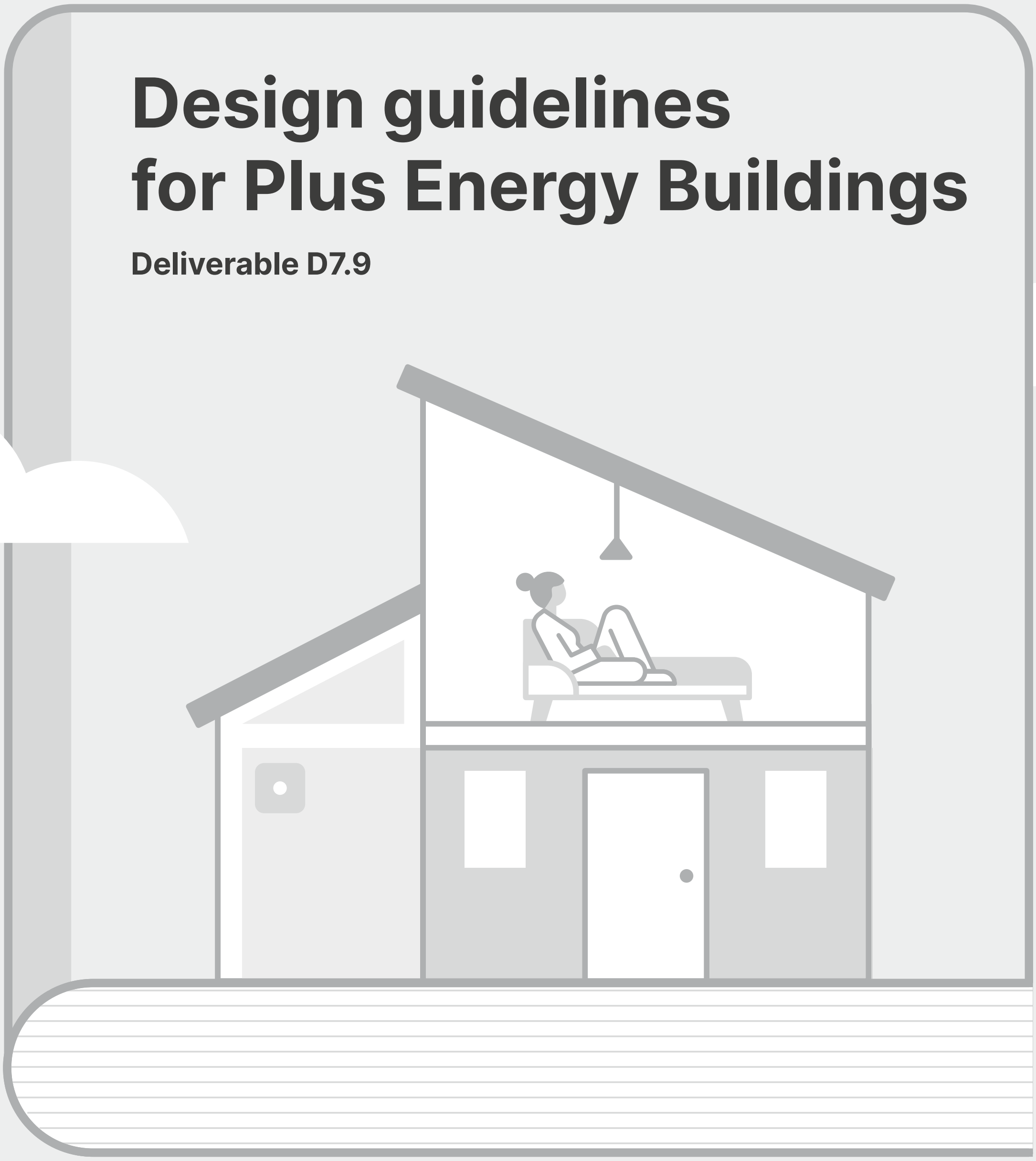
Climate and cultural based design and market valuable technology solutions for Plus Energy Houses



Design guidelines for Plus Energy Buildings

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Executive summary

The European Union's enhanced climate and energy targets emphasize the need for significant improvements in the building sector to accelerate the clean energy transition. The Climate Target Plan 2030 and the Renovation Wave strategy have shifted the focus from operational energy performance to the full decarbonization of the building stock by 2050. This transition requires new buildings to achieve zero-emission standards and existing buildings to be transformed accordingly. Building construction and renovation present opportunities to improve indoor environmental quality, climate resilience, and environmental health standards while enhancing carbon sinks and accessibility.

Zero-emission buildings (ZEBs) are designed with high energy performance, incorporating demand-side flexibility and covering minimal residual energy needs with renewable energy generated on-site or nearby. Plus Energy Buildings (PEBs) go further by producing surplus renewable energy that can be exported to other buildings or the grid. The growing adoption of net-zero and positive energy initiatives across Europe underscores the importance of implementing these advanced building concepts.

The PEB design guidelines target building owners interested in PEB investments and designers embarking on PEB projects. The guidelines introduce designers to key PEB design principles, offer practical tips for implementing technologies effectively and efficiently throughout design and operational phases, and provide recommendations for each project phase, including design, procurement, construction, commissioning, and post-occupancy evaluation.

1. Introduction

In order to accelerate the clean energy transition, the European Union set enhanced climate and energy targets giving a particular emphasis on improving energy performance in the building sector[1]. This regulatory trend has been taken forward in 2020 by the Climate target Plan 2030[2] and the Renovation Wave strategy[3] which shifted the focus from improving the energy performance during building operation to a complete building stock decarbonization by 2050 reducing overall GHG emission in the building life cycle.

Considering the limits to decarbonising existing buildings, there is an opportunity for new Plus Energy Buildings (PEBs) to compensate for existing buildings' emissions. According to the latest revision of the EPBD directive[4] "all new buildings should be zero-emission buildings, and all existing buildings should be transformed into zero-emission buildings by 2050". Furthermore, building renovation and new buildings' construction are considered unique opportunities "to improve indoor environmental quality, living conditions of vulnerable households, sufficiency and circularity, increasing climate resilience, improving environmental and health standards resilience against disaster risks and accessibility for persons with disabilities, and enhancing carbon sinks, such as vegetated surfaces".

In this context, Zero-emission and positive buildings are especially relevant. Zero-emission buildings have very high energy performance, which contributes to the optimisation of the energy system through demand-side flexibility, where any very low residual amount of energy still required is fully covered by energy from renewable sources generated on-site or nearby off-site. When the energy balance, between renewable energy produced and consumed by the building, is positive, it is considered a PEB since it is capable of exporting surplus energy to other buildings or to the network. Net-zero and positive energy buildings initiatives have grown around Europe with the aim of promoting and fostering their wider implementation.

Owners and designers often hesitate to implement innovative technologies and processes that have not yet been widely adopted, for reasons of perceived risk, cost or unfamiliarity. This guideline is designed to encourage how-to awareness of PEBs. These design guidelines are suited to anyone looking to undertake or invest in PEB design and/or construction. The main objectives of these guidelines are to:

- Introduce PEB design principles
- Provide key technologies implementation tips looking at the effectiveness and efficiency of technology implementation and operation processes
- Provide recommendations for design/procurement /construction /commissioning/Post Occupancy Evaluation (POE) phases

[1] Clean Energy for all Europeans, European Union, March 2019
[2] European Commission. Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people (COM/2020/562)
[3] European Commission. A renovation wave for Europe – Greening our buildings, creating new jobs, improving our lives (COM/2020/662)
[4] Amendments adopted by the European Parliament on 14 March 2023 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast) (COM(2021)0802 – C9-0469/2021 – 2021/0426(COD))

2. What is a Plus Energy Building?

A Plus Energy Building [1] is an energy efficient multi-residential building that produces more final energy than it uses via locally available renewable sources over an annual cycle. Energy demand includes both building operation and user related energy consumption. The positive balance shall be reached while ensuring the **lowest greenhouse gas emissions** and a **good dynamic matching** between load and generation, according to economic affordability and to technical viability. The definition applies to all-electric buildings and the energy balance is based on **measured or predicted final energy** between load and generation. In case of new buildings electrification is the base assumption. In case other renewable energy vectors are used in the building (i.e. biomass, biogas...), the primary energy balance shall be net positive.

The energy generation shall be performed **by renewable energy systems located within building footprint** and can be extended to adjacent lots as long as there is a physical connection and direct control of renewable energy generation system relying on ownership of the buildings or lots, neighbourhood grid infrastructure and building management. Besides the plus energy balance verification, PEBs shall ensure an added value i) to the context by providing **building flexibility and easy access to e-mobility and ii) to final users by providing accessible, comfortable and healthy indoor environments.**

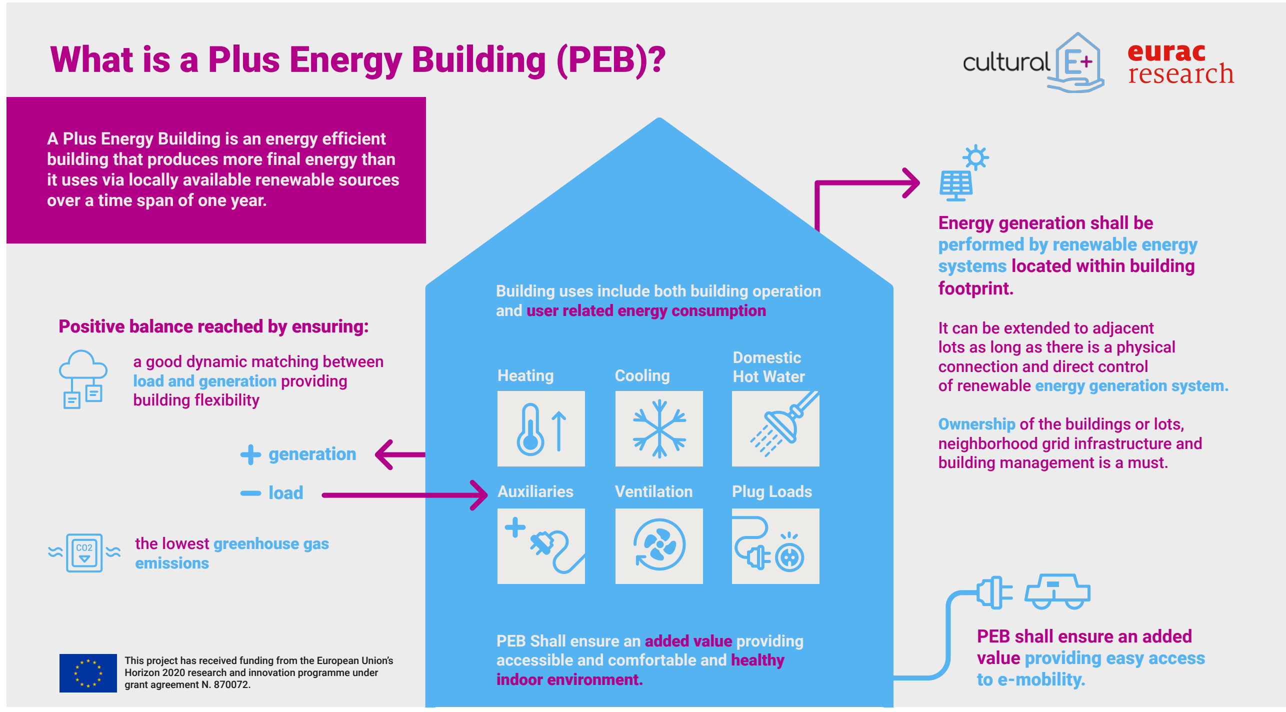
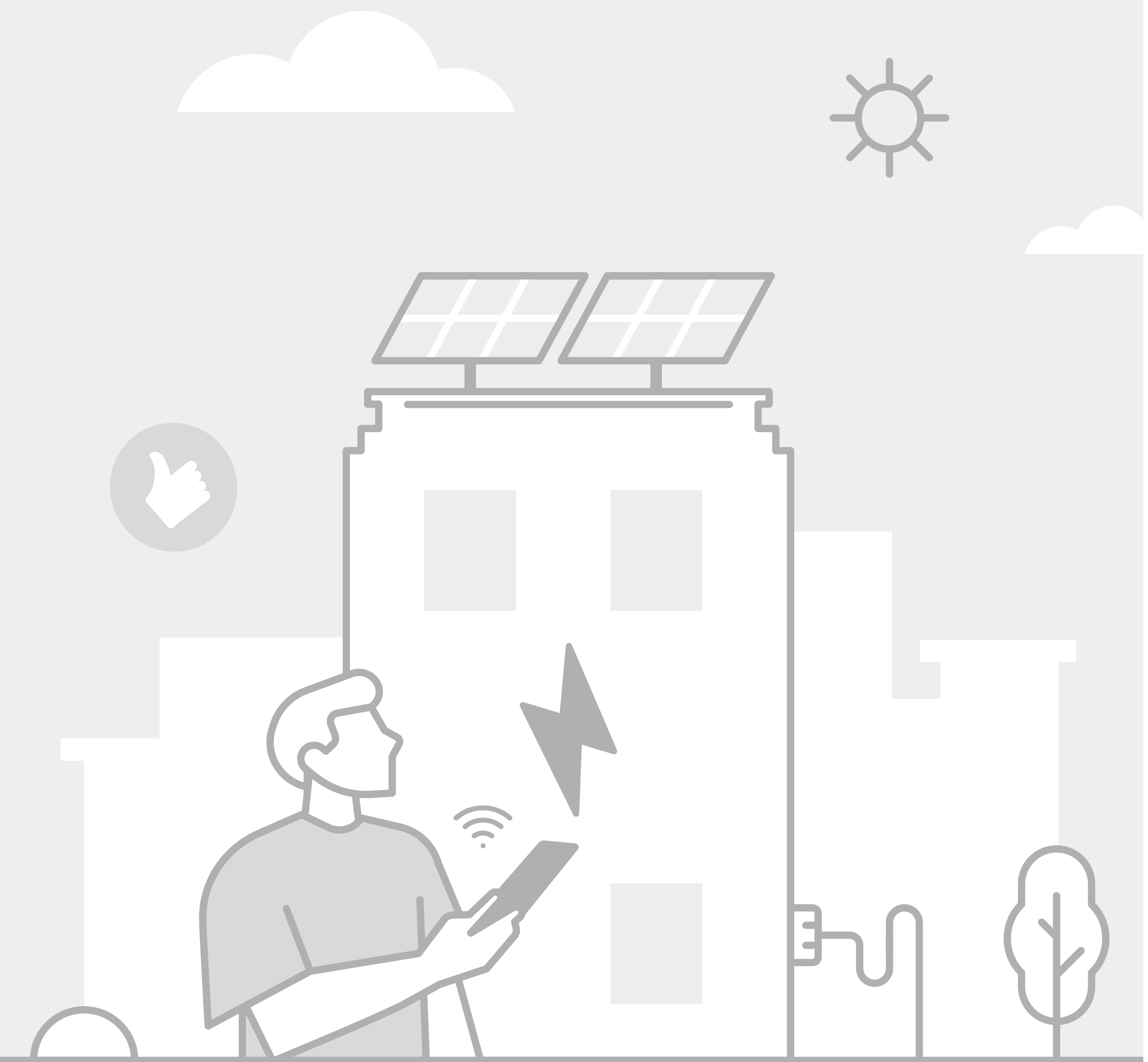


