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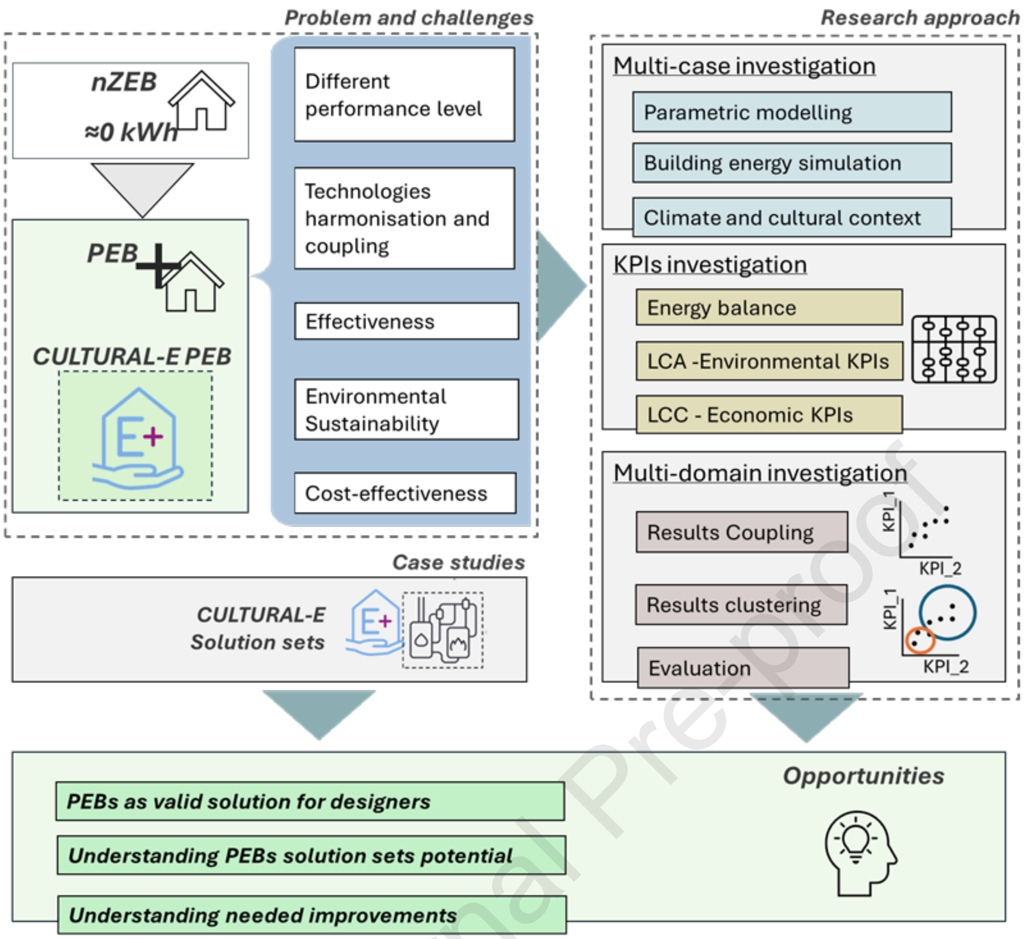


Problem and challenges
nZEB
≈0 kWh
PEB
CULTURAL-E PEB
Different performance level
Technologies harmonisation and coupling
Effectiveness
Environmental Sustainability
Cost-effectiveness
Research approach
Multi-case investigation
Parametric modelling
Building energy simulation
Climate and cultural context
KPIs investigation
Energy balance
LCA -Environmental KPIs
LCC - Economic KPIs
Multi-domain investigation
Results Coupling
Results clustering
Evaluation
KPI_1
KPI_2
KPI_1
KPI_2
Case studies
CULTURAL-E Solution sets
Opportunities
PEBs as valid solution for designers
Understanding PEBs solution sets potential
Understanding needed improvements

Effectiveness and Sustainability of solutions sets aimed at Plus Energy Buildings. A multi-case and multi-domain investigation

Di Bari, Roberta[1,2*]; Turrin, Francesco[3]; Leis, Hermann[4]; Isaia, Francesco[3]; Belleri Annamaria[3].

[1] University of Birmingham, School of Engineering, Department of Civil Engineering, Edgbaston, B15 2TT Birmingham, United Kingdom

[2] University of Stuttgart, Institute for Acoustics and Building Physics, Department of Lifecycle Engineering (GaBi), Nobelstraße 12, 70569 Stuttgart, Germany

[3] EURAC Research, Viale Druso 1, 39100 Bolzano, Italy

[4] Steinbeis-Innovationszentrum Energieplus, Gropiusplatz 10, 70563 Stuttgart, Germany

*Corresponding author: r.dibari@bham.ac.uk

Abstract. Purpose. Plus Energy Buildings (PEBs) are gaining attention in construction for providing advantages not only on the singular building but also on higher levels, namely neighbourhoods and national grids. Different from the current standard of net zero energy buildings, PEBs lack broader and holistic investigations that consider energy, environmental, and economic performance indicators. These are needed to evaluate their often-debated effectiveness and environmental sustainability. To this purpose, this work assesses technical equipment functional systems aimed at PEBs by considering energy, environmental and cost performance indicators and by carrying out a multi-case and multi-domain investigation. **Method:** A parametric modelling is carried out based on building energy simulations and user energy profile modelling in 16 case studies. Relevant Key Performance Indicators are derived and followed to attempt result clustering and to derive general considerations for the designed solution. **Finding:** The study showed that the effectiveness of such systems is limited if PV modules are located on the roof exclusively. Moreover, heat pumps and PV technologies need to be better coupled and harmonised in subarctic regions. Overall, centralised systems perform better, and environmental and economic advantages depend on the national energy and economic context. Such results can be considered valid under the same conditions and circumstances; therefore, an extension of case studies is needed.

Keywords: Plus Energy Buildings; PEB; energy efficiency; Building energy simulation; Life Cycle Assessment; Life Cycle Cost.

List of Abbreviations and Nomenclature

APL	Appliances
BoM	Bill of Materials
DHW	Domestic Hot Water
DIS	Distribution system
GWP	Global Warming Potential
HMS	House Management System
HP	Heat Pump
HR	High Rise Building
KPI	Key Performance Indicator
LGT	Lightning
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOD	Level of Detail
LR	Low Rise Building
NFA	Net Floor area
NPV	Net Present Value
nZEB	Net Zero Energy Building
PEB	Plus (or Positive) Energy Building
PIP	Pipework (including Valves, Heat Exchangers and Circulation Pumps)
PWG	Power Generation
PV	Photovoltaic systems
SC	Space Cooling
SH	Space Heating
SS1	Solution set, the building functional system having installation - Centralised
SS2	Solution set, the building functional system having installation - Decentralised
TES	Thermal Energy Storage
VEN	Ventilation system

1 Introduction

Improving building energy efficiency is currently one of the most commonly adopted policies at the national level to reduce emissions, as required for countries under the Paris Agreement [1]. In the European context, the EU has established a legislative framework that includes the Energy Performance of Buildings Directive (EPBD) (Directive 2010/31/EU) and the Energy Efficiency Directive 2012/27/EU. Together, the directives promote policies for EU countries that will help to 1) achieve a highly energy-efficient and decarbonised building stock by 2050; 2) create a more environmentally aware investment environment; 3) enable consumers and businesses to make more informed choices to save energy and money [2]. In this context, Zero Energy Buildings (ZEBs) are required as a minimum standard for new and renovated buildings and have become a part of the energy policy in several countries [3,4]. For instance, all new buildings and deep renovations constructed in the European Union from 2021 must be nearly Zero Energy Buildings (nZEBs) by 2050 [3]. However, more efforts are still required. The construction sector is one of the main contributors to greenhouse gas (GHG) emissions, and higher energy performance should be investigated, especially for new buildings, aiming to reduce embodied and operational environmental impacts [5,6].

Thanks to extensive research to improve building performance and efficient technologies and equipment for the building sector, nZEB can be improved one step further to achieve the so-called *Plus* (or Positive) Energy Building (PEB) [7,8]. The topic of PEB has received increasing attention in recent years, and it is foreseen to become part of the energy policy in several countries. One of the main barriers to including PEBs in energy policy is the lack of literature on a harmonised definition [8]. This leads to different practices and strategies for achieving a PEB [9–11]. The literature review provided by Hawila et al. [9] demonstrated, e.g., that most of the studies on nZEB and PEB do not present a common way to balance energy consumption with renewable energy (RE) production. Physical boundaries can be established in several ways [12], and user-related energy consumptions are evaluated differently[9]. As a result, some examples in the literature demonstrated reduced energy gains. Buildings designed as PEB perform as nZEB due to additional user-related operational energy consumption [13,14].

To tackle these issues, a different definition and evaluation approach to PEBs is provided by Hawila et al.[9], and demonstrated in CULTURAL-E. As conceived in CULTURAL-E, PEBs exploit the so-called “operational approach”, where the energy balance is measured or predicted by considering the final energy between load and generation related to each single energy vector [9]. In addition, in order to offer a substantial *plus* in different domains, key functional requirements of Plus Energy Buildings are established, related to, e.g., the interaction with the energy grid, cost-effectiveness, environmental sustainability and indoor environmental quality [9].

An evaluation based on different perspectives is needed for such defined PEB systems to demonstrate their effectiveness, cost-effectiveness, and environmental sustainability metrics. Overall, a few works in the literature attempted a more holistic evaluation of PEBs [15–18]. As a result of these investigations, the environmental advantages of PEBs are questioned due to their higher amount of components and consequent increase of embodied impacts [18]. Analogously, due to objectionable cost-effectiveness [10,15], optimisation strategies are required. Overall, there is a lack of studies that consider at least three domains, energy, environmental, and economic performance, which are essential to assess PEB systems.

Given the above, the main problem of this study is the investigation of the effectiveness of PEBs, as conceived in CULTURAL-E [9]. The effectiveness in terms of energy performance and building energy balance is evaluated along with economic and environmental Key Performance Indicators (KPIs), which measure their environmental sustainability and cost-effectiveness. Objectives of the analyses are, in particular, *solution sets* (SS) aimed at PEBs. Depending on their overall functional logic, they are groups of building installations classified as centralised or decentralised. This problem is particularly challenging since all technical installations can perform differently based on the climate and cultural contexts and building archetypes where they are allocated. An additional challenge in energy performance is represented by the use of specific technologies, e.g., photovoltaics, which only ensure that a building will behave as a PEB sometimes. These technologies need, therefore, to be correctly coupled and controlled in a harmonised way.

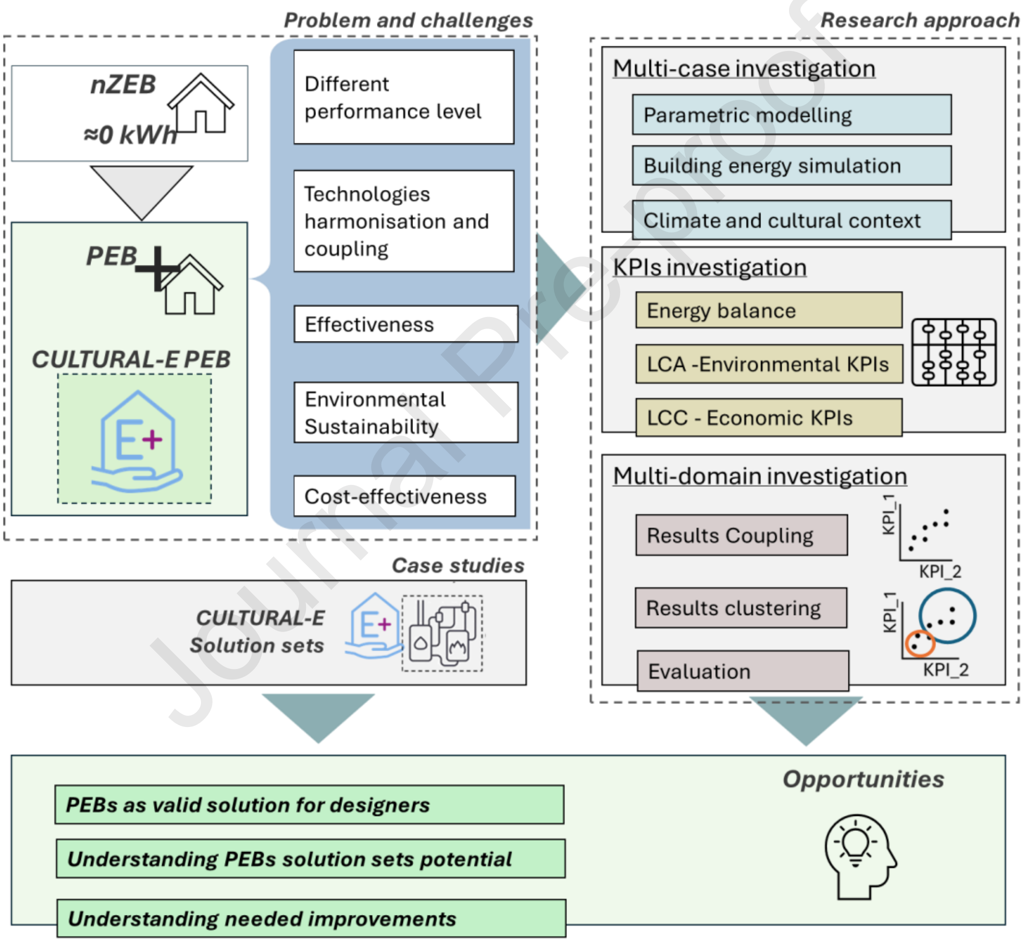


Figure 1. Research approach for the investigation of solution sets aimed at PEBs.

