the life cycle of these materials was unknown and beyond the scope of the paper. Results could vary dramatically and lead into an order of magnitude of difference from the ones provided.
- Mobility results are very variable and require a very detailed modelling starting from accurate interviews and data elaboration. The different scenarios proposed account for a very wide variability which mirrors the uncertainty in the specific parameters included for the specific case. This specific sector can account for the most impactful one among those being taken in consideration at this stage, especially if very limited efforts are paid towards the principles decarbonisation and all the inspiring ideas behind the 15-minutes cities.

- Carbon balances follow closely the results found within the energy ones. A true carbon neutrality is therefore as challenging to be accomplished as an energy one.

On a more general note an as a direct consequence of the results discussed in the paper, while the approach to a qualitative definition to Positive Energy Districts has undoubtedly merits (more comprehensive and inclusive, it allows to focus qualitative aspects) it is clear that if the final aim is decarbonization of cities it is needed to truly aim at a comprehensive energy balance / carbon footprint of the urban areas.

In this perspective, the paper has highlighted the problems in achieving an actual positive balance, in simple cases with mere use stage calculations as well as in more complex energy balances.

The concept itself of merely pointing towards the fulfilment of a mathematical balance could be re-structured and integrated with other solutions to label an energy and environmentally efficient district. The energy – carbon balance to couple with the definition of PEDs requires a strong calculation based approach, which is already very difficult to be fulfilled, even in small cities with low-storey buildings, and requires around double the PV area which is available on the buildings' rooftops in the case-study proposed in the paper. The applicability of this solution towards larger cities with higher building density is going to be of further complexity and difficulty and could ultimately lead to more precise and scientifically based calculations but, in the perspective of favouring the diffusion of PEDs, could ultimately be a hindrance from some perspectives.

The solution to this issue could point towards different alternatives:

- the determination of "context factors", aiming thus to scale the results of energy generation and consumption to take in consideration the difficulty of achieving a Positive balance in the site of interest. Examples of domains of interest for said factors could lie i.e. in the urban density, occupants' density, average elevation of the buildings, climate features.
- another solution could lie with the development of a structured rating system with credits / malus for districts to take in consideration factors which would otherwise generate with near certainty a negative energy balance. This could be the case for the deployment of appropriate car sharing solutions for the district, the deployment of convincing biking routes, as practical examples for mobility, or the use of products and procurement goods to be provided with environmental labels to guarantee a lower amount of embodied environmental impacts.
- the two solutions could also be combined into a modified energy/carbon balance accompanied by a set of credits for neighborhoods aiming for the level of positive energy district, which could further enhance or integrate the balance calculations or structure a proper rating system for PEDs in the way that is currently available for high performance buildings. This could represent a compromise between scientific solidity of the data being computed and of the methodology being adopted and the need to help the diffusion of PEDs as tools to push decarbonisation in the built environment."

5. Conclusions

The study is introduced in the framework of the general activities developed at the international level aimed at decarbonizing the built environment through the development of positive energy districts. It has highlighted the feasibility of the road towards Positive Energy Districts also for existing districts, proposing benchmarks for both energy performances and carbon footprint for similar district in comparable climatic conditions. Furthermore, the paper has investigated energy uses and carbon contributors which could be significant and comparable to the impact of the use stage of buildings i.e. transportation and embodied energy/carbon, which are usually overlooked, by investigating an expansion of the boundaries of the district energy/carbon balance. The paper could therefore contribute to a more general Positive Energy District definitions framework, introducing further balance elements and different calculations procedures.

The district case-study is in Balaguer, a city located in the province of Lleida, Catalunya, Spain, with a population of approximately 15,000 residents. The investigation focused on a collection of buildings which cover a total area of approximately 8,825 m^2. These buildings serve various public purposes and are designated for different uses. The district was modelled and simulated in non-steady state, a calibration was performed and the model was considered validated to perform further renovation studies for the district in order to check the viability of the application of the PED concept to the case-study. Different energy and carbon balances were computed, according to relevant existing literature, integrated with further subtractive elements (i.e. mobility and embodied energy/carbon). Life cycle assessment based calculations were performed to corroborate the use stage modelling and several mobility scenarios based on occupants' feedback were implemented.

All energy and carbon balances investigated in the study show that transportation and embodied impacts are at the same order of magnitude than energy uses in buildings. The results have highlighted that the renovation of the district could allow to significantly improve the performances of the district, thus allowing for a large reduction in overall primary energy consumptions. Mobility and embodied energy proved significant in the energy/carbon balance of a district as their respective weight is subject to significant variability: mobility could be higher by up to 10 times than the energy uses during the operation of the buildings but could also be as low as being equal to the 75% of the use stage of the building energy consumptions. The embodied energy of the renovation can instead by variable between the 20% and the 120% of the energy consumptions of the building, according to the different assumptions performed.

All results investigated in this paper point towards the same direction: PEDs should be regarded as a true and complex system of systems, going beyond the mere buildings level and introducing the appropriate depth towards a true and proper carbon and environmental footprint of the urban environment.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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