Figure 1. PEB definition and principles.

3. A social practice-based approach to PEB design

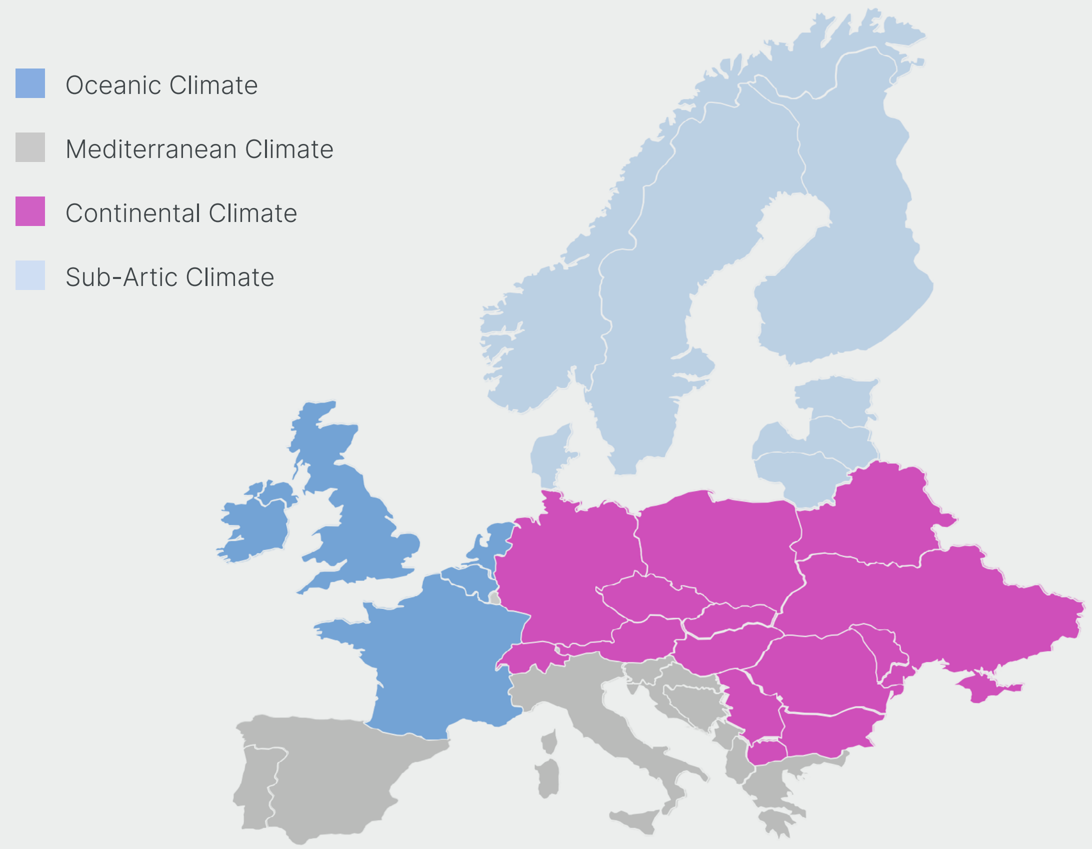


Cultural-E gathered qualitative insights from semi-structured interviews with residents living in highly energy efficient buildings[5] , across four different European geo-clusters.

European climate is clusterized into four climate types according to the Köppen-Geiger climate classification:

- **Oceanic Climate** (Cfb, Cfc, Cwb, Cwc in the Köppen-Geiger classification): characterized by mild temperatures throughout the year with moderate rainfall. Summers are generally warm but not hot, and winters are cool but not severe. Typical regions include Western Europe, such as parts of France, the UK, and Northern Spain.
- **Mediterranean Climate** (Csa, Csb in the Köppen-Geiger classification): characterized by hot, dry summers and mild, wet winters. Found predominantly in Southern Europe, including Italy, Spain, and coastal Greece.
- **Continental Climate** (Dfa, Dwa, Dfb, Dwb, Dsa, Dsb in the Köppen-Geiger classification):marked by significant temperature variations between seasons. Summers can be warm to hot, while winters are cold and often snowy. This climate type is typical of Central and Eastern Europe, including countries like Germany, Hungary, Poland, and Austria.
- **Sub-Arctic Climate** (Dsc, Dsd, Dwc, Dwd, Dfc, Dfd in the Köppen-Geiger classification): characterized by long, extremely cold winters and short, mild summers. Precipitation is generally low, with much of it falling as snow. Found in northern parts of Europe, particularly in Scandinavia and parts of Finland

To determine the climate corresponding to your specific project location, please refer to online Köppen-Geiger maps for accurate classifications.



[5] Clean Energy for all Europeans, European Union, March 2019

One finding that stands out across all geo-clusters, residents were overriding the technologies when their needs were not fulfilled, even if they were aware of the energy demand implications and knew how to properly operate the technologies. This usually happened during care crises, where caring for others took priority over reducing energy demand, or when residents followed long-standing practices like ventilation or connection with the outdoors.

As other research[6-7]shows, approaches that aim to change individual behavior by offering rewards or disincentives, or by providing information to users, do not work as expected. Rational choices are constantly jeopardized by both conscious and unconscious responses that happen when residents' needs are not fulfilled or, particularly, where their need to care for others (babies, children, elderly, loved ones, visitors, etc) override other considerations.

Therefore, **Cultural-E employs a social-practice based approach to inform PEB design**, which consists of four steps:

1. Understanding what the potential **conflicting practices** are in the home that might compromise expected energy efficiency of the PEB (examples of conflicting practices are shown in Table 3).
2. Identifying residents' **needs**, which are at the root of those conflicting practices.
3. Identifying residents' **responses** or **strategies** that residents implement to fulfil those needs.

Thinking of the **design trade-offs** that need to be undertaken during the building design phase or PEB technologies setting up, to respond to those needs. When possible, gather residents' feedback and adjust during the design process.

Some of the residents' needs are not specifically shaped by a certain climate or culture. As project data shows, some needs and responses repeat across different geo-clusters, such as the need to "be in contact with outdoor space/hearing nature" and "open windows", or the need to "take care of a loved one" and "add an extra heating source (radiator) in winter" or, to give a last example, "sleeping at an adequate temperature" and "opening windows". These are common human needs rooted in human biology.

However, there are other needs that are indeed shaped by climatic and socio-cultural factors, as project data has also shown. For example, sleeping with the windows cracked open in winter when it is below 20 degrees outside, is something that Norwegians are used to do but that people in Italy would not consider. Another Norwegian practice such as having many different thicknesses of duvets at home is closely linked to this practice of sleeping with cracked open windows, enabling each other. Hence, window opening should be carefully considered when designing smart-opening window systems in a sub-artic geo-cluster.

Growing up in a place with certain cultural and climatic conditions makes people take certain things for granted, shaping the practices that are performed by local populations, peer groups or family traditions, for example. 'Social rules' that are greater than an individual behaviour thus shape things like dressing practices or indoor comfort and caring practices. As the Norwegian/Nordic saying goes, "there is no bad weather, only bad clothes". This ability to be in contact with nature, no matter the weather conditions, could influence to a certain extent a need for opening windows to have fresh outside air when at home. Similarly, long-held associations with radiant heat sources such as open fires, can have strong links to cultural imaginary and childhood memories. Such preferences can go beyond the conscious, comfort-seeking simplicity of keeping a fixed indoor temperature, and may, for example, lead to preferences for underfloor heat in a bathroom, but radiant heat in a living room, and/or a range of coping strategies in PEBs.

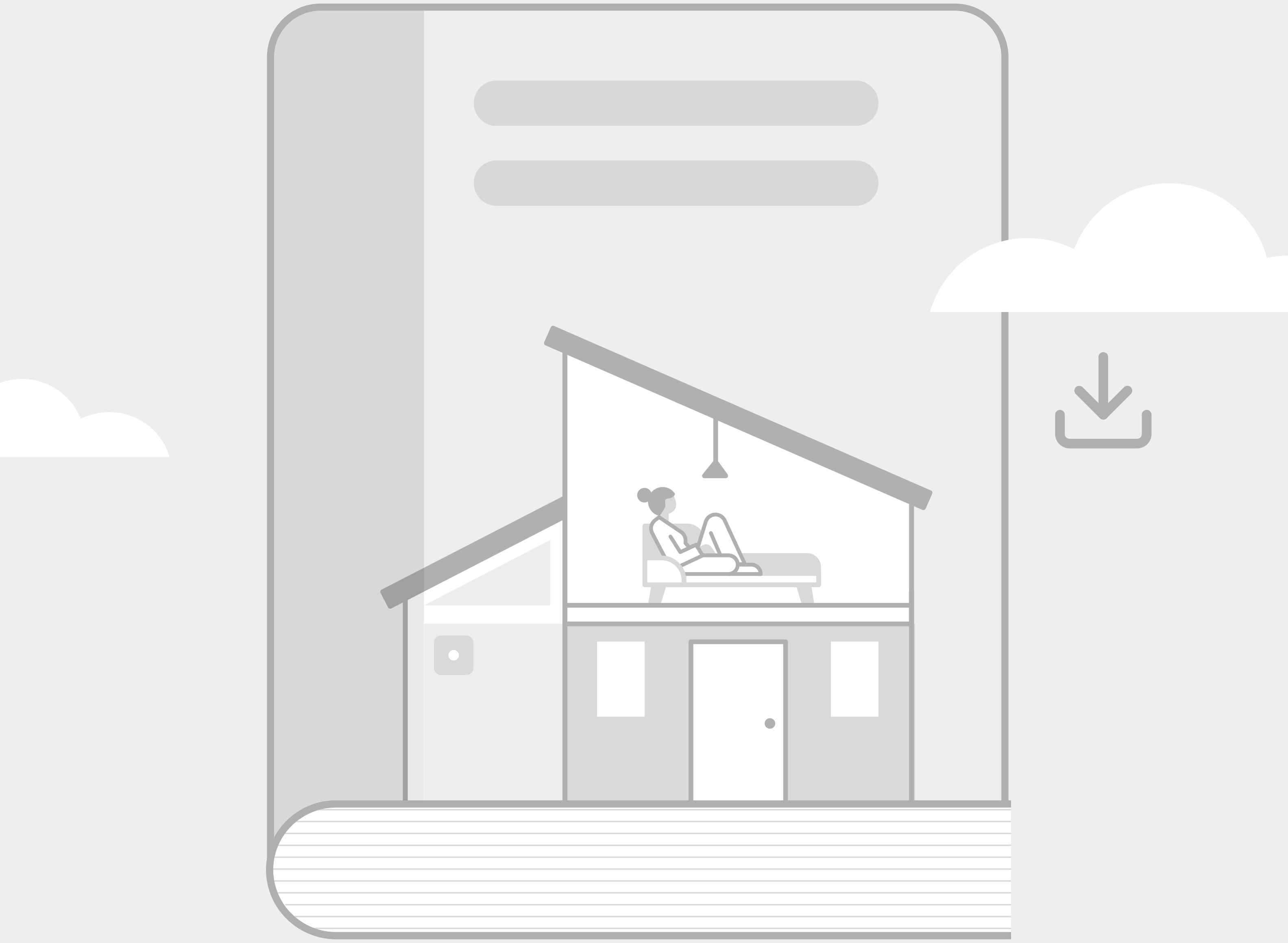
To sum up, **PEB designers aim to take all these climatic and socio-cultural aspects into consideration when designing PEBs and consider PEB technologies.** Cultural-E invites PEB designers to think of all the possible design trade-offs that differences in culture bring, such as design strategies to get rid of cooking odours (considering local ways of cooking), to allow residents to have windows open for longer periods of time, to sleep with windows open in winter, etc. Furthermore, it is also key to consider design features that go beyond technological solutions, such as building compactness, orientation, topography, layouts, use of local construction materials, etc., that contribute to reduce energy demand considerably.