To tackle this problem and the consequent challenges, the research follows an approach based on *multi-case* and *multi-domain* investigation (see Figure 1). The multi-case analysis is provided in this study to provide various examples with different solution set types, building archetypes, climate and cultural (national) contexts. It also allows us to perform a parametric modelling of the solution set. As a novelty of this study, compared with previous works [19,20], an enlarged set of KPIs is established to assess such systems. These are based on building energy simulations, user energy profile modelling, environmental Life Cycle Assessment (LCA), and Life Cycle Cost (LCC). Results are first evaluated for each domain (energy, environmental and economic performance). Analyses on different domains allow for verifying the solution's effectiveness and sustainability, identifying trade-offs, and better harmonising and coupling different technological solutions. Finally, the multi-case and multi-domain investigation allows us to attempt result clustering and derive general considerations for the designed SS type, building type, climate, and cultural contexts.

This research provides opportunities in the current context of building and energy sector decarbonisation. Suppose the advantages of such PEB systems are demonstrated in terms of energy, economic and environmental performance. In that case, PEB can represent a valid solution for designers to reduce building energy consumption and to increase the share of produced renewable energy for national grids. With a particular focus on results obtained by energy simulations, LCA and LCC and the results' coupling allow us to understand in which circumstances the designed solution sets perform better and where improvements are needed.

2 Materials and methods

In this section, methods applied for this work are outlined. Firstly, LCA and LCC methodologies are presented. The KPIs used for the assessment are described, along with the specifications and assumptions used for LCA and LCC analyses. Section 2.3 outlines the procedure for the solution set parametric modelling based on building energy and user energy profile simulation activities. Section 2.4 presents the data structure and requirements used to compile the Bill of Materials (BoM) for LCA and LCC analyses.

2.1 Life Cycle Assessment (LCA)

Through LCA (ISO 14040 – 14044) [21,22], it is possible to evaluate potential environmental impacts associated with identified inputs and releases over all the stages of a product's life. While most building LCA consider 3 levels of assessments (product, functional system and building level), in CULTURAL-E, a more suitable framework for life cycle assessment (LCA) is established [19,20], which considers the experience of practitioners and the latest development in PEBs (see Figure 2). After an agreement on the overall methodology, as a first step, LCA is performed on each technology to understand the environmental potential and optimisation possibilities. As a second step, parametric LCA models for evaluating building solution sets are produced (see Section 2.3), and relevant KPIs are evaluated.

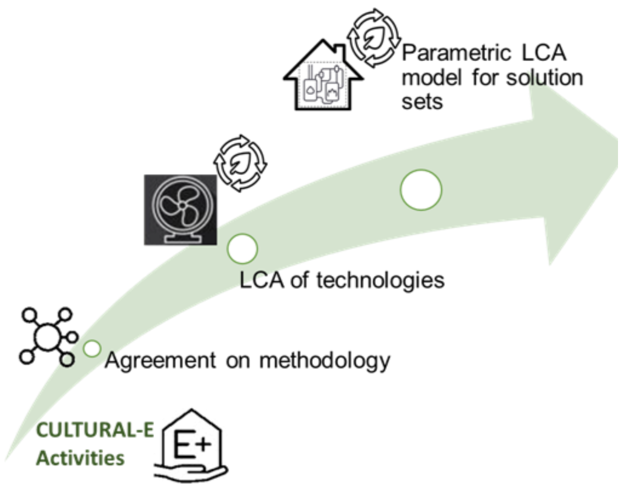


Figure 2. Overall procedure for parametric LCA analyses of solution sets. Source: [20].

Each solution set also considers outcomes and feedback from LCA analyses on the technology level. EN 15804 [23] served for the environmental analysis of technologies based on core rules for the product category and

Environmental Product Declaration (EPD). EN 15978 provided the calculation method for LCA of solution sets and buildings [24].

The performed technologies' LCA analyses are "decontextualised" from the building, its use destination, users, and their climate and cultural context [19]. Consequently, the analyses are cradle-to-grave but without consideration of an operational stage, which depends on the building envelope's characteristics and the final use destination. Differently, solution sets and PEB analyses are carried out through assessments that refer to a specific building within a particular climate and cultural context. With regard to solution sets, which are the focus of the provided investigation, these can be classified as a *functional system* and a group of building products for which the system boundary for the life cycle assessment follows the EN 15804 standard rules [23]. The functional system is defined and designed in a specific manner (Level of Detail – LOD - 400) to reduce the risks related to uncertainty or lacking information, typical of early design stages [25]. This also allows the selection of available EPDs corresponding to the considered technological components and guarantees the reliability of environmental information. A cradle-to-grave system boundary, which includes upstream, core, and downstream processes, is considered. The yearly energy balance will define the operational energy. The energy demand evaluation includes building operation and user behaviour (B6.3) [24] by considering occupancy, plug loads, and lightning usage. Other non-regulated building-related-technical systems (B6.2) [24] are not considered in the analysis; these include security and communication systems and e-vehicle charging (see Section 2.3).

Hence, the system boundaries of the analysis will therefore include the following lifecycle stages [24]:

- the product stage (modules A1-A3),
- Energy for building operation (module B6.1)
- User behaviour (module B6.3)
- the end-of-life (EOL) stage (C1-C4)
- benefits and credits due to recycling (D.1- D.2) (see Figure 3) [24].

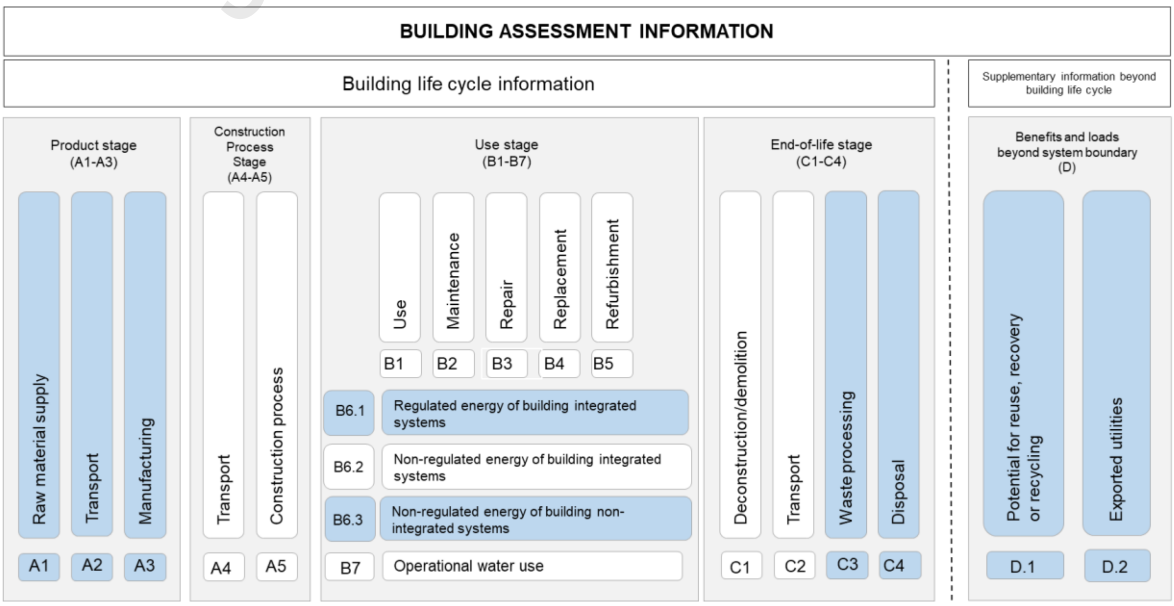


Figure 3. Life cycle stages are considered for the LCA of the technological components in a PEB based on prEN 15978 [24].

As for previous works [19], a 30-year assessment period is selected for solution sets as a simplification. This choice also solves issues related to the modelling of replacement and uncertainties due to the systems' lifecycle. A service life equal to today's technology is assumed. Furthermore, the technologies do not change their environmental profile over time to ensure a conservative approach.

As environmental KPIs, the Global Warming Potential total (according to EN15804 + A2[23]) is calculated for a) embodied impacts and b) over 30 years of building operation (see Table 1). The values are divided by the net surface area (NFA), expressed in m^2. This also represents the functional unit of the analysis. Differently from energy performance analyses, for environmental KPI, *negative* values refer to environmental credits, while positive values refer to are caused by resource consumption. For instance, positive energy balances lead to negative values of operational environmental impacts. Lastly, to assess environmental advantages due to environmental credits due to PV installations, the environmental payback period (PB) is calculated as a further environmental KPI. PB periods are estimated by considering dynamic national energy grids as suggested in the EU Reference Scenario 2020 [26] and carried out in previous works [19].

Table 1: Environmental KPIs definitions.

Environmental KPI	Description	Unit
Embodied GWP	GWP impact (according to EN15804 + A2[23]) of Production stage (A1-A3[24]) and end-of-life (C3-C4-D1[24]) of installed solution set.	kg CO_2 eq./m^2
Total GWP	Total lifecycle GWP (according to EN15804 + A2[23]) impact, including also 30 years building operation	kg CO_2 eq./m^2
Payback period (PB)	Time to pay back the initial environmental investment (due to installation of the solution set) through environmental credits (due to PV energy production). Dynamic energy grids are considered.	years

Overall, the approach aims to reduce uncertainties, which might lead to significant deviations in results, impact underestimations, and environmental credit overestimations.

2.2 Life cycle cost (LCC)

Through Life Cycle Costing (ISO 15686-5 [15]), a valuable technique is available for predicting and assessing the cost performance of constructed assets. Figure 4 shows the elements of LCC as part of the Whole Life cost (WLC). It is essential to mention that income, externalities, and non-construction costs are not part of the LCC. System boundaries of LCC analyses slightly differ from LCA. Due to a lack of information, the end-of-life costs of the investigated systems are not considered within system boundaries. Therefore, the information accounts for construction, operation and maintenance costs. Unlike LCA, maintenance is considered, as deemed relevant, regarding their associated costs.

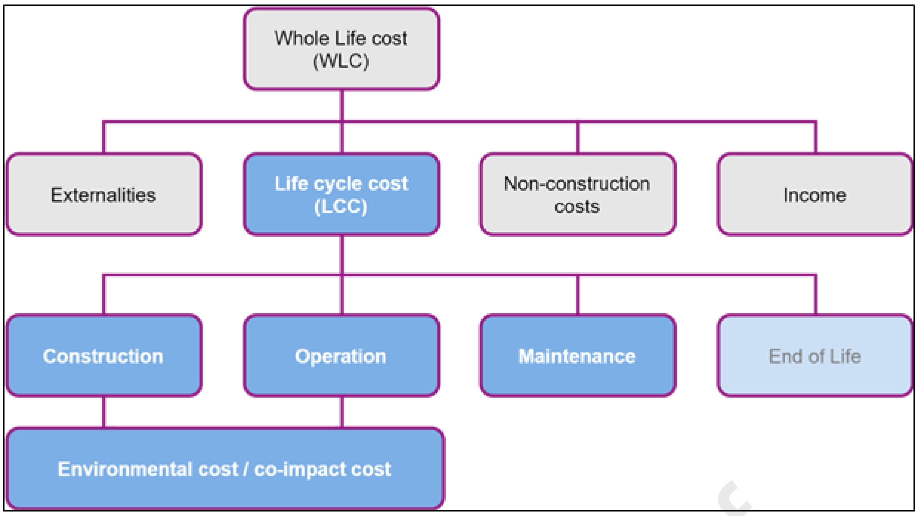


Figure 4. Scheme for Life Cycle Cost (LCC in blue) following ISO 15686-5 [27].

The economic efficiency of investments can be established with various methods, e.g., based on net present value (NPV), annuity, internal rate of return, amortisation, or by using a complete budget plan. According to ISO 15686-5:2017 [27], the LCC of a building is the NPV, which is the sum of the discounted costs, revenue streams, and value during the phases of the selected life cycle period. In this work, the authors refer to the VDI guideline 2067 [28] and the annuity method. The annuity procedure allows for summarising both one-off payments/investments and ongoing payments during a specific observation period using the annuity factor *a*. It also includes a price increase factor and considers the residual value. Costs are subdivided into one-off costs and current costs. The total annual costs are the annuity of the total costs over the observation period, set at 30 years.

Table 2. Economic KPIs definitions.

Economic KPI	Description	Unit
Investment cost	All initial costs that need to be covered until an energy efficiency measure is fully implemented	€/m^2
Capital cost	Capital-related costs, including investment and replacement	€/m^2
Operation-related cost	Energy cost, operational cost, revenues from energy sales	€/m^2
Maintenance cost	Maintenance and service cost for technical building services: heating, cooling, ventilation, electricity from PV	€/m^2
Life Cycle Cost (LCC)	Value of the total annual cost of building usage for the whole calculation period (annuity)	€/m^2

Table 2 reports the economic Key Performance indicators (KPI) selected for the assessment of CULTURAL-E building systems. Initial investment refers to the costs related to the implementation of the measure. Together with replacement expenditure, these are capital costs. In particular, replacement due to a limited service life of the technical components can be significant over the entire service life and is deemed as capital cost. The analysis is based on standard values from EN 15459-1:2018 [29] that provide yearly maintenance costs for each element, including operation, repair, and service, as a percentage of the initial construction cost. As an advantage, the standard also provides a detailed breakdown of the HVAC and electrical systems costs, which are relevant for assessing solutions sets and PEBs. The savings from the self-use of the produced energy and the revenues from selling are considered.

As for LCA analyses, all costs are divided by the building's NFA (expressed in m²). For all other construction costs, the level of detail is lower and based on area-specific data. Furthermore, negative values also refer to environmental losses, while negative values are used for credits.

Cost information is extracted from national statistics and direct producers' information to use more reliable information. Key issues that can affect LCC results and are significant sources of uncertainties are cost fluctuations. For this reason, this study assumes that discount and price increase rates are 1.0% for all costs, which is a value consistent with the current interest rate situation and its forecast. This choice also allows us to obtain conclusions based on cost differences among variants deemed more relevant for the study. These are not affected by the used rates.

2.3 Solution set parametric modelling and energy simulations

The procedure for the parametric modelling of solution sets is described in Figure 5 and entails three main phases:

- The *building energy simulation* activities deriving the operational energy balance.
- A *user energy profile modelling* for the estimation of user-related energy consumption.
- The *extraction of the bill of materials,* i.e., the derivation of components' materials and quantities.

Parameters of the first stage entail the power and capacity of the technical installation components and building envelope characteristics dictated by climate conditions. The parameter for the second stage is the final user energy consumption, which is dictated by climate data and building type. The power and capacity of the technical installation components are also used to extract the bill of materials.

Details regarding the building simulation activities and user energy profile are described in the following section. Details regarding compiling the bill of materials and data requirements are described in the section. The results of these three phases allow for the compilation of the life cycle inventory, described in Section 2.4.

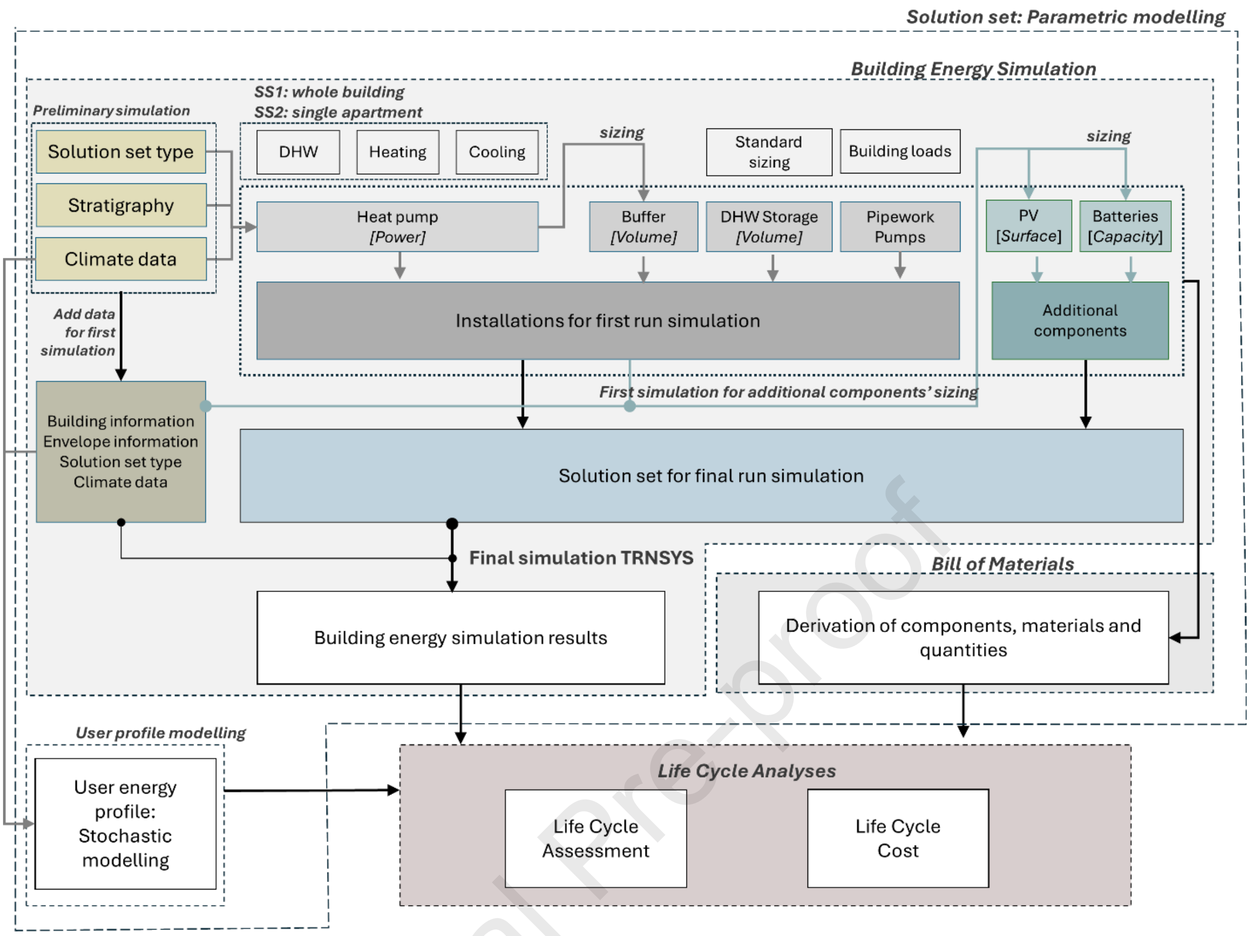


Figure 5. Procedure for parametric modelling of the solution set.

Building Energy Simulation

The building simulation models are built to assess the building energy performance throughout one whole year, with a default time-step of 5 minutes. The building operational energy is derived by accounting for total energy demand due to the following main contributions:

- Domestic Hot Water (DHW)
- Space Heating (SH)
- Space Cooling (SC).

Accordingly, considering all thermal losses, the useful thermal energy provided to the building-end users (DHW + SH + SC) is calculated (Qth_user). Qth_TE is the thermal energy generated by the generator (e.g., Qth_HP if the power generator is a heat pump) for DHW, SH and SC. Furthermore, the final energy uses (Qel) is derived. This includes:

- appliances (APL),
- lighting (LGT),
- ventilation (VEN),
- distribution (DIS)
- auxiliary energy (AUX).

The building energy simulation activities can be divided into three main sub-phases. Each simulation consists of 3 different energy simulations. A preliminary one serves for the derivation of heat pump power and is carried out in ideal conditions (constant setpoints for heating and cooling) without considering the energy system information, but only building geometry, stratigraphy, and climatic data. In this simulation, information regarding the thermal load of the building is collected, and the nominal heat pump power can be defined. The heating and cooling storage volume is sized based on heat pump power, while standard sizing is considered for the DHW storage. Pipework and pumps are modelled based on building loads and the heat pump's previous sizing. Afterwards, a first simulation is run by considering a first solution set, which does not entail photovoltaics and batteries for energy gains. Based on this energy simulation results, it is possible to derive PV surfaces (m^2), power (kWp) and battery capacities (kWh). The sizing of the PV system and battery was performed through a tool that optimises both techno-economic and energy indicators, such as self-consumption and self-sufficiency, considering the goal of reaching a PEB building [30].

The final solution set is modelled by considering building and envelope information, solution set type and climate data. The climatic context uses climatic data taken from Meteonorm [31]. This database allows for considering future weather forecasts to account for future climatic variations and reduce uncertainties due to climate change. Information related to the building envelopes is also considered according to national regulations. If applied to the building system, external venetian blinds are considered shading systems and a Rule-Based control strategy is used to regulate the solar radiation entering the building. This depends on the indoor temperature, solar radiation, and occupancy. Natural ventilation is also modelled as complementary to mechanical ventilation. Ceiling fan use is considered by shifting the indoor air temperature setpoint during mid-season and summer, according to the work of Babich et al. [32]. The heat pump's performance is assessed according to performance maps provided by the manufacturer. According to standard EN 14511-3 [33], the maximum allowed uncertainty for the declared heating or cooling capacities is 5%. Finally, since the energy simulation results depend on the control strategy applied to the system, their variations impact the energy simulation results and the following LCA and LCC analyses. To reduce this uncertainty, the authors selected the setpoints according to technical standards and typical values of the different geo-clusters. The control is kept as simple as possible, using only setpoints and dead bands to define the hysteresis.

User energy profile modelling

The user behaviour is implemented through different profiles for occupancy, plug loads and lighting usage by applying a stochastic approach, as presented by Zambrano et al. (2021) [34]. This model considers the open-access database developed within the International Energy Agency Energy in Building and Community (IEA-EBC) Annex 79, “Occupant-centric building design and operation”, and allows for the generation of stochastic occupant behaviour profile sets to represent the internal gains for the dwelling in the dynamic simulations. Accounting user behaviour ensures a more realistic assessment of operational energy consumption energy. In the study, energy consumption due to e-mobility is not included. In fact, these are deemed energy consumption external to the building's physical boundaries, and they are considered an additional energy carrier. Furthermore, vehicle consumption is related to the number of vehicles and the extent of travel, which may vary considerably for different users [35,36]. Lastly, even though an e-vehicle charge can provide flexible options to the building, an in-depth investigation of charging behaviour patterns and the overall charging infrastructure is needed.

Table 3 presents the results of the building energy simulation and user energy profile derivation activities. The estimated energy credits (positive value) are summed to the derived total energy demand (negative value). When the calculated total energy balance is *positive*, the functional system produces more energy than its demand. Therefore, it is aimed at PEBs.

Table 3. Operational energy contributions simulated. Specifications.

Contributions for B6	Description
Qth_user	Thermal losses
Qth _ HP	Thermal energy generated for DHW, SH and SC
Qel_APL	Appliances
Qel_LGT	Lightning
Qel_VEN	Ventilation
Qel_DIS	Distribution
Qel_aux	Auxiliary energy
PV pre-sizing	Estimation in terms of power and surface
Total energy demand	Energy demand (negative)
PV credits	Energy credits (positive)
Energy balance	**Total energy demand + PV credits**

To reduce uncertainties related to building energy simulation results, the buildings' models were developed with the help of TRNSYS v.18.02 [37]. This tool is considered a white box model, thus ensuring more accurate results than grey or black box models [38,39]. This software is widely recognised for its accuracy in energy simulations.

2.4 Compilation of Bill of Material and data requirements for LCA and LCC analyses

Data collection for solution sets follows technologies-related conditions and the Bill of Materials (BoM) provided by solution set designers. These data should be defined according to geographical representativeness, technical representativeness, and time representativeness.

The agreement between LCA, LCC experts, and designers aims to specify parameters for LCA and LCC analyses based on dynamic building energy simulations, as described in the previous sections. These, in turn, facilitate matching between the information provided by the design of solution sets and the available environmental [40,41] and cost datasets (see Table 4).

Table 4. Solution sets' components. Data requirement for the compilation of Bill of Materials based on parametric modelling.

Component	Technical specifications	Parameter provided for LCA	Parameter provided for LCC
PWG	PWG type (heat pump, boiler), Specify destination (heating, DHW)	• Power (in kW) • items	• Power (in kW)
TES	• Storage Material • Storage Containment material • Insulation material • eventual information on Heating/Cooling buffer and its insulation	• Storage volume (containment estimated based on previous works) • Insulation material amount • Buffer volume + estimation on insulation	Included in PIP
DISTR	Type (fan coils, radiators, etc)	• Items • (if fan coils) power • (if underfloor heating) surface	Surface-specific values of a typical installation
VEN	Ventilation system description	Further information on capacity	Surface-specific values for typical installation
PIP	• Pipes material • insulation material for pipework	Ø x amount x length (ex. ø38mm x 10m)	Surface-specific values of typical installation, including TES
PV+ Battery	Assumed: Average technology with battery, sized to provide a positive balance	Surface estimations	• installed power • capacity of the battery
HMS	Included for energy simulations	Not considered	Surface-specific values

Product-specific datasets, e.g., EPDs, are preferred as a basis of the assessment. The cost parameters are surface-specific and include not only the material costs but also the costs for installation in the building. These account for the fact that both cost shares, material costs and installation costs, are country-specific. Since companies do not usually report the cost shares separately, the cost can be presented only in aggregated matters. The surface-specific costs are based on the designer's experience from recently realised projects.

The total energy demand is quantified for the use stage based on Table 3, and the PV energy credits are provided. These parameters are afterwards matched with information regarding the national energy grid's environmental profile and costs (see Table 5). In this work, for LCA, the environmental profile of the energy mix is considered variable: its variations refer to the EU Scenario 2020 [26] and the estimated decarbonisation rates of each country considered. For cost analyses, a national price increase of 1.0% and a discount rate of 1.0% are considered. When comparing the variants, it is not primarily the absolute amount of the total annual costs that is decisive, but rather the resulting difference between the variants. The assumption of discount rates depends on the current interest rate situation and its forecast; therefore, it fluctuates greatly depending on individual assessments and the economic situation. For this reason, a low value of 1% is selected for the discount factor. A variation of this rate will not affect differences between the two solution sets since the capital costs increase as the discount rate increases. The same applies to higher price increase rates. If a higher price increase is assumed for energy prices compared to the general price increase, the share of energy costs increases. Absolute values change, but differences between several options will not be affected.