The factsheets reporting solution set description and metrics for each climate-cultural geo-cluster also report **examples of conflicti ng practices**, and the **needs** and **responses/strategies** associated, found in the interview data gathered as part of the project.

[6] Davoudi, S., Dilley, L., & Crawford, J. (2014). Energy consumption behaviour: rational or habitual? disP - The Planning Review, 50(3), 11–19. https://doi.org/10.1080/02513625.2014.979039

[7] Frank W. Geels, Tim Schwanen, Steve Sorrell, Kirsten Jenkins, Benjamin K. Sovacool,
Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates, Energy Research & Social Science, Volume 40, 2018, Pages 23-35, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2017.11.003.

4. Key principles



7 key design principles should guide designers in creating Plus Energy Buildings and comfortable, healthy, and environmentally responsible spaces for people to live well in:

1. Create indoor spaces that are easy to access, comfortable, and healthy
2. Align building and technology design with residents' needs
3. Produce more energy than used
4. Use and store renewable energies
5. Enhance building flexibility to maximise energy self-sufficiency
6. Minimize greenhouse gas emissions
7. Keep affordable costs over the building life cycle

4.1 Create indoor spaces that are easy to access, comfortable and healthy for everyone

In modern building design, the ideal indoor climate is typically defined by thermal neutrality — an environment where temperature remains constant and imperceptible to occupants. However, this focus on thermal uniformity has not necessarily led to increased occupant satisfaction. Research has shown[8] that maintaining a narrow temperature range requires more energy and does not significantly improve thermal comfort. In fact, occupants in environments with greater dynamic thermal ranges report higher satisfaction, while those in more controlled spaces develop higher expectations for comfort, leading to potential dissatisfaction. Furthermore, comfort expectations are not symmetrical, as it is easier to increase expectations than to lower them, creating a cycle of rising demand for higher indoor environmental quality (IEQ). To better address the diverse needs of building users, **PEB design should consider moving away from static, homogenized environments and instead promote more dynamic spaces that allow for personal control.** Research indicates that providing occupants with the ability to adjust their environment, such as through personal heating or cooling systems, not only enhances comfort but also improves energy efficiency by accommodating individual preferences.

Various strategies can be implemented in indoor environments to engage building users and provide operability, including to allow them to manage environmental asymmetries, transient and dynamic environments, thermal stimuli, and thermoregulatory activation:

- air motion, across occupants' exposed skin surfaces through purposive natural ventilation or localized mechanical systems;
- localized heating and cooling, by actual contact to exposed body surfaces; thermal gradients, both in vertical and horizontal planes;
- low energy design options, compared with the brute-force, sealed facade air- conditioning monoculture that pervades in recent decades;
- exploitation of natural diurnal, synoptic, and seasonal rhythms in weather and climate, and in so doing minimizing the risk of thermal boredom in built environments;
- building configuration and users occupancy, according to subject's climate history and long-term background;
- personal comfort systems, empowering users' personal control;
- mixed-mode buildings.

[8] Edward Arens, Michael A. Humphreys, Richard de Dear, Hui Zhang, Are 'class A' temperature requirements realistic or desirable?, Building and Environment, Volume 45, Issue 1, 2010, Pages 4-10, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2009.03.014

These strategies can help restore human adaptability to thermal environments without significantly increasing energy consumption. Moreover, they support a shift away from homogenization, embracing diversity in building design by accounting for occupants' climate and cultural differences.

A user-centered design approach should be adopted for the design of PEBs i.e., to provide a comfortable and healthy indoor environment for its occupants, to make building control easy-to-access and raise their awareness of how daily practices impact on building energy demand. The building control system should understand users' preferences and needs and offer the optimal settings to meet these needs. Simple interfaces, clear instructions, and multiple access options to accommodate users of all abilities and preferences.

User expectations towards indoor environment conditions, occupants' needs, health and socio-cultural practices shall be put at the heart of a user-centric PEB design and operation paradigm.

The Cultural-E project team analyzed user feedback from various countries[9] to identify differences in comfort expectations. As a result, acceptability rates of indoor operative temperatures under different ventilation conditions and air velocities have been determinedand reported in Table 1 and Table 2. For naturally ventilated buildings, considering a greater potential of adaptation for users, the guidelines do not give a single value for the operative temperature, but a range for each comfort category, as reported in the tables. For clarity, outputs are reported for each operative temperature limit value of the ranges given by the Standard, being the more extreme set-points of the ranges.

Table 1. Acceptability rates per country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥80%, as prescribed by ANSI/ASHRAE Standard 55. Summer scenario. Source: Pistore et al., 2023 [10]

Acceptability rate [%]		Scenario 1 Summer (MVs) - Vair < 0.1 m s^{-1}			
		I CAT	II CAT	III CAT	IV CAT
		Top = 25.5°C	Top = 26°C	Top = 27°C	Top = 28°C
Countries	France	86%	84%	85%	59%
	Greece	73%	79%	86%	86%
	Portugal	86%	84%	85%	59%
	Sweden	77%	71%	55%	37%
	UK	80%	76%	60%	42%

Acceptability rate [%]		Scenario 1 Summer (MVs) - Vair = 0.6 m s^{-1}			
		I CAT	II CAT	III CAT	IV CAT
		Top = 25.5°C	Top = 26°C	Top = 27°C	Top = 28°C
Countries	France	80%	84%	87%	83%
	Greece	42%	52%	68%	81%
	Portugal	80%	84%	87%	83%
	Sweden	87%	86%	81%	68%
	UK	86%	87%	83%	73%

[9] A statistical analysis was conducted on the Smart Controls and Thermal Comfort (SCATS) database [10], which was built from monitoring and survey campaigns conducted in the late 1990s across five European countries. As a result, the data is limited to the countries and climatic conditions represented in the original database.

Acceptability rate [%]		Scenario 1 Summer (MVs) - Vair = 0.9 m s^{-1}			
		I CAT	II CAT	III CAT	IV CAT
		Top = 25.5°C	Top = 26°C	Top = 27°C	Top = 28°C
Countries	France	68%	75%	84%	87%
	Greece	26%	33%	52%	69%
	Portugal	67%	74%	84%	87%
	Sweden	83%	86%	86%	80%
	UK	80%	84%	87%	70%

Acceptability rate [%]		Scenario 1 Summer (MVs) - Vair = 1.2 m s^{-1}			
		I CAT	II CAT	III CAT	IV CAT
		Top = 25.5°C	Top = 26°C	Top = 27°C	Top = 28°C
Countries	France	50%	60%	74%	84%
	Greece	13%	19%	33%	52%
	Portugal	51%	60%	75%	83%
	Sweden	72%	78%	86%	86%
	UK	68%	75%	84%	87%

Acceptability Rate [%]		Summer (Natural Ventilation) - Air velocity < 0.1 m s^{-1}											
		I CAT			II CAT			III CAT			IV CAT		
		Top = 23.5-25.5 °C			Top = 23-26 °C			Top = 22-27 °C			Top = 21-28 °C		
Countries	France	88%	-	83%	88%	-	81%	88%	-	74%	86%	-	68%
	Greece	77%	-	86%	73%	-	87%	66%	-	89%	57%	-	88%
	Portugal	87%	-	81%	88%	-	78%	89%	-	73%	87%	-	66%
	Sweden	88%	-	86%	88%	-	85%	86%	-	80%	86%	-	74%
	UK	80%	-	67%	82%	-	63%	87%	-	54%	88%	-	44%

Acceptability rate [%]		Summer (Natural Ventilation) - Air velocity = 0.6 m s^{-1}											
		I CAT			II CAT			III CAT			IV CAT		
		Top = 23.5-25.5 °C			Top = 23-26 °C			Top = 22-27 °C			Top = 21-28 °C		
Countries	France	88%	-	86%	88%	-	85%	86%	-	81%	83%	-	75%
	Greece	70%	-	82%	65%	-	84%	57%	-	86%	47%	-	88%
	Portugal	88%	-	86%	88%	-	84%	86%	-	79%	84%	-	73%
	Sweden	87%	-	88%	86%	-	88%	83%	-	86%	78%	-	79%
	UK	84%	-	74%	87%	-	70%	88%	-	63%	89%	-	54%

Acceptability rate [%]		Summer (Natural Ventilation) - Air velocity = 0.9 m s^{-1}											
		I CAT			II CAT			III CAT			IV CAT		
		Top = 23.5-25.5 °C			Top = 23-26 °C			Top = 22-27 °C			Top = 21-28 °C		
Countries	France	88%	-	87%	87%	-	87%	85%	-	83%	80%	-	78%
	Greece	65%	-	79%	61%	-	81%	51%	-	86%	42%	-	87%
	Portugal	88%	-	87%	87%	-	85%	86%	-	83%	81%	-	78%
	Sweden	86%	-	88%	85%	-	88%	80%	-	86%	74%	-	82%
	UK	86%	-	78%	88%	-	74%	88%	-	68%	88%	-	59%

Acceptability rate [%]		Summer (Natural Ventilation) - Air velocity = 1.2 m s^{-1}											
		I CAT			II CAT			III CAT			IV CAT		
		Top = 23.5-25.5 °C			Top = 23-26 °C			Top = 22-27 °C			Top = 21-28 °C		
Countries	France	87%	-	88%	86%	-	97%	83%	-	86%	76%	-	81%
	Greece	60%	-	76%	55%	-	78%	46%	-	83%	37%	-	87%
	Portugal	87%	-	88%	87%	-	86%	83%	-	84%	78%	-	81%
	Sweden	84%	-	89%	82%	-	88%	77%	-	87%	70%	-	86%
	UK	87%	-	81%	88%	-	79%	88%	-	72%	88%	-	65%

Table 2. Acceptability rates per Country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥80%, as prescribed by ANSI/ASHRAE Standard 55. Winter scenario. Pistore et al., 2023 [10]

Acceptability rate [%]		Winter (Mechanical Ventilation)			
		I CAT	II CAT	III CAT	IV CAT
		Top = 21°C	Top = 20°C	Top = 18°C	Top = 16°C
Countries	France	84%	81%	67%	49%
	Greece	52%	43%	25%	14%
	Portugal	86%	82%	70%	52%
	Sweden	81%	75%	59%	41%
	UK	88%	88%	83%	72%

Acceptability rate [%]		Winter (Natural Ventilation)											
		I CAT			II CAT			III CAT			IV CAT		
		Top = 21-25 °C			Top = 20-25 °C			Top = 18-25 °C			Top = 17-25 °C		
Countries	France	86%	-	85%	83%	-	85%	71%	-	85%	63%	-	85%
	Greece	57%	-	84%	48%	-	84%	31%	-	84%	22%	-	84%
	Portugal	87%	-	84%	84%	-	84%	73%	-	84%	66%	-	84%
	Sweden	83%	-	88%	77%	-	88%	64%	-	88%	54%	-	88%
	UK	88%	-	71%	89%	-	71%	85%	-	71%	80%	-	71%

>> For more detailed information on comfort needs in different geoclusters, please refer to the report on redefined comfort zones for each climate-cultural cluster.