Table 5. Energy balance. Technical specifications and parameters were provided for LCA and LCC analyses.

Energy balance	Technical specifications	Information for LCA	Information for LCC
Total energy demand	kWh/m²*y Positive value	• Environmental profile of the national energy grid[40,41] • Decarbonisation rates based on [26] for dynamic assessment	• National energy prices for standard basic tariffs • Price increase
PV Credits	kWh/m²*y negative value		
Energy balance	Total energy demand + PV credits		

Data collected for the 16 case studies are presented in two dedicated annexes (Annex 1. Data collection for LCA and LCC analyses and Annex 2: Comprehensive results of dynamic simulations for LCA and LCC analyses.

3 Case study

In this section, the case studies are described to specify the goals and scope of the analyses and to perform the compilation of the life cycle inventory (LCI).

3.1 Goal and scope of the analyses

Two building archetypes were considered: a low-rise and a high-rise building, representing the two main typologies of multi-family residential buildings in the European building stock.

The low-rise building is a 3-storeys building with 7 apartments (total net area of 663 m^2). Each apartment is divided into two thermal zones (day and night). The average temperature of the two zones is used to activate the heating and cooling units (Figure 6).

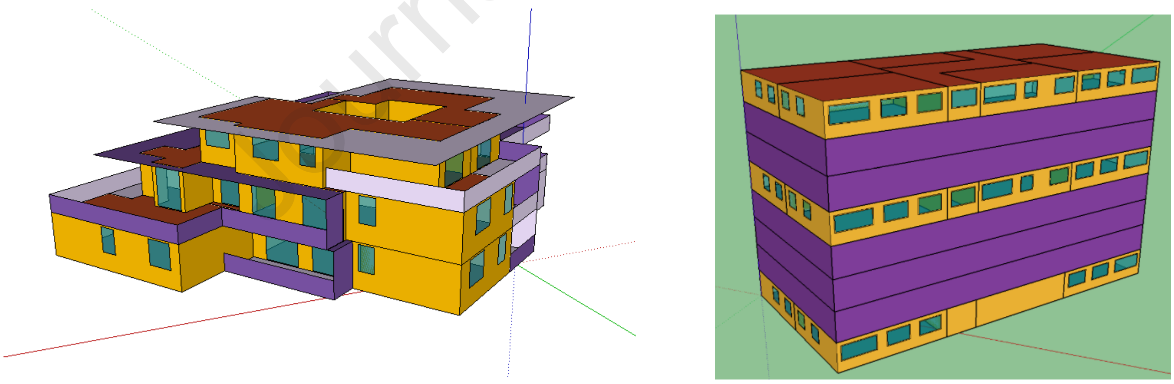


Figure 6. Low-rise (left) and high-rise (right) building archetypes.

The high-rise building is a 7-storey building with 6 apartments for each floor except for the ground floor, which has 4 flats (total net area of 2912 m^2). Each apartment is considered a single thermal zone with one thermostat used to activate the heating and cooling units.

Two solution sets are identified to represent the two main typologies of technological solutions: one centralised and one decentralised technical installation concept (Table 6). These solution sets are derived from designers' experience and everyday praxis.

Table 6. Solution sets description and technologies' specifications.

System/service	Technology	
	Solution set 1 (centralised)	**Solution set 2 (decentralised)**
Ventilation (VEN)	Decentralised ventilation system	
Power Generator (PWG)	Centralised Heat Pump unit	Compact decentralised Heat Pump unit
Space heating (SH)		
Space cooling (SC)		
DHW		
Thermal energy storage (TES)	Stainless steel storage with XPS insulation and buffer.	
Air movement	Ceiling fan	
Pipework, Valves, Circ. Pumps, Heat Exchanger (PIP)	Copper pipelines with XPS insulation: stainless steel valves, circulation pumps and heat exchanger	
Photovoltaics system, battery (PV)	Monocrystalline silicon cells; Lithium iron phosphate (LiFePO4) battery	

The modelled energy systems comprise the following elements: an air-to-water heat pump that generates heating and cooling, a water-based thermal energy storage system for DHW and a buffer tank to provide thermal inertia for space heating and cooling (see Annex 1. Data collection for LCA and LCC analyses).

Each of the designed concepts is analysed in 4 reference cultural-climate contexts, i.e.:

- Mediterranean (Italy – IT),
- Continental (Germany – DE),
- Oceanic (France– FR)
- Subarctic (Norway– NO).

In total, 16 case studies are collected and summarised in Figure 6, together with the acronyms that are consistently used in this work.

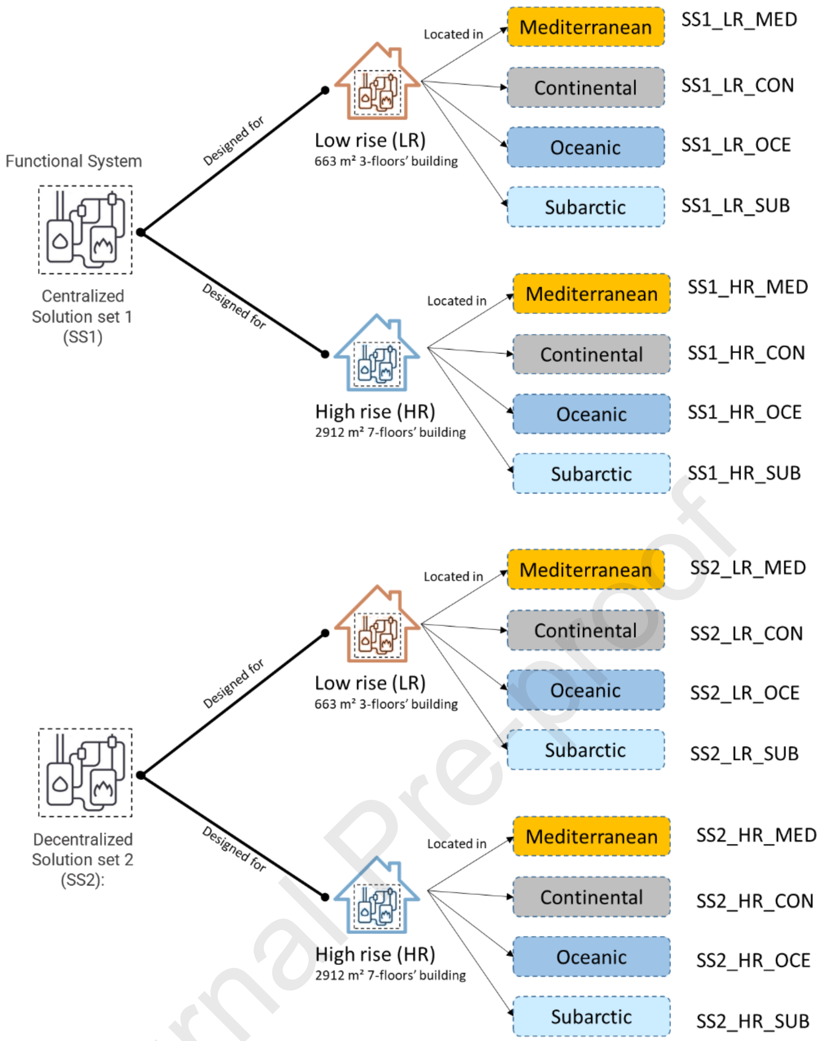


Figure 7. Overview of the collected case studies.

3.2 Dynamic building energy simulation: Specifications provided for presented case studies.

For dynamic building energy simulations, the established profiles are differentiated for the different geo-clusters following cultural and constructive aspects, according to Figure 6.

Building envelope characteristics are consistently tuned based on their respective geo-cluster regulations (Table 7). These refer to the transmittance (U-Value) of external walls, roof, ground floor, and windows required in the Italian, German, French, and Norwegian design regulations, respectively.

Table 7 Building envelope characteristics. U-value parameters for each geo-cluster.

Geo-cluster	Reference Country	U-VALUE External Wall [W/m²K]	U-VALUE Roof [W/m²K]	U-VALUE Ground floor [W/m²K]	U-VALUE windows [W/m²K]
Mediterranean	Italy	0.18	0.12	0.12	2.89
Continental	Germany	0.13	0.09	0.11	1.12
Oceanic	France	0.25	0.12	0.25	1.3
Sub Artic	Norway	0.10	0.08	0.09	0.76

In Table 8, the characteristics of PV systems are outlined. These refer to the required nominal power, the panels' slope, and the number of necessary panels. The three characteristics are specified for the panels installed on the roof and southeast (SE) and southwest (SW) façades. Finally, an estimation of the capacity of installed batteries is provided.

Table 8 Characteristics of the PV system (nominal power, slope, and number of panels).

		Mediterranean		Continental		Oceanic		Sub-Artic	
	unit	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**
Nominal power roof	[kW]	17.7	34.0	17.7	34.0	17.7	34.0	17.7	34.0
The slope of the panels' roof	[°]	37.0	44	37.0	44	38.0	44	44.0	44
Number of panels on the roof	[-]	77	148	77	148	77	148	77	148
Nominal power SE façade	[kW]	9.4	62.5	9.4	65.9	9.4	68.0	8.5	68.0
Panels on SE façade	[-]	41	272	41	287	41	296	37	296
Nominal power SW façade	[kW]	5.5	0	5.1	39.7	5.5	39.7	5.5	39.7
Panels on SW façade	[-]	24	0	22	173	24	173	24	173
Nominal power NW façade	[kW]	-	39.7	-	0	-	67.3	-	65.3
Panels on NW façade	[-]	-	173	-	0	-	293	-	284
Capacity of the battery	[kWh]	46.0	48.7	42.7	128.5	63.6	108.0	16.2	167.0

The different building surface area to volume ratio (S/V) implies different thermal behaviours. Moreover, the specific roof surface, normalised to the total surface area of the dwellings in the high-rise building, is smaller compared to low-rise if normalised to the total surface area of all the houses, so PV integration in the high-rise building roof is limited, with relevant implications on essential KPIs such as the self-sufficiency and the self-consumption. The stochastic approach outlined in Section 2.3 is used to model the occupant behaviour, particularly for the appliances' energy consumption and, consequently, the relative internal gains [34].

4 Results and Discussion

The results presented here follow the approach outlined in Section 1 and Figure 1. Results are first presented for each domain and then coupled. The results' clustering and the final solution set evaluation are presented in Section 4.4.

4.1 Dynamic building energy simulation

Table 8 provides results from dynamic energy simulations for the 16 case studies. Values marked with green indicate negative energy balances (energy KPI), denoting cases aiming at PEBs. Values marked in orange refer to case studies in which PV credits did not cover the whole building's energy demand. Other surfaces aimed at the PV module must be spotted for these specific cases.

Results of the dynamic simulation demonstrate that for only 5 out of 16 case studies, PEBs' performance is potentially reached. These refer to case studies that have centralised solution sets for low-rise buildings. In the case of decentralised solution sets, PEBs' performances are achieved only for Mediterranean low-rise buildings. This is primarily due to the high PV credits coming from high solar yields. Regarding the results for SS1, despite similar PV credits, Oceanic and Subarctic cases have higher total energy demands, which consequently affects the total energy balance. In the Subarctic case, the higher total energy demand is caused by a much higher space heating demand due to a colder climate and a higher temperature setpoint used in the simulation [42] [43].

Table 9. Energy simulation results for the 16 case studies.

Energy simulation results (kWh/m²*y)			Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
SS1	**LOW RISE**	Total energy demand	-52	-53.6	-61.8	-62.5
		PV credits	+72.35	+72.42	+72.38	+72.45
		Energy balance	**+20.4**	**+18.8**	**+10.6**	**+10.0**
	HIGH RISE	Total energy demand	-42.2	-44.6	-62.7	-53.1
		PV credits	+36.28	+36.26	+36.24	+36.28
		Energy balance	**-5.9**	**-8.3**	**-26.5**	**-16.8**
SS2	**LOW RISE**	Total energy demand	-58.39	-64.89	-69.30	-78.42
		PV credits	+61.80	+48.07	+40.24	+41.66
		Energy balance	**+3.4**	**-16.8**	**-29.1**	**-36.8**
	HIGH RISE	Total energy demand	-54.5	-63.3	-71.6	-74.7
		PV credits	+46.26	+41.01	+45.00	+45.96
		Energy balance	**-8.2**	**-22.3**	**-26.6**	**-28.7**

In the Oceanic climate, the higher total energy demand is mainly caused by a higher energy consumption of the appliances. From the stochastic approach used to define the occupancy profile of the building and the energy consumption due to lightning and appliances, it emerged that in the Oceanic case, the energy consumption due to the appliances is about 30% higher than in the other climates. On the one hand, this increases the total energy consumption of the building; on the other hand, this increases the space cooling demand and decreases the space heating demand of the building because part of this consumption is transferred as heat to the building. Nevertheless, the net effect is an increase in the total energy consumption of the building [43].

4.2 LCA Analyses – Environmental KPIs

As shown in the LCA results of Table 10, constructive aspects and embodied impacts can significantly influence the overall life cycle impact assessment (LCIA), and photovoltaic modules are the main contributors. By accounting for embodied impacts only, HR buildings perform better regarding environmental profile. This is due to an optimised installation of components and a larger NFA for a given building footprint. Cases with SS2 have slightly higher environmental impacts due to the higher number of technical components, such as heat pumps.

Operational impacts related to energy demand only are higher in continental/subarctic climate areas and low-rise buildings. High-rise buildings present in this respect also optimised thermal energy and electricity consumption. However, due to a higher number of potential users and a more limited roof surface, they should use other surfaces, aiming at a positive energy balance. This is also valid for most decentralised concepts, in which only the low rise in the Mediterranean context reaches a positive energy balance (Table 11).

Table 10. Results of LCA analyses for the 16 case studies. Global Warming Potential (GWP 100 ys in kg CO_2) – Embodied impacts.

	Component	LR	HR
		GWP [kg CO_2 eq.]	GWP [kg CO_2 eq.]
SS1	PWG	1057.71	1.60
	TES	891.81	1.35
	DIS	84.46	0.13
	PW	3152.08	4.75
	VEN	4212.40	6.35
	Tot. embodied [impact/m²]	**111.8**	**57.36**
	Tot. embodied [impact/m²*y]	**3.802**	**1.811**
SS2	PWG	2423.81	3189.49
	TES	1185.52	5884.73
	DIS	113.59	507.65
	PW	4691.00	5959.98
	VEN	627.85	177.27
	Tot. embodied [impact/m²]	**126.6**	**55.49**
	Tot. embodied [impact/m²*y]	**4.221**	**1.850**

Table 11. Results of LCA analyses for the 16 case studies. Global Warming Potential (GWP 100 ys in kg CO2) – Operational impacts.

National Electricity mix	**Mediterranean (IT)**		**Continental (DE)**		**Oceanic (FR)**		**Subarctic (NO)**	
[kg CO_2 eq./kWh]	0.285		0.337		0.057		0.027	
SS1	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**
[kg CO_2 eq./m²*y]	-5.80	1.69	-6.34	2.81	-0.60	1.51	-0.31	0.52
SS2	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**	**LR**	**HR**
[kg CO_2 eq./m²*y]	-0.97	2.35	5.67	7.52	1.66	1.52	0.99	0.77

As the LCA results prove, PV modules are expected to contribute mainly to the total assessed solution sets' embodied impact. Therefore, the environmental performance of PEB's solution sets should be evaluated with respect to their production of renewable energy. Regarding environmental impacts and GHG emissions, they allow credits by avoiding emissions related to energy consumption from non-renewable sources in the national energy mix. In Figure 8, PB periods are computed by considering dynamic national reference scenarios [26]. In Figure 9, these are calculated by considering an average European scenario [26]. For both figures, cases a) and b) report results for low-rise buildings, with SS1 and SS2, respectively. Cases c) and d) show results for high-rise buildings with SS1 and SS2.

Over 30 years of service life, cases reporting negative operational impacts can reduce their total initial environmental investment. Such an investment can, in some cases, even be paid back in the next 30 years. This occurs in the Italian and German examples with centralised solution sets in low-rise buildings. Despite their negative operational energy balance, Norwegian and French cases cannot significantly reduce their environmental profile. This is due to their national energy grid, which has a hydropower and nuclear baseline. Both energy sources present low carbon intensities, and, in this sense, PV installation does not provide high advantages to the national energy mix's CO_2 environmental profile.

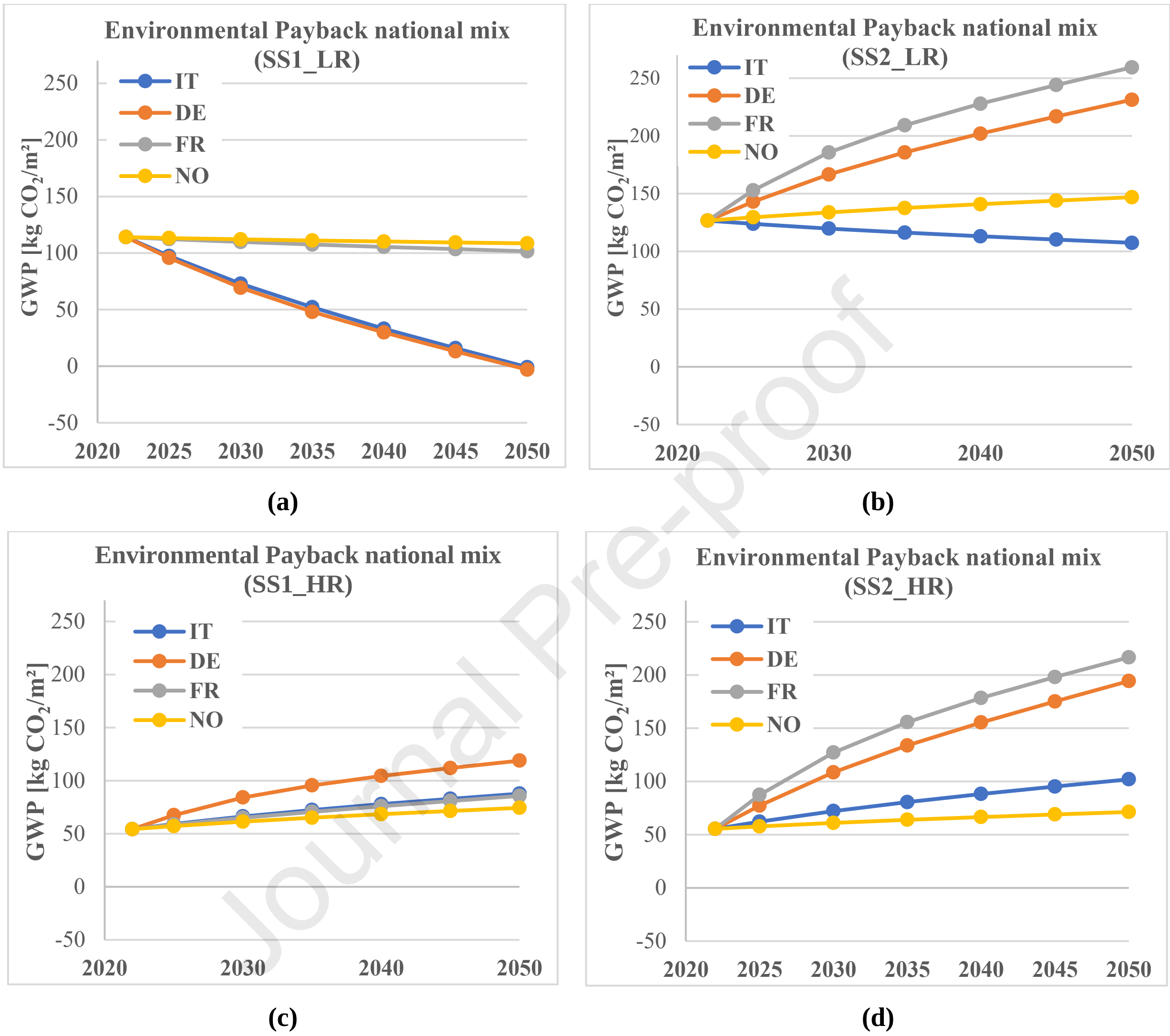


Figure 8. Environmental Payback (PB) period of a) centralised solution sets (SS1) and b) decentralised solution sets (SS2) based on the environmental profile of the national energy mix.

When both SS1 and SS2 are installed in high-rise buildings, a significant increase in emissions is recorded over the period considered, especially for the German demo case, due to lower energy credits and carbon-intensive energy mix. In Figure 8 d), the French example also presents high lifecycle impacts due to increased energy consumption. Italian and Norwegian high-rise buildings with the two different solution sets do not show significant variations.

Supposing the same solution sets allocated in the same geographical context but with an average energy mix production, CO_2 eq. reductions increase significantly (see Figure 9. a). Regarding results for decentralised systems, in this case, the Italian demo case can slightly decrease their initial environmental impact. In contrast, this value can increase significantly for other cases, such as German and French cases. In Germany, this is due to the carbon intensity of the national grid, while in France, this is due to high energy consumption. In fact, by considering the average European mix instead of their national one, the French demo can further increase its total GWP, while for the German demo case, such a variation is still like the previous one. The Norwegian demo case can also show slight variation when calculated with the national grid.

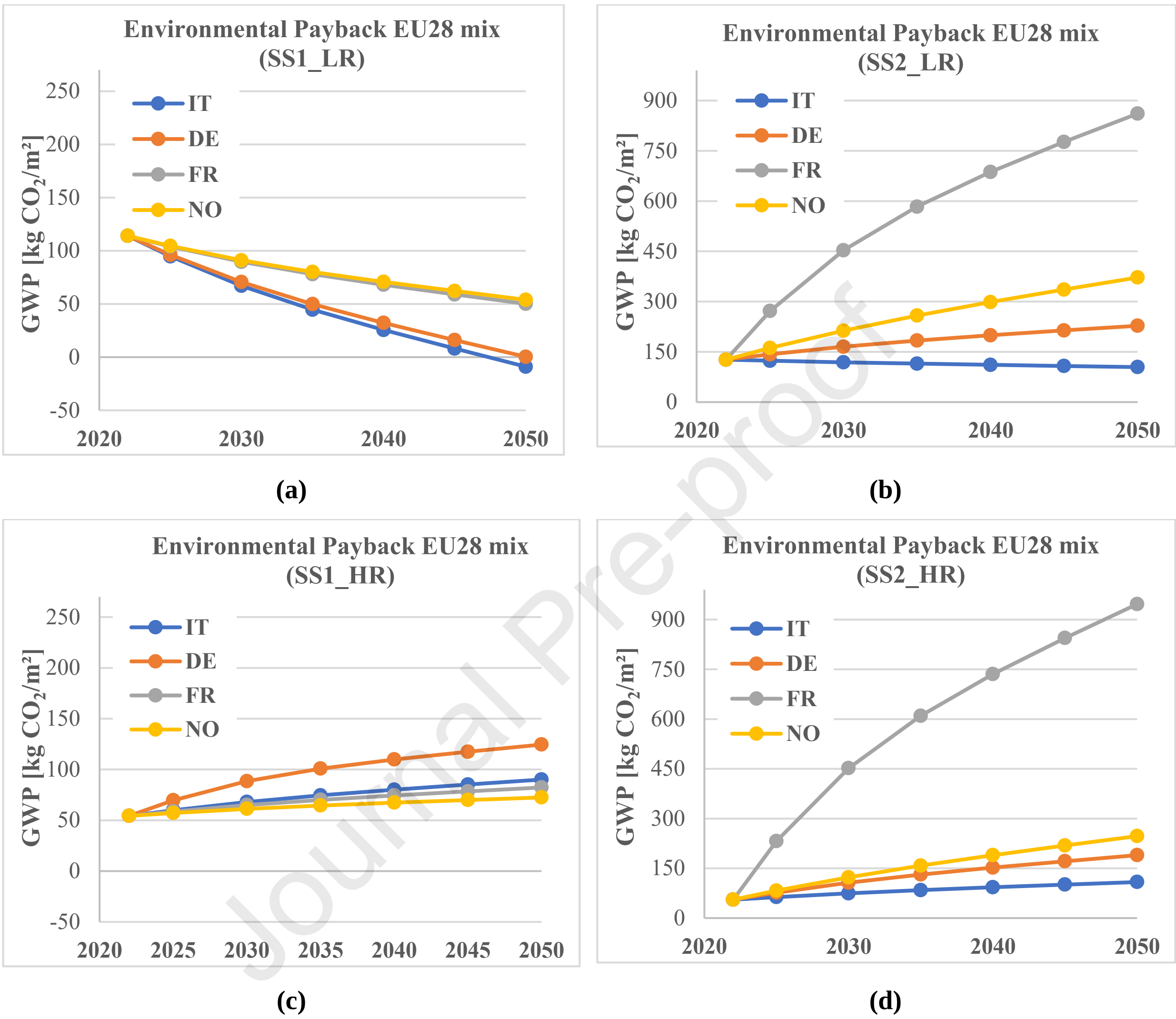


Figure 9. Environmental Payback (PB) period of a) centralised solution sets (SS1) and b) decentralised solution sets (SS2) based on the environmental profile of an average European energy mix.

In the hypothesis of an average energy mix production, the total GWP will consequently increase. Concerning results for HR buildings, there are no cases in which emissions reductions are recorded. All examples increase their impacts over time.

4.3 LCC Analyses – Economic KPIs

First, the initial investment cost analysis of the solution sets shows that prices are country-specific. Further, it can be noticed that, especially for high-rise buildings, the cost for SS2 is significantly higher than that of SS1, as seen in Figure 10. The reason for this lies in the decentralised concept approach of SS2, in which the heat pumps and the battery are installed separately for each apartment. In addition to the investment costs, the costs for maintenance and servicing are also higher, as instead of one central device, many individual machines must be serviced in the apartments. Except for the subarctic region, the specific costs with SS1 are lower for high-rise buildings than for low-rise buildings. There is a shift in the cost shares of ventilation and heating, as the decentralised appliances are assumed to be combined appliances that ensure the heating and ventilation function. This reduces the costs of the ventilation system. Finally, cultural (user-related) differences can be seen in the level of equipment used by HMS. These costs are summarised under "Other building services" and are higher in the subarctic region.