4.2 Align building design and technologies configuration with residents' needs

The **key to designing a PEB or a PEB technology that will be used as intended, and in turn maximizing energy efficiency, is to anticipate residents' needs as much as possible.** Optimized PEBs and PEB technologies will be those that are flexible enough to adjust to residents' requirements fulfilling their needs in the most energy efficient way. Otherwise, residents will find creative strategies to override the technologies to fulfil their needs.

As highlighted in chapter 3, **PEB designers should take climatic and socio-cultural aspects into consideration when designing PEBs and PEB technologies.** Cultural-E invites PEB designers to think of all the possible design trade-offs that differences in culture bring, such as design strategies to get rid of cooking odors (considering local ways of cooking), to allow residents to have windows open for longer periods of time, to sleep with windows open in winter, etc. Furthermore, it is also key to consider design features that go beyond technological solutions, such as building compactness, orientation, topography, layouts, use of local construction materials, etc., that contribute to reduce energy demand considerably.

Table 3 shows **examples of conflicting practices,** and the **needs** and responses/strategies associated, found in the interview data gathered as part of the project[10]. This table illustrates some of the examples of residents' needs that PEB designers should keep in mind in PEB design.

Table 3. Examples of conflicting practices and the associated needs and responses strategies.

MEDITERRANEAN GEO-CLUSTER		
Examples of 'Conflicting practices' that decrease energy efficiency (coming from the interview data)	**Need**	**Response/Strategies to get needs fulfilled**
Ventilating and being in contact with outdoor space & Opening windows	Ventilate and be in contact with outdoor space	Open windows and not use the mechanical ventilation frequently
Sleeping comfortably (right temperature/no noise from mechanical ventilation) & Heating / Cooling down	Sleep comfortably at an adequate temperature	Turn off the heating (and with that not being enough) and open windows
Taking care of a loved one & Extra heating	Take care of a loved one	Increase heating by raising the temperature on the thermostat and/or adding an electric heater
Cleaning (with cleaning products) & Opening windows vs. Mechanical ventilation	Get rid of cleaning odours (cleaning products) and ventilate	Open windows vs. Use of mechanical ventilation

[10] A total of 23 semi-structured interviews were conducted and analyzed across the four geo-clusters. Findings are thus subject to the interviews conducted.

OCEANIC GEO-CLUSTER		
Examples of 'Conflicting practices' that decrease energy efficiency (coming from the interview data)	**Need**	**Response/Strategies to get needs fulfilled**
Ventilating and being in contact with outdoor space ("hearing nature") & Opening windows	Ventilate and be in contact with outdoor space ("hearing nature")	Open windows
Sleep comfortably (right temperature/no noise from mechanical ventilation) & Heating / Cooling down	Sleep comfortably at an adequate temperature	Cooling – always having a fan always on to feel good
Taking care of a loved one & Extra heating	Take care of a loved one (with special health needs)	Extra heating by adding an electric heater
Ventilating & Having health issues (asthma, allergies) and a personal feeling of 'being cold'	Ventilate & Have health issues (asthma, allergies)	Open windows but not for long due to personal perceptions of 'being cold'
CONTINENTAL GEO-CLUSTER		
Examples of 'Conflicting practices' that decrease energy efficiency (coming from the interview data)	**Need**	**Response/Strategies to get needs fulfilled**
Relaxing ("hanging out" on the balcony) & Heating	Relax/ "hang out" on the outdoor balcony (all year round) and to be in contact with outdoor space.	Use an electric heater on the balcony in winter
Sleep comfortably (right temperature/no noise from mechanical ventilation) & Heating / Cooling down	Sleep comfortably at an adequate temperature	Turn off the heating + Open windows + Change dressing habits.

Practices of care (having visitors) & Extra heating	Please visitors when hosting at home.	Adjust temperature to the visitors' thermal comfort expectations
Cooking (fried foods) & ventilating naturally / mechanically / Turning lights on	Cook and get rid of cooking dours (fried foods)	Use both mechanical ventilation and natural ventilation (creating a draught)
SUBARTIC GEO-CLUSTER		
Examples of 'Conflicting practices' that decrease energy efficiency (coming from the interview data)	**Need**	**Response/Strategies to get needs fulfilled**
Heating (floor heating) & adding an extra electric radiator & "Feeling the heat"/ Missing a direct warmth source (fireplace)	Feel cold/Miss a direct warmth source (fireplace)	Add an extra electric radiator
Being in contact with outdoor space ("hear the birds"/"feel nature") & Smoking & Opening windows & Heating (floor heating) & Ventilating mechanically	Be in contact with outdoor space ("hear the birds"/"feel nature")/ smoke	Open windows, which interferes with floor heating & mechanical ventilation
Working easier with the residents & Leaving apartment main doors open & Mixing two independent mechanical ventilation systems (apartments and common areas) & Interacting incorrectly with the technologies to adjust apartment temperature	Work easier with residents that have special needs.	Leave apartment main doors open, which jeopardizes mechanical ventilation.
Sleeping comfortably at an appropriate temperature & opening windows ("leaving a crack open, 'cracked open' windows") & having appropriate duvets	Sleep comfortably at an adequate temperature	Open windows (having "cracked open" windows) & having appropriate duvets

These social practice insights can be used to create **Home Guides** that are structured from residents' needs. For each of the most common residents' needs identified, home guides shall include: (i) guidelines for interacting with the home management system; (ii) practical suggestions for reducing energy consumption and improving indoor environmental quality; (iii) a description of the technologies involved in fulfilling that need; and (iv) energy saving information.

In this way, home guides do not instruct residents, instead they anticipate diverse social practices and adopt innovative assumptions and controls aimed to fulfil their needs while also optimising energy demand.

Providing PEB occupants with these guidelines and best practices, using "an everyday life language", particularly regarding the use of the control system, is essential for understanding and increasing effectiveness of the installed technologies, enhancing the overall building system performance.

Providing PEB residents with in-person **conversations about the technologies and sensitivities to over-rides,** and the possibility to ask questions face-to-face, was mentioned as desirable on multiple occasions during the interviews conducted in the project.

Collecting users' feedback through surveys or direct interviews is fundamental to understand what happens behind closed doors and how residents interact with the installed technologies. This information is key to refining PEB building and technology design, increasing in turn user acceptance and ensuring PEB targets are reached.

Ideally, home guides should be a 'live document' that is regularly updated by demo owners, as new recurrent residents' needs emerge among PEB occupants. Being aware of how time and resource consuming it is to collect residents' feedback, it is suggested to combine face-to-face meetings currently happening, such as owners' association annual meetings, to gather this feedback.

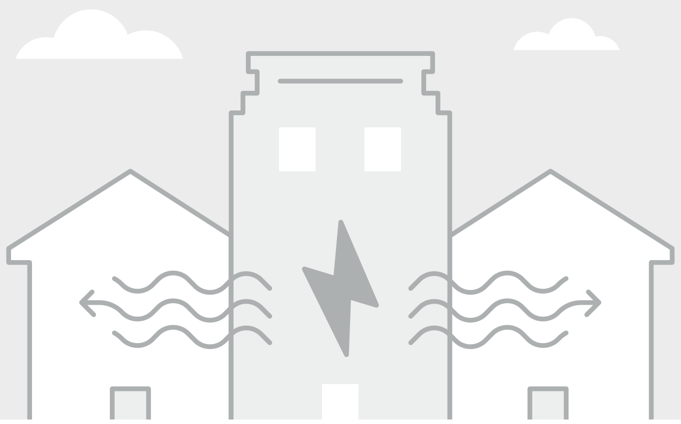
Cultural-E has delivered two relevant information sources useful for PEB designers.

- The European Climate and Cultural Atlas for Plus Energy Building Design or 2CAP-Energy Atlas is designed for researchers and is a repository of project findings including statistical data on (i) household energy demand; (ii) socio-economic factors; (iii) climatic factors; (iv) indoor environmental quality aspects; and literature review data on (v) energy cultures drives and (vi) occupant behaviour modelling. The 2CAP-Energy Atlas can be accessed here: Cultural-E Atlas

- The PEB HUB, is designed for all kinds of practitioners, as a repository of PEBs that aspires to become a community powered by Plus Energy Building professionals. With a focus on multifamily-residential buildings, the PEB HUB supports a wide range of designers in their work transitioning the practices of producing such buildings across Europe, so that they produce more final energy than they demand. The PEB HUB targets PEB designers (architects and engineers) and gathers PEB cases showcasing information on (i) the technology solution sets employed; (ii) performance and energy saving information; (iii) envelope technology; (iv) cultural and climatic considerations for PEB design and (v) PEB tips for designers by designers. The PEB HUB can be accessed here: https://energyefficientbuilding.eurac.edu/en/pebhub/

>> Cultural-E demo cases are early adopters who pave the way for PEBs' wider uptake. For more information on Cultural-E demonstration cases and other inspiration case studies, please refer to the PEB HUB community: https://energyefficientbuilding.eurac.edu/en/pebhub/

4.3 Produce more energy than used



Major benefit of PEBs lies in their energy generation potential and in the possibility of selling the energy surplus as part of an energy community.

Figure 2 presents a graphical representation of the building energy balance, which can be calculated in terms of energy load and generation or energy exported and imported to the grid. In Plus Energy Buildings, the energy exported to the grid is generally lower than the energy generated onsite because of self-consumed energy. Self-consumed energy refers to the part of energy generated by the on-site renewable energy systems (also considering the one stored by batteries) that is directly consumed by the building to meet its own energy needs. If the energy generated onsite is higher than the energy load of the building over a time span of 1 year, the energy balance of the building is positive, and the building can be considered a PEB [1]. If the building is all-electric, in most cases the balance can be expressed in terms of final energy (electricity energy use) since only one energy carrier is involved. In case more energy carriers are involved, the balance can be expressed in terms of primary energy. The amount of surplus energy generated by the building shall be determined according to economic affordability and the viability of the installation of suitable RE generation systems. Including all energy uses (heating, cooling, ventilation, domestic hot water, lighting, auxiliaries, house appliances and plug loads) in the balance ensures that the building has an energy production surplus to be shared with other buildings or to be exported to the grid.

PEB balance=G-L>0

G = tot primary energy generated onsite
L = tot primary energy load of the building

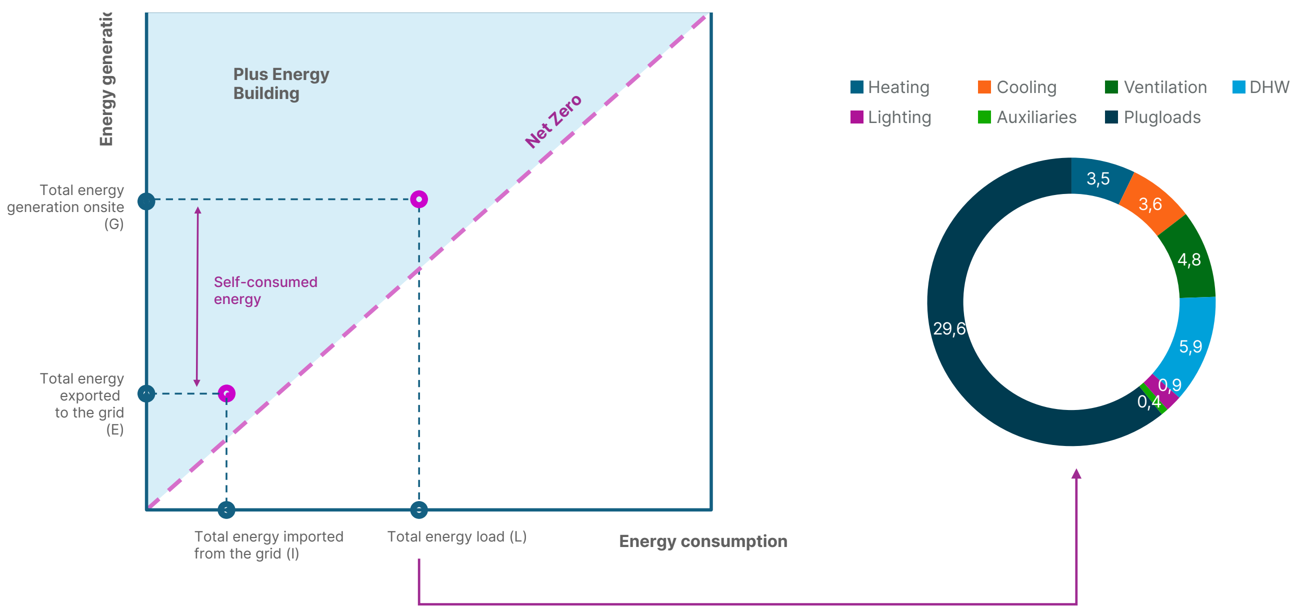


Figure 2. If the energy generated onsite is higher than the energy load of the building over a time span of 1 year, the building can be considered as a PEB. Image credits: Giulia Olivieri, Eurac Research

Accounting for the user-related energy use in the balance may discourage, or prevent compact or high-rise buildings achieving PEB status, given that in these buildings the technical and economic viability for deploying sufficient renewables onsite could be limited in comparison to the on-site demand. Thus, the location of renewable energy systems can be extended to building surroundings and neighborhoods. The energy generation shall be performed by renewable energy systems located within building footprint and can be extended to adjacent lots as long as there is a physical connection and direct control of renewable energy generation system relying on ownership of the buildings or lots, neighborhood grid infrastructure and building management (Figure 3).

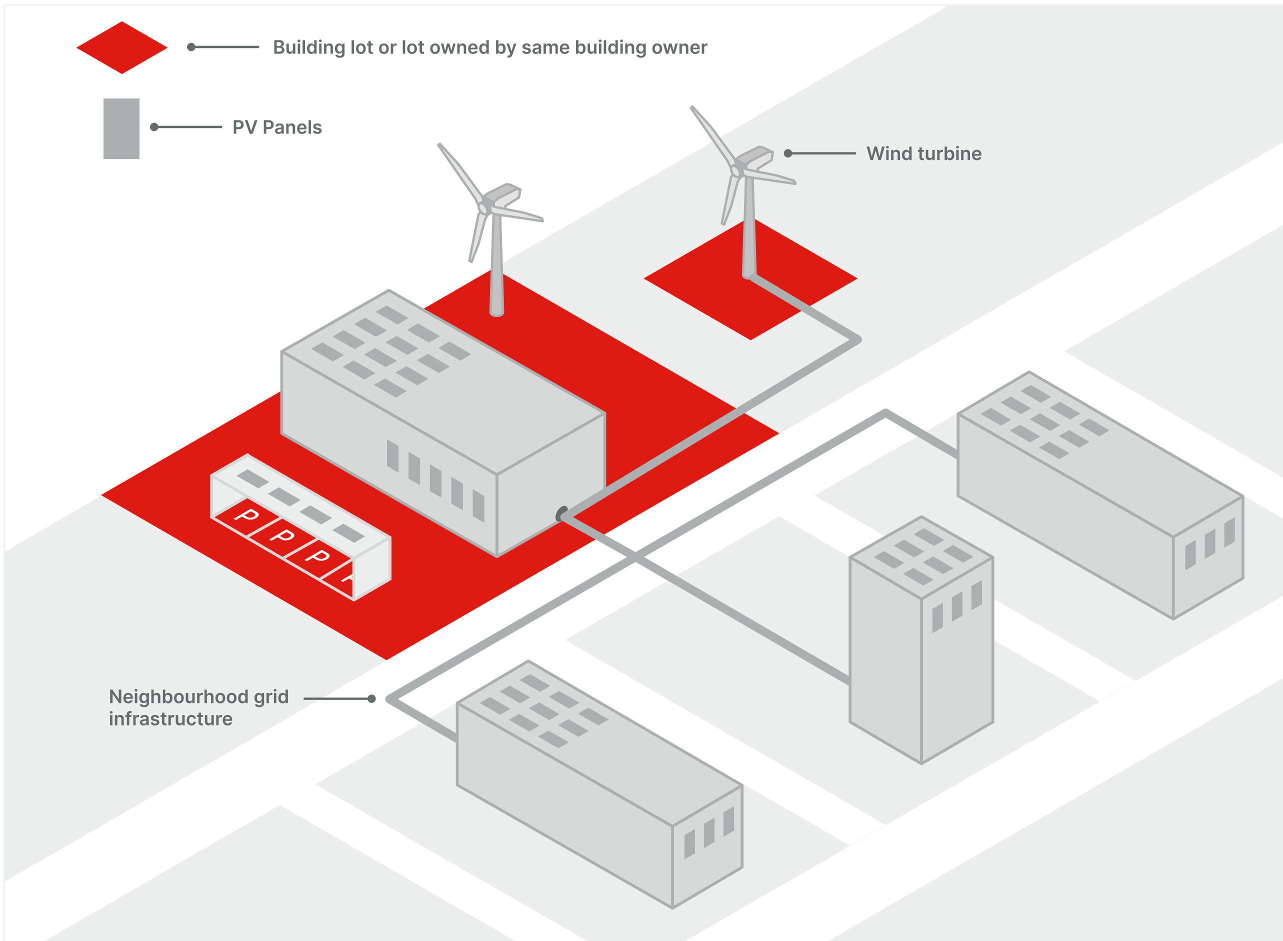


Figure 3. Renewable energy system location. Image credits: Giulia Olivieri, Eurac Research

A set of technologies and building systems was analyzed for their energy consumption, as well as their economic and environmental impacts, by applying them to two multi-family building typologies: a compact 8-storey high-rise building and a 3-storey low-rise apartment building. This analysis was conducted across four distinct climate and cultural geo-clusters—Mediterranean, Oceanic, Continental, and Sub-Arctic Köppen-Geiger climate classification. In each scenario, the sizing of the building-integrated photovoltaic (PV) system and battery storage was optimized based on economic performance and energy flexibility indicators [12].

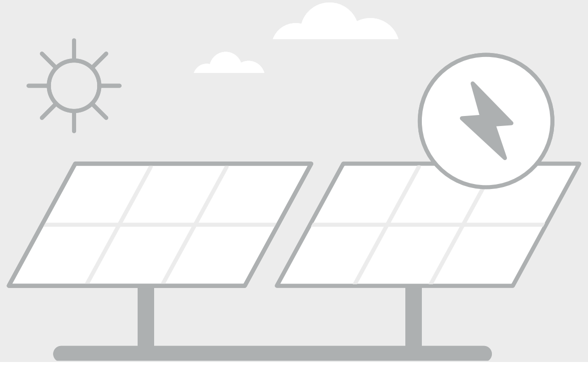
Factsheets are available here reporting solution set description and energy, economic and environmental performance evaluations for each climate-cultural geo-cluster.

Despite the low operational energy needs (heating, cooling, domestic hot water, ventilation, lighting, and auxiliary systems), achieving a positive energy balance was not possible for all solution sets due to the high proportion of energy consumed by household appliances and plug loads relative to the building's operational energy needs. Furthermore, in compact or high-rise buildings, the technical and economic viability for deploying renewable energy production on-site could be limited, due to low roof area available per living area.

To attain a positive energy balance powered by renewable energy systems, multiple strategies will inevitably be needed, including reducing appliance-related energy demand and optimising PV installations.

>> For more information on PEB solution set and their energy, economic and environmental performance evaluations for each climate-cultural geo-cluster, please refer to Factsheets reporting solution set description and metrics for each climate-cultural geo-cluster

4.4 Optimize the use and store of renewable energies



According to the PEB definition, on-site renewable generation is an important element, although off-site could be included if generated nearby the building (i.e. in the neighborhood or district) with direct connection to the building's energy system and under direct control of the PEB system. Renewable energy supply options shall consider the need for energy generation to cover building loads, the availability of resources, ownership of buildings and other available lots, the performance of the grid in terms of energy mix and transportation, the distance of renewable energy supply from the building, and the availability over building lifetime.

Our designers' recommendations for the integration of renewable energy generation plants in residential buildings:

1. Designers should **prioritize identifying renewable energy resources that align with the site's characteristics and the overall design of the building.** Solar energy remains a primary option due to its scalability and adaptability, but wind energy systems and use of geothermal probes as source for heat pumps should also be evaluated based on site-specific conditions, local climate, and regulatory frameworks. Early-stage integration of these resources into the design process is crucial to ensure seamless incorporation without compromising the building's architectural integrity.

2. An **in-depth analysis of available surfaces for PV panel installation** is essential. This includes not only rooftops but also façades, balconies, and even innovative elements like solar-integrated windows and shading devices. Designers should model expected energy generation patterns throughout the year to optimize system sizing and orientation for maximum efficiency.

3. **Roof surfaces should be approached with multifunctionality in mind.** Besides housing solar panels, rooftops can be designed as green roofs or retention roofs to manage stormwater runoff, improve thermal mass, and enhance biodiversity.

4. To further optimize energy performance, designers should **consider integrating battery energy storage systems to manage energy supply and demand effectively** (par 4.5). Coupling these with smart energy management systems allows for dynamic control over energy flows, enhancing self-consumption and grid interaction.

5. **Community-based renewable energy solutions,** such as shared solar installations or Renewable Energy Communities (RECs), can be explored when on-site generation is limited. These strategies offer opportunities to expand renewable energy use beyond individual building footprints while fostering community engagement and economic benefits.

Another option for PEBs is to join a **Renewable Energy Community (REC**). The REC is a legal entity aggregating passive consumers and PV owners to enable their participation in the electricity market. RECs enable collective self-production and consumption of renewable energy, primarily through photovoltaic (PV) systems, fostering local energy markets and reducing electricity costs. By sharing energy within a community, the payback period for renewable investments can be significantly reduced, and the share of renewables in energy consumption can be increased.

The definition and implementation of REC and the related regulations vary by jurisdiction. In the energy management of an energy community, two distinct groups of actors stand out. On the one hand, the individual users are involved; on the other, **a third entity is responsible for coordinating or managing energy flows within the community.** A REC supervisor carries out a virtual balance of the consumption of the community as a whole by summing up the information derived from the various users. The control task is to try to zero the balance resulting from the sum of the individual contributions of the buildings involved. On the practical side, this means trying to store the surplus energy produced within the storage systems available in the community, even if not directly part of the building that generated the renewable production. Similarly, where the community requires a power greater than that available, the control requires the intervention of the available storage systems to reduce the energy withdrawn from the grid by the entire community.

Several key elements support the implementation of an energy community:

1. Early integration of PV systems and energy storage: Optimize the size and placement of PV panels and Battery Energy Storage Systems (BESS) during the early design stages. Prioritize smart-metering infrastructure to monitor and balance production and consumption effectively.

2. Heterogeneus user consumption patterns: A greater heterogeneity between users' habits and consumption patterns can increase the benefits of introducing a community logic. On the other hand, users who concentrate their higher consumption in the same time slots, or with the same habits, can reduce the potential benefits introduced by the community logic.

3. Implement control-logics at community level: Implement advanced control strategies for BESS to maximize self-consumption of the community and minimize energy drawn from the grid. Use predictive models and real-time data to manage energy flow efficiently.

4. Community Energy Sharing Models: Explore decentralized (Peer-to-Grid) or centralized (Peer-to-Peer) energy sharing strategies to distribute surplus energy among community members, improving flexibility and reducing waste.

5. User Diversity and Consumption Patterns: Encourage diverse user profiles within RECs to optimize energy sharing. Varied consumption habits improve the balance between production and demand.

If no incentives for selling energy are available, feeding energy into the grid results in limited financial benefit. In these cases, **self-consumed energy has a higher value than exported energy.**

Various strategies can be implemented in building design to maximise self-consumption:

1. **optimize energy generation** to align with peak demand hours by positioning PV panels on surfaces where PV panels are more likely to generate energy generation during peak demand hours (i.e. if the highest electricity consumption occurs in the morning, PV panels shall be oriented accordingly);
2. **Allocate space for battery systems** to store surplus energy for later use;
3. Incorporate **thermal storage systems** to heat water
4. Use **energy-efficient and smart appliances** that can adjust their energy use to align with peak solar generation times;
5. Include **house management systems** that monitor energy use and production and inform users when it is most convenient to use energy;
6. Consider the installation of **charging points for EV.**

>> For more detailed information on self-consumption maximization practices, please refer to the Report on multi-system control strategies for House Management Systems

4.5 Build-in flexibility to maximize energy self-sufficiency

Simply meeting a positive annual energy balance is not enough to ensure optimal environmental performance or efficient building operations. For instance, a Plus Energy Building (PEB) might generate more energy than it consumes over the year, but if energy production does not align with consumption patterns, it could result in exporting a high share of the overall renewable energy production and a need to purchase more expensive peak demand energy. This means losses for bill payers and more stress on the energy grid.

This scenario highlights the importance of carefully sizing and integrating energy systems to optimize energy generation, storage, and consumption. An optimized design ensures that renewable energy systems are scaled appropriately, maximizing both environmental benefits and economic performance within the framework of PEB standards.

In this context, building flexibility becomes a vital design strategy. Flexible buildings can adapt their energy consumption and production in response to external factors, such as fluctuating energy prices, grid demand, or the availability of renewable energy. This adaptability involves intelligently shifting or reducing energy use, efficiently storing energy, and managing on-site generation to support grid stability and minimize operational costs. Importantly, this dynamic approach ensures that occupant comfort and building functionality are never compromised.

Several indicators should be used to evaluate building flexibility of PEBs:

- Self-sufficiency or self-generation (%): Percentage of the energy demand covered by renewable energy production. It refers to load matching. It is calculated as the ratio between the self-consumed generated energy (from PV to the building) and the total annual electric energy use, that takes into account the Heat Pump electric consumption, appliances, lighting, ventilation, ceiling fans, auxiliaries and fan coils.
- Self-consumption (%): Percentage of generated energy which supplies local loads. It refers to load matching. It is calculated as the ratio between the Self-consumed generated energy (from PV to the building) and the total renewable energy generation (energy generated from the PV system). This indicator is influenced by the losses in the electrical storage and supply system and the electrical energy that is sent to the electrical grid.
- Peak export (kW): highest power export over the year.
- Peak import (kW): highest power import over the year.

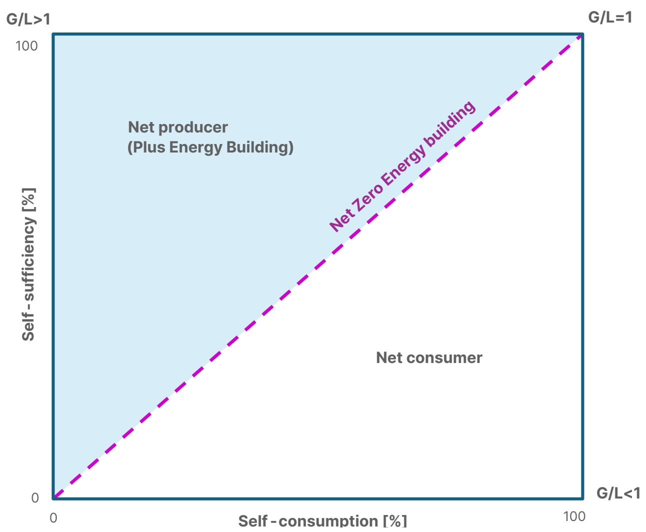


Figure 4. Load matching indicators chart. Re-elaborated from Luthander R., et al. 2019 [11], with modifications by the authors. Image credits: Giulia Olivieri, Eurac Research

Figure 3 proposes a graphical representation of the production/consumption balance behind the concept of PEB. This graphical representation serves both as a sizing tool and as a device to allow the qualitative analysis of the performance of a building and fast identification of possible improvement directions. PEBs can play a significant role in reducing the stress on the energy grid infrastructure. Simulations performed on building archetypes for low rise and high-rise residential buildings [3] resulted in **self-sufficiency rates up to 70% in the mediterranean climate** and over 40% in the other climates, except for the Subarctic climate (Figure 5).

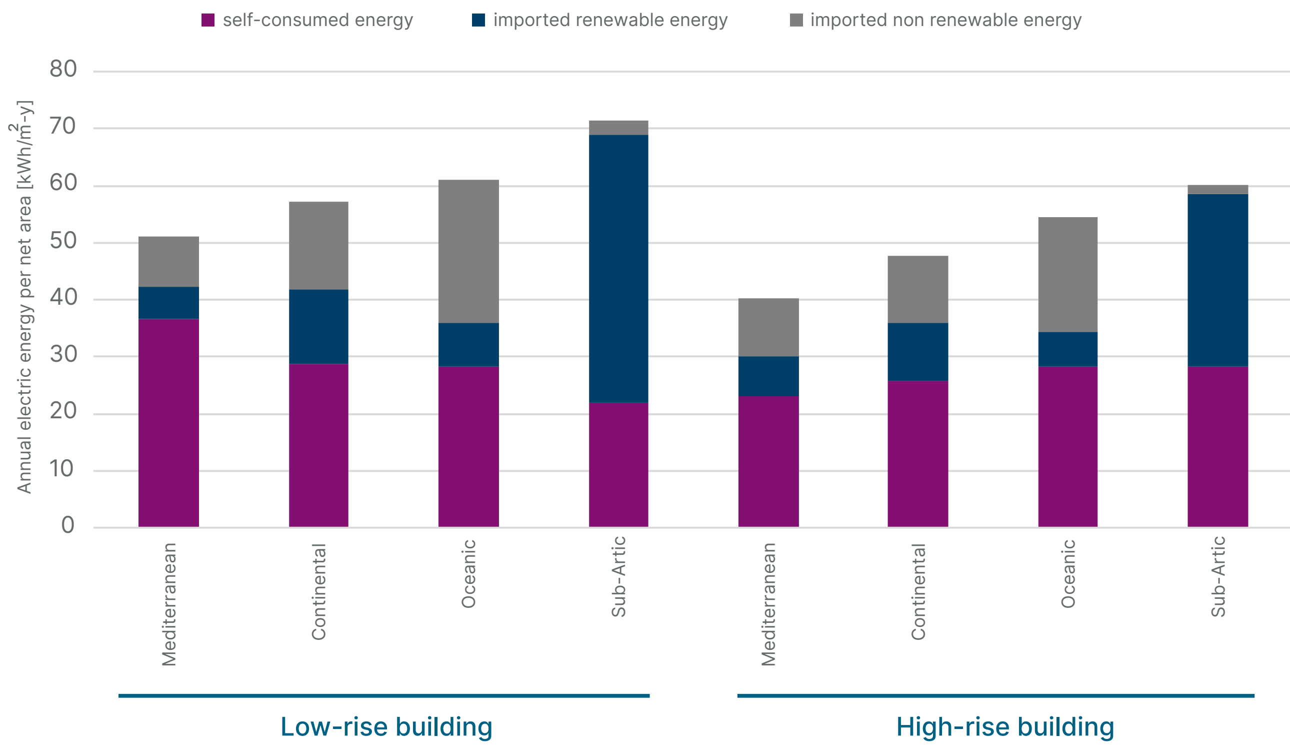


Figure 5. Annual electric energy per net area disaggregated by self-consumed energy, imported renewable and non renewable energy for a low rise residential building and a high rise residential building in the four climate geo-clusters. Re-elaboration of simulation data calculated using the building energy models described in D4.3 [3][4] for solution set with centralized HVAC system.

In the Mediterranean climate, energy demand peaks during the hot summer months due to extensive cooling needs, while solar photovoltaic (PV) system is also at its highest production. This natural alignment between energy demand and solar generation offers a significant opportunity for self-consumption. However, during transitional seasons and winter, when cooling demand drops and solar generation decreases, buildings may still rely on grid electricity. Integrating energy storage solutions, such as batteries, and adopting predictive control strategies can mitigate this mismatch by storing excess solar energy for later use.

[11] Rasmus Luthander, Annica M. Nilsson, Joakim Widén, Magnus Åberg,Graphical analysis of photovoltaic generation and load matching in buildings: A novel way of studying self-consumption and self-sufficiency, Applied Energy, Volume 250, 2019, Pages 748-759, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.05.058

Strategies for flexibility in Mediterranean climates:

The primary driver of building flexibility in the Mediterranean region is the need to manage cooling loads efficiently during peak summer demand and minimize energy costs. Smart control of PV-battery systems, combined with demand-side management strategies, enables buildings to shift energy-intensive tasks to periods of high solar generation or lower energy prices. Energy imports during high-price hours can be reduced by 10%-13% using advanced control strategies based on predictive models [5]. Additionally, integrating smart electric vehicle (EV) charging infrastructure further enhances flexibility by balancing grid loads and maximizing on-site renewable energy use.

Strategies for flexibility in Subartic climates:

In subarctic climate there is a discrepancy between energy demand and the potential for electricity production using solar PV, but this mismatch decreases as the energy efficiency of the building increases. The installation of technologies such as heat pumps can further reduce this mismatch. However, even with a very efficient building envelope and heating technologies, a high overproduction is needed in summer to compensate for all energy demand with PV panels. Strategies for flexibility in subarctic climates: The primary driver of building flexibility in Norway is the volatility in electricity spot prices. Night temperature setback has been applied as an energy saving measure for some apartment buildings. However, this shifts peak demand in the morning when the heating is turned back on and when the electricity price is the highest. From an economic point of view, it might be beneficial to overheat at night when prices are low. A challenge in shifting heating time at night is that people living in subarctic climates prefer to sleep in cold rooms.

>> For further information on building flexibility and flexibility strategies, please refer to the report on strategy for building flexibility and to the report on flexibility potential and operation strategy of the Norwegian demo case.

Advanced building performance optimization

Basic control operates the energy system and the other technologies to cover the domestic hot water, space heating and space cooling demand of the building while trying to minimize the thermal load.

Advanced control can increase the synergy between the generation systems (heat pump and photovoltaic system), the storages (thermal storage and battery) and the building's technologies to reduce the electrical energy withdrawn from the grid and maximize self-sufficiency and self-consumption. The control acts on the temperature setpoints of the thermal energy storage and the building to shift the thermal loads toward the central part of the day when the electrical consumption can be covered by the PV production. To reduce the electricity withdrawal from the grid it is important to know if the production of the PV system for the next 24 hours is higher or lower than the electricity consumption of the building in the same time span (predictive models based on weather forecast can do that).

Increasing the size of thermal energy storage for domestic hot water (i.e. tripling it beyond standard specifications) allows for better load shifting and reduced reliance on the grid during low-production periods, but increases investment costs and space needed for thermal storage. Adjusting the thermal storage setpoint to charge during peak PV production times maximizes self-consumption but requires careful balance to avoid reducing heat pump efficiency. Therefore, this strategy might not be cost-effective.

For space heating, shifting the heating load to align with midday PV peaks by increasing indoor setpoints can improve the heat pump's performance and reduce grid electricity use. This strategy is most effective during colder months when thermal demand is high, provided PV generation is sufficient. During milder seasons, more modest setpoint adjustments prevent overheating while still leveraging PV production.

Space cooling, however, requires a different approach. Since cooling loads naturally align with peak solar production, shifting these loads earlier in the day may reduce system efficiency and occupant comfort. The control should instead focus on minor setpoint reductions during high-production periods and utilize ceiling fans to maintain comfort with minimal energy use (par. 5.2).

Integrating larger battery storage systems—up to 20% larger—can further enhance flexibility, especially during spring and autumn when thermal loads are lower. However, during winter, maximizing PV coverage might require additional PV installations beyond the building envelope, which may not always be feasible.
Careful placement of air-to-water heat pump external units in shaded but ventilated areas can optimize performance by improving the coefficient of performance (COP) in winter and avoiding efficiency losses in summer.

>> For further information on advanced control strategies, please refer to the report on multi-system control strategies for House Management System

4.6 Minimize greenhouse gas emissions

To verify the environmental performance and make sure that designers promote sustainable design practices, it is important to assess the entire lifecycle impact of a building. Such an approach supports to minimize greenhouse gas emissions, while allows informed decisions when selecting building materials and technologies. In the case of PEBs, it helps to verify that additional impacts due to appliances and PV modules can be paid back with environmental credits and renewable energy production.

As for most buildings, load-bearing and envelope elements are the biggest contributors to a building's carbon footprint. For structures with reinforced concrete (RC) frames, these elements can account for up to 20% of total CO_2 equivalent emissions. Choosing between a timber-based frame and an RC frame involves balancing structural, energy, and architectural needs and preferences, along with costs and environmental impact.

To minimize life cycle emissions of buildings, technological improvements aiming at low carbon emission building materials are compelling. However, due to the complexity of building systems, it is necessary that designers carefully trade-off different performance requirements to identify optimal solutions meeting project sustainability goals. For instance, a common factor in all PEBs is the significant carbon footprint from photovoltaic (PV) modules. This results from the high carbon intensity of current PV production technologies. At present, finding lower-emission alternatives is challenging. However, this would not necessarily lead to higher total life cycle impacts of developed PEBs. In fact, in some cases PEBs demonstrated lower life cycle GHG emissions, when compared with reference nZEBs.

A recommended metric to evaluate the overall environmental impact of technology solutions is the environmental payback. It represents the time required to recoup the initial embodied CO_2 expended for the building construction through building operation carbon positivity. Constructive aspects and therefore embodied impacts can significantly influence the initial lifecycle impact.

In this regard, analyses conducted on solution sets level [6], showed that PV modules are the main contributors to the embodied environmental impact of the building. On the other side, PV plants can help to payback the initial environmental climate investment. An additional factor that affects the environmental payback of the PEB technologies is the carbon intensity of the energy coming from the grid. Globally, payback periods are primarily affected by the national carbon intensities for electricity generation: the Italian and German cases, for examples, reach environmental payback periods by 2050. In the French and Norwegian cases, the payback curve presents a slower trend, which may lead to question the proposed solutions and their environmental advantages. However, France has a nuclear baseline, while in Subarctic region, there are less chances for the installation of local PV and a high share of hydropower production.