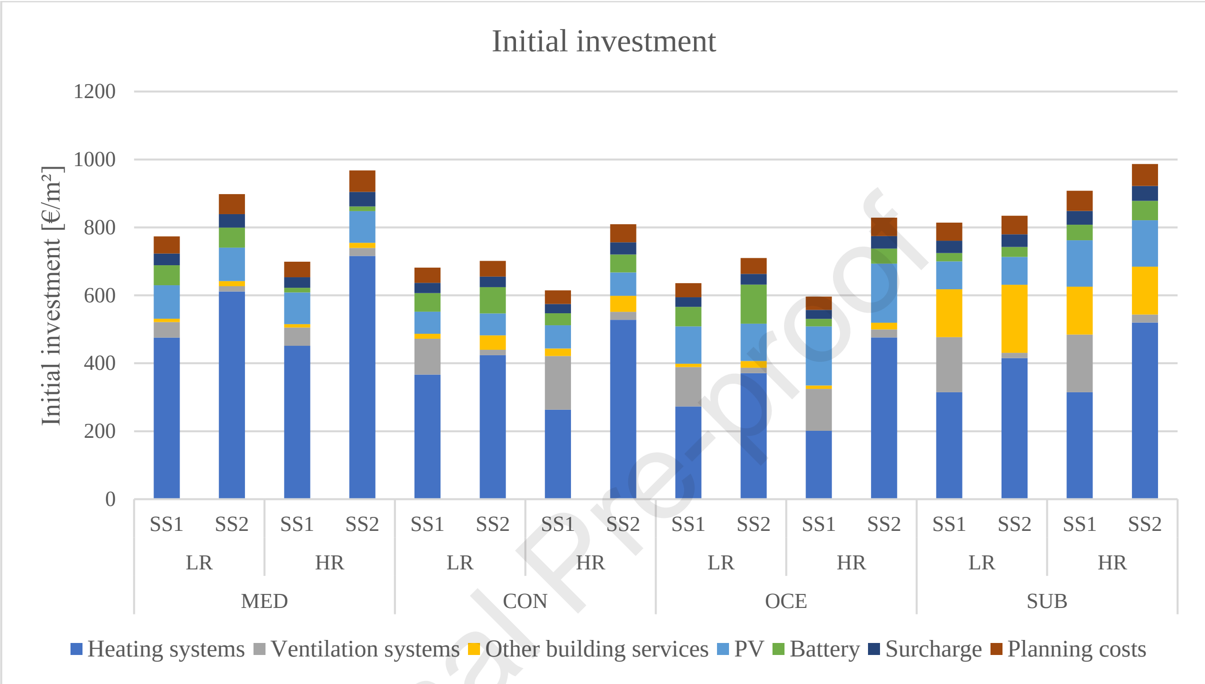


Figure 10. Initial investment of the studied solution sets in the four regions.

Total annual costs are compared in Figure 11 and Figure 12. The capital costs also include replacing the appliances at the end of their service life. The limited service life of the heat pumps (15 years), the ventilation units (20 years) and the battery, with a life expectancy of only 10 years, significantly influence the capital cost. In the LR building, we cannot find a clear difference between SS1 and SS2 in capital cost for heat pump and ventilation units (30-35%). In contrast, with SS1 of HR-Building, the percentage of capital cost for the heat pump and ventilation units is about 20% to 30%, while in SS2, it is about 40 %. This results in a clear economic disadvantage for the decentralised variant of SS2 in the HR-Building, as many individual appliances must be replaced.

The different revenues from the marketing of surplus energy are due, on the one hand, to the different electricity prices of the countries investigated and, on the other hand, to the very different remuneration for grid feed-in (see Table 12).

Table 12: Electricity prices and remuneration for grid feed-in the four considered locations.

		IT (MED)	DE (CON)	FR (OCE)	NO (SUB)
electricity price	€/MWh	250	380	245	209
renumeration for grid feed-in	€/MWh	50	66	100	5

In addition to the local differences in energy prices, this reflects the country-specific legal framework conditions for electricity marketing. In variant SS2, the higher energy demand due to the setting is also reflected in the prices.

If we look at the resulting specific total annual costs, these are lower for SS1 than for SS2 in all cases. For SS1, the total yearly price is lower in all regions besides the subarctic area for the HR building than for the LR building. SS2, on the other hand, shows an inverse effect with higher specific total annual costs for the HR building compared to the LR building.

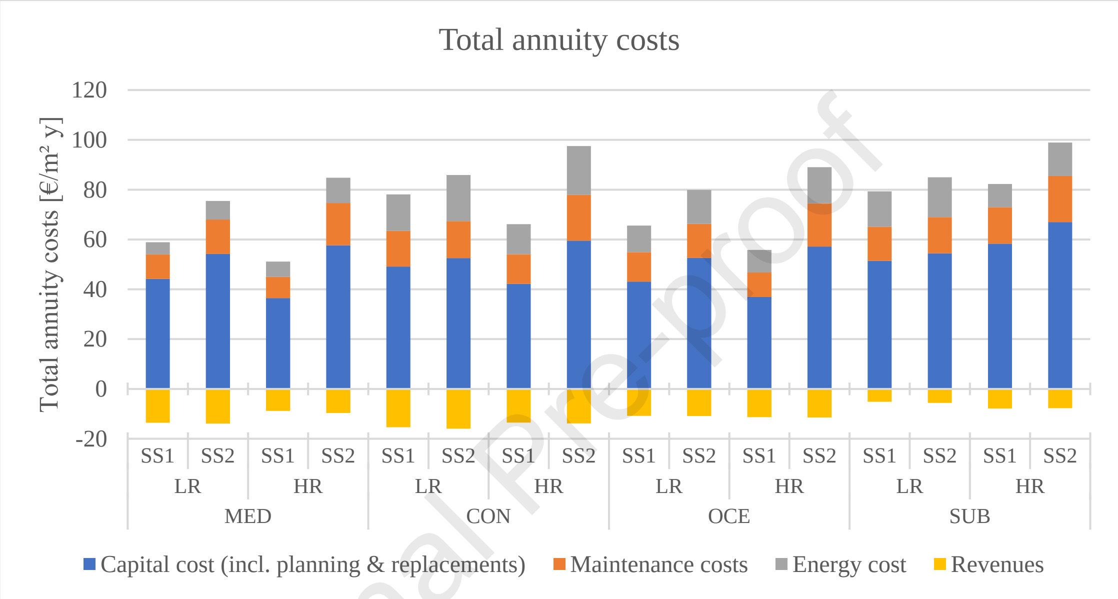


Figure 11. Total annual cost (annuity) broken down by group.

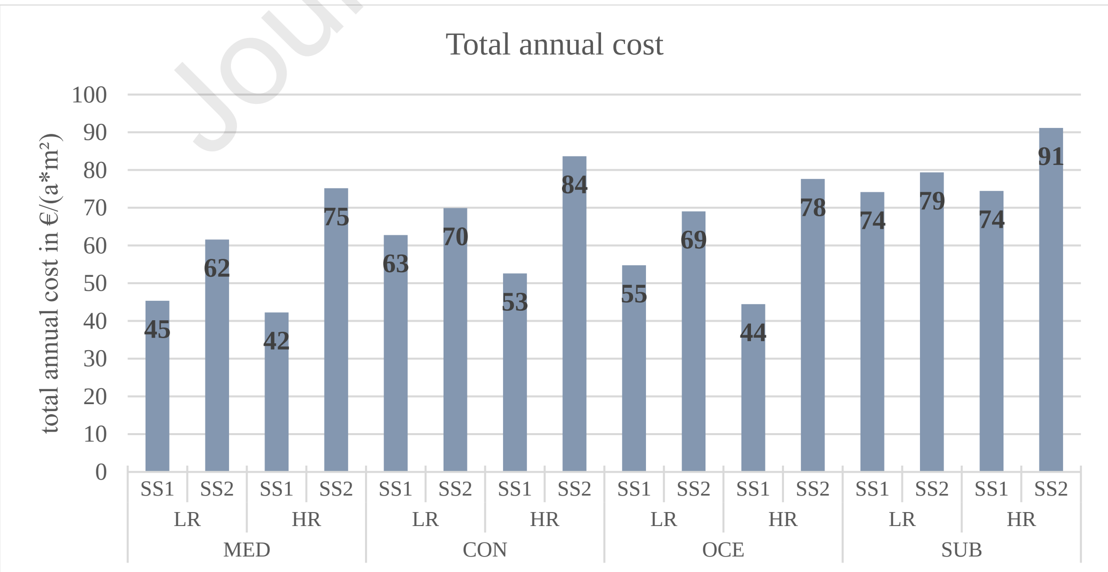
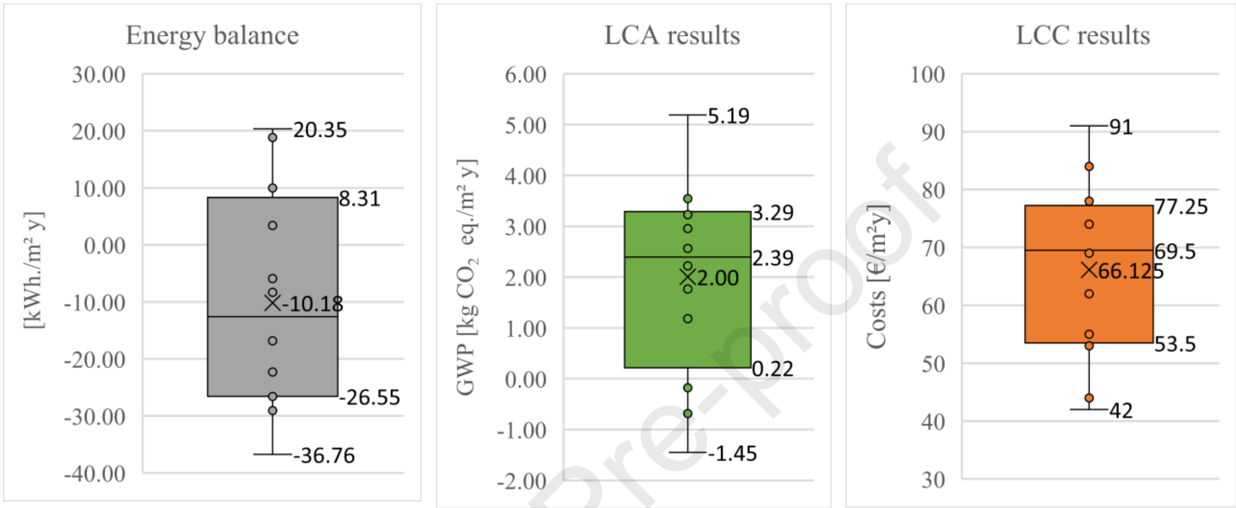


Figure 12. Total annual cost (annuity) considering all costs and revenues.

4.4 Multi-domain analysis and overall evaluation

In the following section, results from energy balance, LCA and LCC are jointly investigated to find the best and worst cases and identify trade-offs between energy performance and environmental and economic quality. For the Energy balance, the selected KPI is the total energy balance. For the environmental domain, the annual GWP is used (results of Figure 8 are divided by 30 years of service life). For the economic one, the total yearly cost is considered (results presented in Figure 12).

As a first step, all results coming from each analysis are collected, and statistical records are derived. These are minimal, maximal, median and average values. Median values are shown with an x marker. The average value is displayed with an inner line of the square and will be used afterwards for the multi-domain assessment. The square refers to the range of values between 15% and 85% cumulative probability of occurrence.

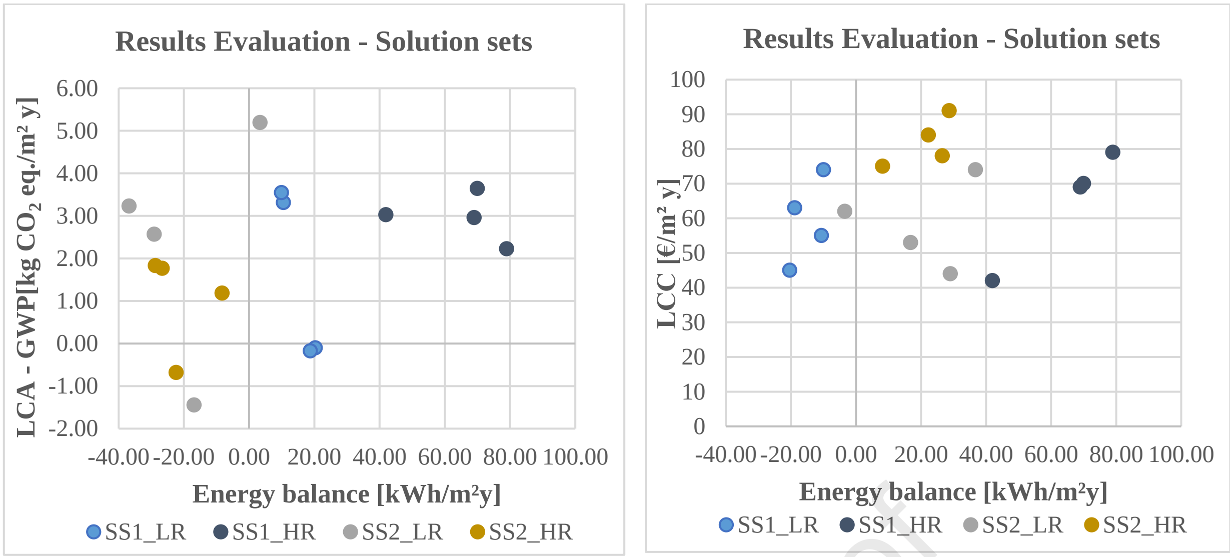


(a) **(b)** **(c)**

Figure 13. Statistical records of multiple case studies investigation. a) Energy balance; b) LCA results (GWP100ys); c) LCC results (total annual cost).

Higher variations are recorded for the results of energy balances and environmental impact analyses. Most of the examples for energy balances do not reach a positive balance. Despite the high variations, impact values can be deemed low for environmental studies. As demonstrated in section 4.2, these values can be significantly reduced using PV modules with lower embodied impacts. Cost analyses (section 4.3) revealed that the potential for improvement lies in capital and maintenance costs.

In Figure 13, the results of energy balances, LCA and LCC are coupled in an X-Y diagram. Results are clustered in a first instance based on the solution set type (centralised- SS1- or decentralised – SS2) and archetype (LR or HR building). Figure 13a) couples the results of dynamic simulations with LCA analyses. The diagrams prove higher advantages for centralised solution sets installed in low-rise buildings and lower benefits for the solution sets conceived for high-rise buildings. Decentralised systems demonstrate higher advantages in high-rise buildings.



(a) **(b)**

Figure 14. Multiple case study investigation. Results coupling of energy balances and a) LCA (GWP100ys) and b) LCC (annual cost) results.

The coupled results of energy balances and LCC (Figure 14 b)) also demonstrate higher advantages of centralised systems on low-rise buildings (SS1-LR). However, unlike LCA analyses, decentralised systems have higher advantages when applied to low-rise buildings (SS2-LR). Solutions for high-rise buildings are not economically convenient, especially with decentralised solution sets (SS2-HR). Figure 14 also allows us to understand how operational energy consumption might affect the LCA and LCC. LCC seems to be more affected by the total building energy consumption. In high-rise buildings (SS1_HR and SS2_HR), e.g., the total costs are directly affected by energy balances. This dependency is, while not so evident for LCA, where presumably embodied impacts affect primarily the total lifecycle.

Finally, in Figure 15, LCA and LCC are reported in a xy graph. The horizontal brown line shows average costs, while the vertical one (dark green) refers to the average GWP calculated. This is to possibly evaluate the solutions based on the provided clustering.

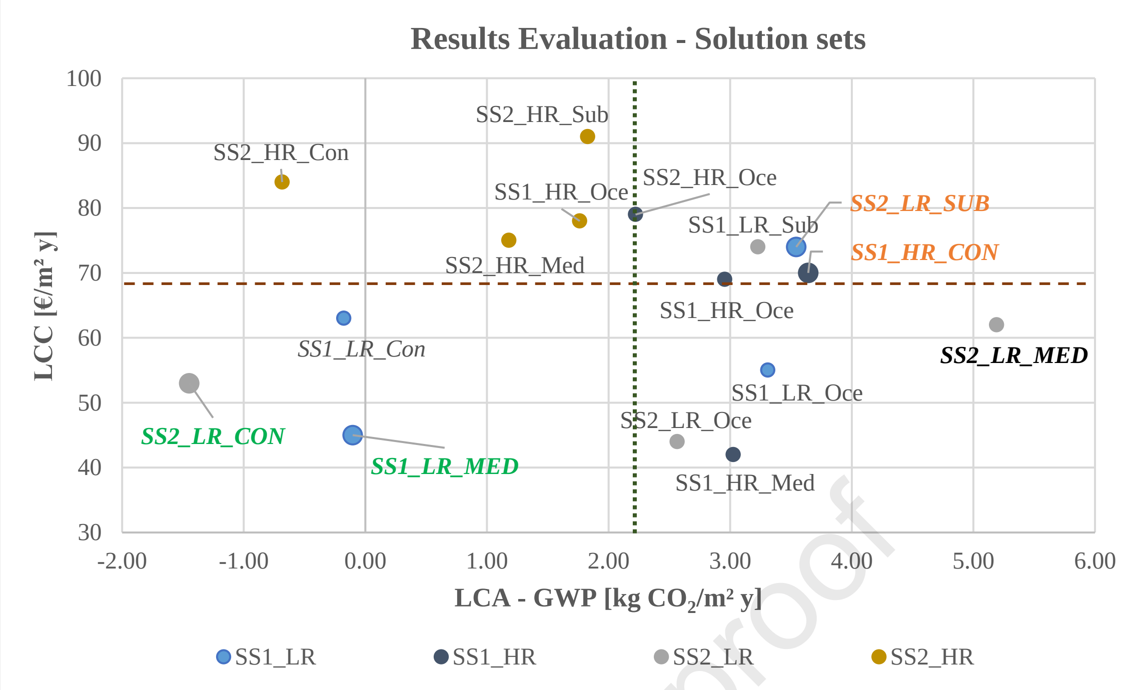


Figure 15. Multiple case study investigation. Results coupling of LCA (GWP100ys) and LCC (annual cost) results.

This graph shows that providing clustered results dependent on the solution set and building type is not always possible. Figure 15 also demonstrates that all decentralised systems installed in high-rise buildings (SS2-HR) have better environmental performance, but they are not convenient from an economic perspective. The worst cases are labelled with an orange caption. These refer to the decentralised system in low-rise and subarctic buildings (SS2-LR_SUB) and the centralised one in high-rise continental buildings (SS1-HR_CON). Therefore, the considered building and solution set type do not dictate advantages in an absolute manner.

The best options are labelled with a green caption. These refer to 1) the centralised solution set in a low-rise building and Mediterranean geo-cluster (SS1_LR_MED) and 2) the decentralised solution in a low-rise continental building (SS2_LR_CON), which presents, in comparison with the previous example, higher environmental advantages but slightly higher costs. This allows us to deem applications in a low-rise building more advantageous.

The highest cost is reported in the subarctic high-rise building with a decentralised solution set (SS2_HR_SUB). In this regard, it should be noticed that the highest economic values belong to the subarctic examples, as also outlined in Section 4.3. All 4 cases in the Mediterranean geo-cluster have an economic value below the average, coming from a country-specific context. The highest GWP is associated with the low-rise Mediterranean building with a decentralised solution set (SS2_LR_MED, in Figure 15 with a bold black caption). However, most cases with GWP higher than the average are associated with the oceanic and subarctic geo-cluster.

All in all, Figure 15 shows that results can be clustered based on the geo-cluster and, more precisely, the country-specific context. This outcome aligns with previous works demonstrating that the national context is one of the most relevant aspects affecting PEB systems' lifecycle advantages.

5 Conclusion and Outlooks

This work assesses the effectiveness and sustainability of 16 solution sets aimed at PEBs in different climate and cultural contexts in three domains, i.e. energy balance, environmental and economic performance. The analysis considered technical constructive specifications and information derived from dynamic building energy simulations and parametric modelling. This information served to derivate building energy balance and verify whether the system can effectively perform for PEBs. Furthermore, the information derived by the parametric modelling allowed the compilation of a BoM for carrying out LCA and LCC analyses. These estimated environmental and economic KPIs, i.e. embodied and lifecycle GWP, environmental payback periods, and economic value for each defined functional system. A novelty of the work is the consideration of 3 three different domains (energy, environmental and economic performance) separately and jointly to perform holistic assessments, which is still lacking in the literature for PEB systems. User-related energy consumption through stochastic user energy profile modelling is considered, allowing for a more accurate evaluation of the systems' effectiveness and environmental performance.

The study contributes to understanding that a positive energy balance, in which energy credits are higher than building energy demand, is not always provided. Strategies for reducing building and user-related energy consumption or increasing energy credits are necessary. Furthermore, the study results suggest that environmental payback through PV environmental credits is not always achievable, even if the systems aim at PEBs. A relevant factor that can increase or reduce environmental advantages is the carbon intensity of the national energy mix. Therefore, in national contexts like France and Norway, PEBs only present advantages limited to the building level. For these cases especially, it is necessary to focus on reducing embodied impacts, which are strongly affected by the grey emissions due to PV production and installation for all instances. Based on all energy performance and environmental and economic KPIs, the study confirms the advantages of centralised solution sets over decentralised ones in new buildings. A higher number of devices to be installed leads to higher maintenance costs and economic disadvantages. The advantages are more significant when applied in low-rise buildings and Italian and German contexts. However, it should be recognised that decentralised systems can present advantages, especially for building retrofit cases, thanks to easier installation and replacement of old systems. They can also better adapt and optimise their behaviour based on the user's needs. Therefore, optimisation strategies to improve energy performance and cost-effectiveness must be investigated.

The outlined conclusions are valid under the same conditions and circumstances. In fact, the study assesses two main solution sets with specific and detailed design (LOD 400) in specific contexts. This reduces uncertainties due to designers' choices, input data and data quality, as classified in the work of Warrier et al. [25]. Uncertainties related to future stages and used methods persist. In [44,45], these sources are also called "exogenous" since they cannot be influenced by designers' choices. Some of them, e.g. climate change, are handled using a database [31] that considers future climatic variations. Other sources of uncertainty and their effects need to be addressed in future works. Among them, we can mention variations in heat pump performance, fluctuations in energy grid production and costs for LCA and LCC analyses. To decrease such uncertainties, it will be necessary in future works to use, e.g., accurate performance maps, develop more advanced models and model further scenarios. Lastly, it will be necessary to expand the data collected and to enrich the analysis further with, e.g., different archetypes and solution sets' components, allowing for more robust results of dynamic building energy simulations.

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Conceptualisation: R.D.B.; **Methodology:** R.D.B., F.I.; **Formal analysis and investigation:** R.D.B., F.T., H.L.; **Writing - original draft preparation:** R.D.B., F.T., H.L.; **Writing - review and editing:** F.I, B.A..; **Funding Acquisition**: B.A.; **Supervision:** R.D.B., B.A.

6 References

[1] J. Du, W. Pan, Behavioral energy efficiency with environment sensors: A case in Hong Kong, Energy and Buildings 299 (2023) 113590. https://doi.org/10.1016/j.enbuild.2023.113590.

[2] European Commission, Energy performance of buildings directive (EPBD) - EU/2010/31 EU/2010/31. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed 4 October 2023).

[3] R. Galvin, Net-zero-energy buildings or zero-carbon energy systems? How best to decarbonize Germany's thermally inefficient 1950s-1970s-era apartments, Journal of Building Engineering 54 (2022) 104671. https://doi.org/10.1016/j.jobe.2022.104671.

[4] J.F. Walter Costa, C.N. David Amorim, J.C. Ribeiro Silva, Retrofit guidelines towards the achievement of net zero energy buildings for office buildings in Brasilia, Journal of Building Engineering 32 (2020) 101680. https://doi.org/10.1016/j.jobe.2020.101680.

[5] N. MIRABELLA, M. Röck, M. Ruschi Mendes Saade, C. SPIRINCKX, M. BOSMANS, K. ALLACKER, A. Passer, Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact, Buildings 8 (2018) 105. https://doi.org/10.3390/buildings8080105.

[6] M. Röck, M.R.M. Saade, M. Balouktsi, F.N. Rasmussen, H. Birgisdottir, R. Frischknecht, G. Habert, T. Lützkendorf, A. Passer, Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, Applied Energy 258 (2020) 114107. https://doi.org/10.1016/j.apenergy.2019.114107.

[7] A. Passer, C. Ouellet-Plamondon, P. Kenneally, V. John, G. Habert, The impact of future scenarios on building refurbishment strategies towards plus energy buildings, Energy and Buildings 124 (2016) 153–163. https://doi.org/10.1016/j.enbuild.2016.04.008.

[8] V. Arslan, S. Ulubeyli, A systematic literature review on positive energy buildings, IOP Conf. Ser.: Earth Environ. Sci. 1196 (2023) 12001. https://doi.org/10.1088/1755-1315/1196/1/012001.

[9] A.A.W. Hawila, R. Pernetti, C. Pozza, A. Belleri, Plus energy building: Operational definition and assessment, Energy and Buildings 265 (2022) 112069. https://doi.org/10.1016/j.enbuild.2022.112069.

[10] S. Firląg, Cost-Optimal Plus Energy Building in a Cold Climate, Energies 12 (2019) 3841. https://doi.org/10.3390/en12203841.

[11] M. Ala-Juusela, C. Pozza, J. Salom, I. Luque Segura, A. Tuerk, R. Lollini, N. Gaitani, A. Belleri, Workshop on Positive Energy Buildings—Definition, Environmental Sciences Proceedings 11 (2021) 26. https://doi.org/10.3390/environsciproc2021011026.

[12] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: A consistent definition framework, Energy and Buildings 48 (2012) 220–232. https://doi.org/10.1016/j.enbuild.2012.01.032.

[13] A. David, M. Leeb, T. Bednar, Comparison of the planned and the real energy consumption of the world's first (Plus-)Plus-Energy Office High-Rise Building, Energy Procedia 132 (2017) 543–548. https://doi.org/10.1016/j.egypro.2017.09.726.

[14] T.H. Dokka, M. Myrup, M. Solsem, Lia Kindergarten – A plus energy building: First year experience with regard to energy use, IOP Conf. Ser.: Earth Environ. Sci. 352 (2019) 12061. https://doi.org/10.1088/1755-1315/352/1/012061.

[15] S. Firląg, Cost-Optimal Plus Energy Building in a Cold Climate, Energies 12 (2019) 3841. https://doi.org/10.3390/en12203841.

[16] T. Recht, P. Schalbart, B. Peuportier, Ecodesign of a 'plus-energy' house using stochastic occupancy model, life-cycle assessment and multi-objective optimisation, Building simulation and optimisation, third international building performance simulation association (2016).