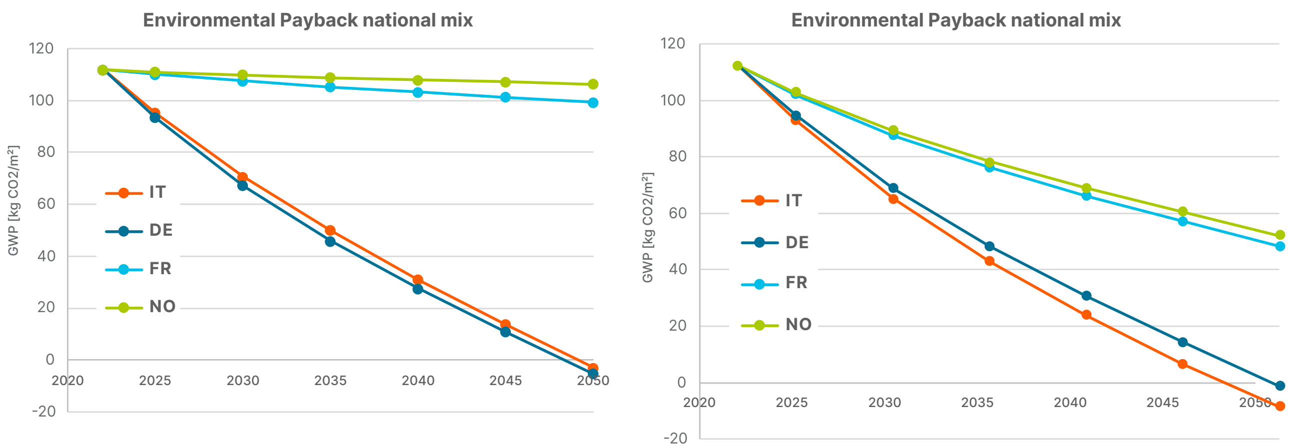


Figure 6. Payback periods of demo cases in Italy (IT), France (FR), Germany (DE) and Norway (NO) considering the specific national energy mix (left) and the EU averaged energy mix (right). Source: Di Bari et al., 2024.[12]

All in all, based on analyses conducted, the solution sets developed in Cultural-E have a total Global Warming Potential (GWP) over the lifecycle (30 years) lower than 5 kg CO_{2eq}/m2-y, considering all geo-clusters and building archetypes. High-rise buildings have a better environmental profile because of the optimization of resources.

>> For further information on LCA, please refer to the Guidelines to evaluate the environmental impact and payback of a PEB

[12] Turrin, F., Leis, H., Isaia, F., & Belleri, A. (2024). Effectiveness and sustainability of solutions sets aimed at plus energy buildings. A multi-case and multi-domain investigation. Journal of Building Engineering, 94(109914). https://doi.org/10.1016/j.jobe.2024.109914

4.7 Keep affordable costs over the building life cycle

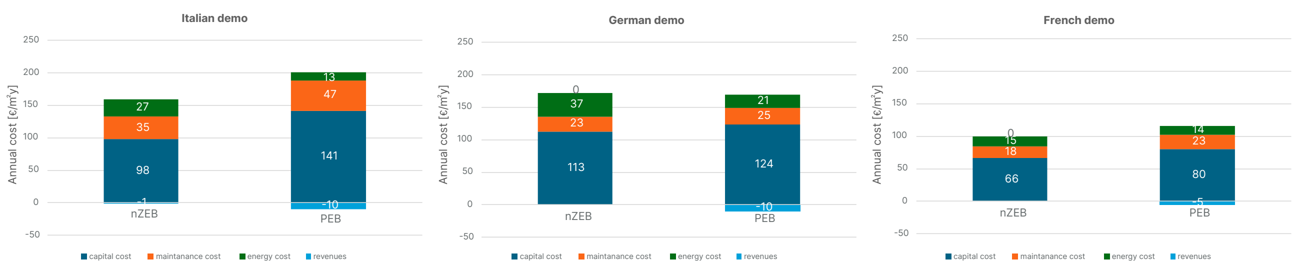
When designing Plus Energy Buildings, it is essential to conduct a comprehensive economic analysis that considers the total annual costs over a 30-year period. This analysis should apply a discount rate (suggested value is 1.0%) to accurately reflect the present value of future expenses. Designers must account for both initial investment and replacement costs as capital expenditures, recognizing that replacements due to the limited-service life of technical components — such as photovoltaic panels, battery storage systems, heat pumps, boilers, and ventilation units — can significantly impact long-term costs. Operational expenses, including energy use, maintenance, and system upkeep, should also be thoroughly evaluated to ensure the building's ongoing performance and economic viability.

Additionally, it is crucial to factor in the financial benefits derived from self-use of generated renewable energy and the revenue from selling excess energy back to the grid. These savings and earnings contribute to the overall economic performance of the building and can influence design decisions aimed at maximizing self-sufficiency. Potential price increases should be anticipated in all cost categories and economic models adjusted accordingly to safeguard against market volatility. Detailed guidelines to LCC analysis and hands-on tool for calculations are provided here.

The plus in a PEB generally comes from the electricity generated by the PV. This means that the revenue that can be generated from this electricity has a major impact on the economic viability and life cycle costs [9]. Meanwhile, the remuneration for the electricity fed into the grid is significantly lower than the purchase price. For the building system, it is therefore most interesting to sell the surplus electricity primarily to the residents of the building, if possible. If there is still a surplus of electricity, it is fed into the grid. To make such a business model attractive for the residents, the price for the PV electricity should be set 10% lower than the standard tariff that the residents have.

Minimizing energy imported from the grid and maximizing self-consumption of on-site produced renewable energy is crucial to make Plus Energy Buildings affordable in scenarios with fixed energy prices and no peak power tariffs.

Figure 7. Source: data courtesy of demo owners and elaborated by Steinbeis-Innovationszentrum energieplus.



Cultural-E demo cases compared to a reference nZEB needed an extra investment of 200-250 €/m2. The choice of technologies shall be contextualized and carefully considered. Even though decentralized HVAC systems have several other advantages, they impact significantly the overall investment costs (up to 10% more compared to centralized HVAC systems). For buildings with many apartments a centralized heat pump system is often more economical and practical.

>> For more information on investment costs and total annual costs calculated for solution sets in each geo-cluster, please refer to <u>Factsheets reporting solution set description and metrics for each climate-cultural geo-cluster</u>

>> For more information on LCC analysis, please consult the <u>manual of the tool for economical assessment of life cycle costs in PEBs</u>

>> For information on PEB business models, please refer to the <u>Guidelines for Plus Energy Buildings business models</u>

5. Design recommendations

Main design recommendations:

1. Set performance targets: set key design targets for energy, cost, environmental impact, social aspects, and indoor environmental quality and acknowledge the added value of PEBs for the user and the society over their lifespan
2. Engage key stakeholders and actors in the design process to integrate the energy concept into the building design.
3. Most of the total electrical consumption is due to plug loads, which are difficult to reduce or to shift in time. Empowering users to reduce energy consumption is fundamental (the home guides can play a key role here).
4. Understanding social and cultural practices is key to ensure an added value for users and an energy efficient usage of the technologies.
5. Life Cycle Assessment (LCA) and Lifa Cycle Cost analysis shall be applied during the design phase to support the decision-making process on construction materials and PV-battery system size.
6. Collecting users' feedback through survey or direct interviews is fundamental to increase user acceptance and ensure PEB targets are reached

5.1 Design phase

The overall Cultural-E recommendation on this matter is to keep a holistic approach, especially in bridging the gap between technical and behavioral aspects. The design phase shall be focused on what technologies are important to integrate in the design and how to reach IEQ targets.

SETTING GOALS

Set clear performance targets and verify them throughout the whole design process. Plan monitoring architecture from the beginning to ensure performance targets measuring and integrate it into a Building Management System (BMS).

ACTORS INVOLVED IN THE DESIGN PHASE

Architects and engineers should collaborate closely from the early stages of the design process, providing valuable feedback based on their respective expertise. This synergy fosters a deeper understanding of the building and ultimately enhances the project's quality.

Set procedures to effectively communicate between the different actors involved in the design, installation, maintenance and use of building technologies (project management, contractors, technicians, staff members, if any).

Key figures in the design process:

- Architect
- Energy Consultant is paramount if Architect cannot provide the service. Regulations are too complicated and techniques such as simulation of energy use are too specialistic for most architects. Energy consultants or Architects should also assist the Owner in navigating the available options for subsidies that the national government / EU is providing.
- MEP Engineer to design the technology (mechanical if needed, plumbing, electrical, heating / cooling). Could be substituted by MEP contractor who can also provide design services. MEP should be experienced in low energy buildings and understand the key principles of a PEB (see chapter 4).
- Structural Engineer.
- Other complementary expertise can include socio-technical professionals, data-driven service specialist, façade engineers, acoustic consultants, technical specification specialist for bid/tender preparation.

USE OF ENERGY MODELLING THROUGHOUT THE PROCESS

Use of energy simulations to assess the energy consumption of different archetypes in different climatic conditions. The use of energy simulations is important to replicate real-world scenarios and explore interactions within different building systems. Executable files of building simulation models are available on Cultural-E Zenodo repository and enable to simulate pre-defined building archetypes while tailoring the model by changing some input variables, such as envelope characteristics, technological solution sets for the HVAC system and weather data. Two building archetypes are available representing low rise and high rise multi-residential buildings with the project defined Plus Energy Buildings solution sets. The models allow for tailored input parameters options to account for 4 different climatic and cultural geo-clusters characteristics. Detailed HVAC models and controls are available for two different solutions: 1) centralized HVAC system and 2) decentralized HVAC service performed by a compact heat pump unit for heating, cooling, dehumidification and Domestic Hot Water (DHW). The models have been developed with TRNSYS software (version 18.02) and have been exported into executable files to be used by anyone, without the limitations of needing a TRNSYS license or having to be expert users of this simulation software. Due to its limitation of offering only two archetypes and solution settings, the tool is suitable primarily for the early project phase but cannot support the entire design process. Additionally, it does not account for varying building footprints or the number of floors, despite their significant impact on meeting the PEB target. At later project stages, we recommend conducting energy simulations that consider the specific footprint, shape, orientation, and location of the planned building.

SOLUTION SETS

Addressing at an early stage both passive design and innovative technologies, and when it is the latter, to consider their maintenance, robustness and integration with the construction material. This will help reach more sustainable solutions.
Building envelope characteristics should be tailored to climate conditions and material choices should be guided by LCC and LCA analysis to ensure low greenhouse gas emissions and economic viability.

Use all available techniques to limit heat loss (compact volume to surface ratio, orientation of building on site regarding sun and wind, consideration of existing vegetation to provide shading etc.)

Limit heat gain through windows by using shading or minimizing window sizes (need to be balanced versus power necessary to light interior when not enough day light).

Multi-residential PEBs in continental and subarctic climates have very low space cooling demand, which can be covered by implementing a device for smart air movement.

Pre-defined solution sets have been analyzed by Cultural-E project team on two building archetypes (high-rise, low-rise building) in four geo-clusters [8]. They can be a source of inspiration and offer hands-on benchmark performance and tips for designers on cultural habits.

Focus on the following aspects:

1. The importance of passive systems design;
2. HVAC system design and sizing taking into account passive solutions, users' habits, controllability at building scale and adaptability;
3. Integrating user-centered system controls and dashboard for data sharing with different access privileges;
4. PV design optimization, considering load profile and price dynamics - also an architectural matter in terms of exploiting available and usable roof and facade area - and battery system possible capacity;
5. Electric Vehicles (EV) charge integration.

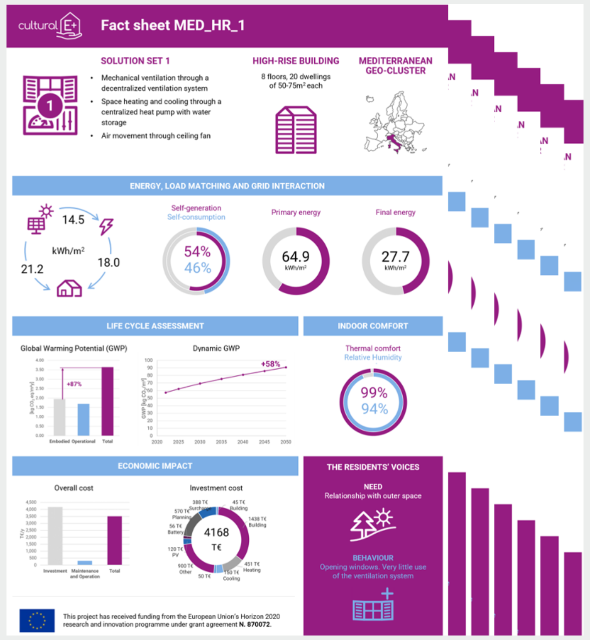


Figure 8. Factsheets reporting solution set description and metrics for each climate-cultural geo-cluster [8].

USERS' NEEDS AT FIRST

Anticipate how occupants will use the technologies and prioritizing their needs and comfort – which might not strictly relate to the most efficient way of using those technologies; if possible, involve tenants or tenants' representative in the process. Engage socio-technical professionals who can understand residents' and other occupants' needs and how they currently use the technologies, as well as habits driven by local cultural and social-economic features, determining peculiar boundary conditions. After that, those same professionals shall inform technicians about these behaviors for an adequate recalibration of the installed solutions and technologies.

CONNECT AND COMMUNICATE

The PEB includes different components and systems that use different data protocols and connections and proprietary software which cannot always "talk" to each other. Make sure that all components and systems can be completely incorporated in the BMS.

USE LOW CARBON MATERIALS

The load bearing structure and envelope elements are mainly responsible for the total building carbon footprint. If the building has a structural frame made by reinforced concrete elements, the latter contributes up to almost 20 % of the total environmental impact.

As a common feature, all Cultural-E demo cases environmental impact is significantly affected by their photovoltaic modules, reflecting the high carbon intensity of the current technology production.

While the CO_2 emissions of PV is an issue related to technological advancement, the choice between a timber-based frame or a reinforced concrete one lies on trade-offs among structural, energy and architectural requirements, costs and environmental quality.

Preliminary LCA analysis of the building design can raise a certain awareness in terms of environmental quality during the whole design process and lead to controlling the environmental impacts of the building.

5.2 Procurement phase

The procurement phase represents a critical juncture in realizing the objectives of PEBs. This stage requires careful coordination to translate design aspirations into practical, executable plans while addressing inherent complexities. One of the primary challenges lies in simplifying the process and ensuring clear communication among all stakeholders.

ENGAGING A GENERAL CONTRACTOR

as the central point of contact can streamline interactions and improve coordination. While general contractor involvement can streamline communication and coordination, its effectiveness depends on aligning contractual obligations with PEB objectives, particularly regarding energy performance and system integration. Additionally, exploring innovative contract forms, such as Public-Private Partnerships (PPP) or Private Finance Initiatives (PFI), offers opportunities to effectively distribute risks and responsibilities, fostering a collaborative approach to project execution.

BRIDGING THE GAP BETWEEN TECHNICAL SPECIFICATIONS AND BEHAVIORAL ASPECTS

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EARLY INVOLVEMENT OF CONTRACTORS

during the tendering phase is another crucial factor. This proactive approach enables the identification and resolution of potential challenges, ensuring that bids align with the project's complexity and objectives.

PERFORMANCE-BASED PROCUREMENT

is a procurement approach that focuses on strategic performance metrics of the building and directly relating contractors' performance to building energy performance. Building energy simulations helps contractors to assess design decisions related to advanced HVAC design, building materials, and renewable energy generation systems and storage design, based on long-term energy efficiency, operational cost, and indoor comfort. Building energy simulations allow teams to compare design scenarios, ensuring materials and systems align with performance goals and lifecycle costs. In PEBs, an optimal integration of passive (e.g., envelope materials, shading system) and active solutions (e.g., HVAC, ventilation) is essential to achieving an energy surplus. Building energy models also establish a performance benchmark for commissioning and monitoring, enabling procurement teams to set contractual requirements that hold contractors accountable for meeting modeled energy targets. By focusing on outcomes rather than prescriptive solutions, the continuous monitoring of performance become the main mean to check if the building meets the PEB performance targets and helps understanding the potential causes

BRIDGING THE GAP BETWEEN TECHNICAL SPECIFICATIONS AND BEHAVIORAL ASPECTS

of an eventual performance gap between predicted and measured performance. Clearly defining roles and responsibilities for commissioning activities in the procurement phase, such as performance evaluations and system testing, ensures accountability and alignment with overarching project goals.

VISUAL AIDS, SIMPLIFIED GUIDELINES, AND QR CODES

enhance contractor understanding by providing structured, easily accessible information relevant to PEB projects. Visual aids, such as system schematics or step-by-step installation diagrams, clarify integration challenges and performance expectations. Simplified guidelines translate complex procurement requirements into practical checklists or workflows, ensuring contractors meet PEB efficiency targets. While QR codes link to digital resources, in a PEB context, they can be placed on installed systems—such as a heat pump or energy management panel—allowing contractors or users to instantly access instructional videos, troubleshooting steps, or digital manuals. These tools collectively reduce misinterpretations and facilitate smoother procurement and implementation (see Section 5.5). Additionally, comprehensive onboarding materials further support contractors in navigating system integration and performance requirements.

TRAINING AND USER-CENTRIC TOOLS

play a vital role in the procurement contracts to anticipate diverse social practices and adopt innovative assumptions and controls aimed to fulfil users' needs while also optimising energy demand. Incorporating Post Occupancy Evaluation and monitoring during first year of building operation in procurement contracts ensures that building executive design and construction is oriented towards user satisfaction and operational success (see section 5.5).

5.3 Construction phase

The construction phase is a critical step in transforming design objectives into operational PEBs. This stage demands a strong emphasis on bridging the gap between technical installation and design, ensuring alignment with both functional and user-centric goals. Addressing the challenges specific to construction requires a structured approach focused on workforce capabilities, project scale, quality assurance, and user engagement.

A key challenge in PEB construction is ensuring access to a workforce skilled in renewable energy systems, high-performance building envelopes, and advanced HVAC installations. Designers and project managers can address this by collaborating with contractors who specialize in energy-efficient construction and by specifying experience requirements in procurement documents. Engaging suppliers and installers early in the design process ensures that workforce capacity aligns with project demands. Additionally, leveraging pre-certified professionals and training programs provided by manufacturers of PEB-related technologies—such as high-efficiency HVAC systems or smart energy management tools—can help guarantee that the construction team has the necessary expertise to implement the design effectively

SCALE OF THE PROJECT

The scale of the project influences construction dynamics. Larger projects often necessitate intermediary actors to ensure smooth coordination across teams and adherence to timelines. Implementing lean construction management practices can further streamline operations, reduce bottlenecks, and maintain focus on meeting performance goals. By balancing project management strategies with clear communication protocols, stakeholders can address the complexities inherent in large-scale PEB construction.

QUALITY ASSURANCE

is paramount during the construction phase. Comprehensive system-level checks should be conducted to verify that all components function cohesively within the broader design framework and contribute to meet the expected performance. Digital tools, such as Building Information Modeling (BIM), play a vital role in supporting real-time collaboration and documentation, reducing errors and ensuring seamless integration of systems. This approach not only enhances the efficiency of the construction process but also safeguards the intended performance outcomes of the building.

INTEGRATION OF USER-CENTRIC PRINCIPLES

is another critical consideration. Simplified, visual materials, such as QR codes linked to instructional resources, can assist construction teams in understanding and correctly installing complex technologies. Drawing on feedback from the Cultural-E one-off surveys ensures that user needs are considered and addressed, promoting alignment with end-user expectations (See Section 5.5).

ESTABLISHING FEEDBACK LOOPS

during construction provides a mechanism for on-site teams to communicate challenges and successes promptly to the contracting body. This iterative approach enables stakeholders to refine practices, address emerging issues, and ensure that construction aligns with the broader objectives of the PEB project

ADOPT LEAN CONSTRUCTION METHODOLOGIES

to maximize value and profitability for all stakeholders. Lean construction systematically employs the methodology of 'lean thinking,' a philosophy widely used in various industries to reduce waste, minimize productivity loss, and address environmental issues in the construction industry. It contributes to make building projects run efficiently and smoother, streamline operations, cut costs, and elevate the standards of the final output.[13]

[13] https://www.lcmd.io/en/blog/lean-construction-management#what-is-lean-construction

5.4 Commissioning phase

The commissioning phase serves as a critical step in validating the functionality and performance of all systems within a PEB. This phase not only ensures that the building operates as intended but also lays the groundwork for long-term success by addressing performance gaps and fostering user satisfaction.

COMPREHENSIVE TESTING

during the run-in phase is essential. All technical systems should be tested and debugged under normal building operation conditions, ideally with tenants already in place. Engaging independent commissioning agents can further enhance this process by providing an unbiased evaluation of system performance and identifying discrepancies between design intent and operational realities. This rigorous approach minimizes performance gaps and ensures that the building's systems function as an integrated whole.

PHASED COMMISSIONING APPROACH

For larger projects, a phased commissioning approach is recommended. By prioritizing a subset of dwellings for initial testing, stakeholders can gather valuable insights and refine processes before scaling up to the entire building. This strategy reduces the risk of widespread issues and allows for a more controlled and efficient commissioning process.

A STREAMLINED HANDOVER PROCESS

is vital for ensuring that building operators and residents are well-prepared to interact with the installed systems. Comprehensive training sessions, supported by visual and digital aids, can enhance understanding and promote user confidence. Home guide principles should be referenced to provide user-friendly explanations of system functionalities and maintenance requirements, fostering greater acceptance and effective use of the technologies.

MONITORING FRAMEWORKS

established during the commissioning phase play a pivotal role in capturing real-time data and identifying potential issues early. These insights enable stakeholders to fine-tune system performance, optimize efficiency, and ensure that the building meets its intended objectives.

A STREAMLINED HANDOVER PROCESS

To achieve optimal energy performance in PEBs, it is essential to move beyond relying solely on measurements of energy uses. While measurements provide valuable data, they often fall short in uncovering the underlying causes of inefficiencies. Therefore, it is recommended to develop a digital twin of the building (with optimal level of detail) to be used for simulations that accurately predict building and HVAC systems performances and can be used to set the optimal control strategies. By integrating real-time Building Management System (BMS) data with these advanced building energy simulations, commissioning teams can gain deeper insights into building operations, diagnose inefficiencies, and implement targeted optimizations. This approach allows for a more comprehensive understanding of energy dynamics, leading to more effective interventions that enhance the energy performance and overall functionality of Plus Energy buildings.

5.5 Monitoring and POE

Monitoring and Post-Occupancy Evaluation (POE) are essential for validating the long-term success of PEBs in real-world conditions. By combining advanced monitoring systems with active resident engagement, this phase ensures alignment with design objectives while fostering continuous improvement.

A COMPREHENSIVE MONITORING SYSTEM ARCHITECTURE

is crucial for capturing key metrics related to energy uses, renewable energy production, self-consumption rate, energy exchanges with the grid and indoor environmental quality (temperature, relative humidity, CO_2 levels, and air pollutants). Communication protocols and sensors compatible with cloud-based systems should be employed to facilitate real-time data collection and analysis. Utilizing a combination of continuous monitoring, one-off surveys and spot measurements provides a nuanced understanding of indoor environmental quality (IEQ) and overall comfort.

FLEXIBILITY AND DEMAND MANAGEMENT STRATEGIES

are integral to optimizing energy use in PEBs. Measures such as demand-side management and reducing peak demand can enhance energy self-consumption, ensuring efficient operation and alignment with sustainability goals (see section 4.4 and 4.5).

RESIDENT FEEDBACK

plays a pivotal role in POE. Tools such as surveys, focus groups, and semi-structured interviews should be employed to gather insights at multiple points throughout the year, capturing seasonal variations in user experience. For example, the Cultural-E one-off survey evaluates IEQ satisfaction, user interaction with technologies, and overall comfort (see Appendix: Post-Occupancy Evaluation Survey for POEs in CULTURAL-E).

PROVIDING TAILORED TRAINING AND HOME GUIDES

is essential to empower residents in optimizing their use of PEB technologies. Resources such as the Cultural-E home guides, incorporating visual aids and QR codes, can simplify complex concepts and promote energy-saving behaviors. These guides are particularly valuable for ensuring user-friendly interactions with installed systems.

PLUG LOAD OPTIMIZATION

should not be overlooked, as it constitutes a significant share of energy consumption in low-energy buildings. Recommendations include adopting high-efficiency appliances and promoting behavioral strategies to reduce unnecessary energy use.

KEY PERFORMANCE INDICATORS (KPIS)

are instrumental in systematically evaluating building performance. Metrics such as energy efficiency, peak export and import rates, and user satisfaction should be monitored to assess the effectiveness of PEB systems. These indicators align POE findings with pre-defined objectives, enabling data-driven decision-making.

AN ITERATIVE APPROACH

to improvement is essential. By analyzing monitoring data alongside resident feedback, stakeholders can identify gaps between predicted and actual performance, recalibrate systems, and refine operational strategies.

A GUIDING TOOLKIT