[17] M. Dabaieh, Design and build with straw, earth and reeds for a minus carbon and plus energy building practice, IOP Conf. Ser.: Earth Environ. Sci. 352 (2019) 12063. https://doi.org/10.1088/1755-1315/352/1/012063.

[18] S. Thiers, B. Peuportier, Energy and environmental assessment of two high energy performance residential buildings, Building and Environment 51 (2012) 276–284. https://doi.org/10.1016/j.buildenv.2011.11.018.

[19] R. Di Bari, O. Jorgji, F. Turrin, R. Pinotti, C. Pozza, Environmental lifecycle impact assessment for CULTURAL-E climate and cultural based solution sets, IOP Conf. Ser.: Earth Environ. Sci. 1085 (2022) 12061. https://doi.org/10.1088/1755-1315/1085/1/012061.

[20] R. Di Bari, O. Jorgji, Guidelines and calculation methods for Lifecycle Environmental Impact Assessment of Plus Energy Buildings: Deliverable 4.5, 2021. http://www.cultural-e.eu/wp-content/uploads/2022/09/CULTURAL-E_D4.5.pdf (accessed 22 December 2023).

[21] International Standardization Organization, Environmental management — Life cycle assessment — Principles and framework, Geneva, Switzerland ISO 14040:2006, 2006. https://www.iso.org/standard/37456.html (accessed 3 June 2021).

[22] International Standardization Organization, Environmental management — Life cycle assessment — Requirements and guidelines, Geneva, Switzerland ISO 14044:2006, 2006. https://www.iso.org/standard/37456.html (accessed 3 June 2021).

[23] European Committee for Standardization, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, Brussels, Belgium EN 15804:2020, 2020. https://www.cencenelec.eu (accessed 3 June 2021).

[24] European Committee for Standardization, Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method, Brussels, Belgium EN 15978:2011, 2011. https://www.cencenelec.eu (accessed 3 June 2021).

[25] G.A. Warrier, S. Palaniappan, G. Habert, Classification of sources of uncertainty in building LCA, Energy and Buildings 305 (2024) 113892. https://doi.org/10.1016/j.enbuild.2024.113892.

[26] Energy European Commission - COMM/DG/UNIT, EU Reference Scenario 2020 - Energy European Commission, 2019. https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2020_en (accessed 30 July 2021).

[27] International Standardization Organization, ISO 15686-5:2017: Buildings and constructed assets Service life planning: Part 5: Life-cycle costing, 2017. https://www.iso.org/standard/61148.html (accessed 24 October 2023).

[28] Verein Deutsche Ingenieur, VDI 2067 Blatt 30 - Economic efficiency of building installations - Energy effort for distribution, Düsseldorf, Germany VDI 2067 Blatt 30. https://www.vdi.de/en/home/vdi-standards/details/vdi-2067-blatt-30-economic-efficiency-of-building-installations-energy-effort-for-distribution (accessed 22 December 2023).

[29] European Committee for Standardization, Energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: Calculation procedures, Brussels, Belgium EN 15459-1:2018, 2018. https://www.cencenelec.eu/.

[30] M. Dallapiccola, G. Barchi, J. Adami, D. Moser, The Role of Flexibility in Photovoltaic and Battery Optimal Sizing towards a Decarbonized Residential Sector, Energies 14 (2021) 2326. https://doi.org/10.3390/en14082326.

[31] Meteotest, Meteonorm v. 8.2.0, Bern, Schweiz, 2023.

[32] F. Babich, M. Cook, D. Loveday, R. Rawal, Y. Shukla, Transient three-dimensional CFD modelling of ceiling fans, Building and Environment 123 (2017) 37–49. https://doi.org/10.1016/j.buildenv.2017.06.039.

[33] European Committee for Standardization, Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors: Part 3: Test methods, Brussels, Belgium EN 14511-3:2022, 2022. https://www.cencenelec.eu/ (accessed 29 May 2024).

[34] J. Mahecha Zambrano, U. Filippi Oberegger, G. Salvalai, Towards integrating occupant behaviour modelling in simulation-aided building design: Reasons, challenges and solutions, Energy and Buildings 253 (2021) 111498. https://doi.org/10.1016/j.enbuild.2021.111498.

[35] A. Ghosh, M.Z. Zapata, S. Silwal, A. Khurram, J. Kleissl, 2022. Effects of number of electric vehicles charging/discharging on total electricity costs in commercial buildings with time-of-use energy and demand charges. J. Renewable Sustainable Energy 14, 035701. https://doi.org/10.1063/5.0086924.

[36] S. Uimonen, M. Lehtonen, Simulation of Electric Vehicle Charging Stations Load Profiles in Office Buildings Based on Occupancy Data, Energies 13 (2020) 5700. https://doi.org/10.3390/en13215700.

[37] Transient System Simulation Tool - TRNSYS, Thermal Energy System Specialists, LLC, Madison, WI 53703, USA, 2022.

[38] H. Wang, Z. Zhai, Advances in building simulation and computational techniques: A review between 1987 and 2014, Energy and Buildings 128 (2016) 319–335. https://doi.org/10.1016/j.enbuild.2016.06.080.

[39] Y. Li, Z. O'Neill, L. Zhang, J. Chen, P. Im, J. DeGraw, Grey-box modeling and application for building energy simulations - A critical review, Renewable and Sustainable Energy Reviews 146 (2021) 111174. https://doi.org/10.1016/j.rser.2021.111174.

[40] ÖKOBAUDAT, Federal Ministry of the Interior, Building and Community, Berlin, Germany, 2021.

[41] Fraunhofer IBP, GENERIS®.

[42] R. Gazzin, F. Turrin, F. Isaia, C. Pozza, Repository of reference building models and related solution-sets, Zenodo, 2022.

[43] F. Turrin, G. Barchi, E. Della Maria, Report on multi-system control strategies for HMS.

[44] A. Passer, T. Potrc Obrecht, N. Alaux, T. Lützkendorf, M. Röck, B. Soust-Verdaguer, A. García-Martinez, M. Ruschi Mendes Saade, R. Frischknecht, E. Hoxha, Z. Szalay, B. Kiss, L. Wastiels, A. Hollberg, A. Houlihan Wiberg, S. Lasvaux, A. Galimshina, G. Habert, R. Horn, R. Di Bari, K. Lenz, C. Llatas, Gómez de Cózar, Juan Carlos, J. Veselka, H. Birgisdottir, M. Balouktsi, D. Plazza, M. Ortmann, D. Kaushal, D. Dowdell, J. Butler, C. Ouellet-Plamondon, B. Peuportier, T. Reisinger, Guidelines for design decision-makers, Zenodo, 2023.

[45] A. Galimshina, M. Moustapha, A. Hollberg, P. Padey, S. Lasvaux, B. Sudret, G. Habert, Statistical method to identify robust building renovation choices for environmental and economic performance, Building and Environment 183 (2020) 107143. https://doi.org/10.1016/j.buildenv.2020.107143.

Annex 1. Data collection for LCA and LCC analyses

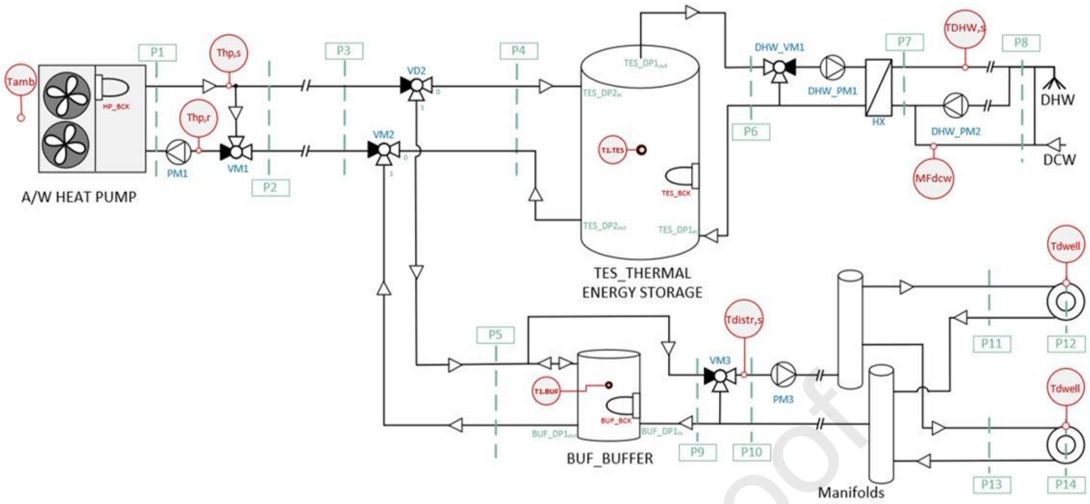

Figure 16. Exemplary schematic representation of a solutions set.

Table 13. Data collection for SS1. Case Low Rise (LR) and High Rise (HR) buildings.

Component	**LR**		**HR**	
		Total		**Total**
PWG [unit]		1		1
TES [unit]		1		1
VEN [unit]	3 units* apartment	21	3 units* apartment	60
DISTR [items]	38 IT, 39 DE, 36 FR, 44 NO		121 IT, 115 DE, 137 FR, 103 NO	
PIP	1300 kg copper 0,2 m³ XPS		3000 kg copper 0,5 m³ XPS	
PV [m²]		240		528

Table 14. Data collection for SS2. Case Low Rise (LR) and High Rise (HR) buildings.

Component	**LR**		**HR**	
		Total		**Total**
PWG [unit]		7		20
TES [unit]		1		1
VEN [unit]	3 units* apartment	21	3 units* apartment	60
DISTR [items]	38 IT, 39 DE, 36 FR, 44 NO		121 IT, 115 DE, 137 FR, 103 NO	
PIP	1300 kg copper 0,2 m³ XPS		3000 kg copper 0,5 m³ XPS	
PV [m²]		240		528

Annex 2: Comprehensive results of dynamic simulations for LCA and LCC analyses

Table 15. Dynamic energy simulation results. Case SS1, Low Rise.

LOW RISE(kWh/m²)	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
Qth_user	36.9	33.3	35.3	85.5
Qel _HP	14.1	14.4	13.3	17.7
Qth_HP	47.8	41.1	46.3	48.1
Qel_APL	29.7	31.3	39.6	34.8
Qel_LGT	0.9	0.7	1.2	1.1
Qel_VEN	3.7	3.7	3.7	3.7
Qel_CF	1.1	0.7	1.3	0.8
Qel_aux	0.4	0.5	0.4	1.1
Qel_FNC	2	2.2	2.3	3.3
Total energy demand	-52	-53.6	-61.8	-62.5
PV surface (m²)	172.5	177.6	204.9	207.0
PV credits	+72.35	+72.42	+72.38	+72.45
Energy balance	+20.4	+18.8	+10.6	+10.0

Table 16. Dynamic energy simulation results. Case SS1, High Rise.

HIGH RISE (kWh/m²)	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
Qth_user	28.9	27.1	34.4	31.9
Qel _HP	9.8	10.3	10.3	12.8
Qth_HP	36.2	31.7	44.1	37.3
Qel_APL	23.6	26.9	35.6	30.6
Qel_LGT	1.1	0.8	1.9	1.4
Qel_VEN	2.4	2.4	2.4	2.4
Qel_CF	1.6	1.1	1.7	1
Qel_aux	2.4	1.8	8.3	3
Qel_FNC	1.4	1.3	2.5	2
Energy demand	-42.2	-44.6	-62.7	-53.1
PV surface (m²)	614.14	649.43	913.48	772.84
PV credits	+36.28	+36.26	+36.24	+36.28
Energy balance	-5.9	-8.3	-26.5	-16.8

Table 17. Dynamic energy simulation results. Case SS2, Low Rise.

LOW RISE (kWh/m²)	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
APL	29.70	31.33	39.64	34.85
LGT	0.94	0.72	1.15	1.11
VENT+CF	4.31	3.62	4.11	3.60
PMP+FNC	2.33	3.59	2.39	6.33
HP_DHW	14.52	16.00	15.35	17.12
HP_SH	2.87	7.62	4.22	13.62
HP_SC	1.58	0.01	0.31	0.00
Total energy demand	-58.39	-64.89	-69.30	-78.42
PV surface (m²)	240	240	240	240
PV credits	+61.80	+48.07	+40.24	+41.66
Energy balance	+3.4	-16.8	-29.1	-36.8

Table 18. Dynamic energy simulation results. Case SS2, High Rise.

HIGH RISE (kWh/m²)	Mediterranean (IT)	Continental (DE)	Oceanic (FR)	Subarctic (NO)
APL	23.6	26.9	35.6	30.6
LGT	1.1	0.8	1.9	1.4
VENT+CF	3.1	2.4	3.3	2.3
PMP+FNC	4.9	5.4	5.5	6.5
HP_DHW	17.3	19.6	19.9	20.1
HP_SH	3.3	8.0	4.1	13.8
HP_SC	1.3	0.0	1.4	0.0
Total energy demand	-54.5	-63.3	-71.6	-74.7
PV surface (m²)	528	528	528	528
PV credits	+46.26	+41.01	+45.00	+45.96
Energy balance	-8.2	-22.3	-26.6	-28.7

Journal Pre-proof

Highlights

- Energy, environmental and economic analysis of Plus Energy Buildings installations
- Limited energy credits for most case studies
- Higher advantages for centralised functional systems
- Environmental and economic advantages dependent on the national context
- Coupling of PV and heat pump in cold climates to be improved

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: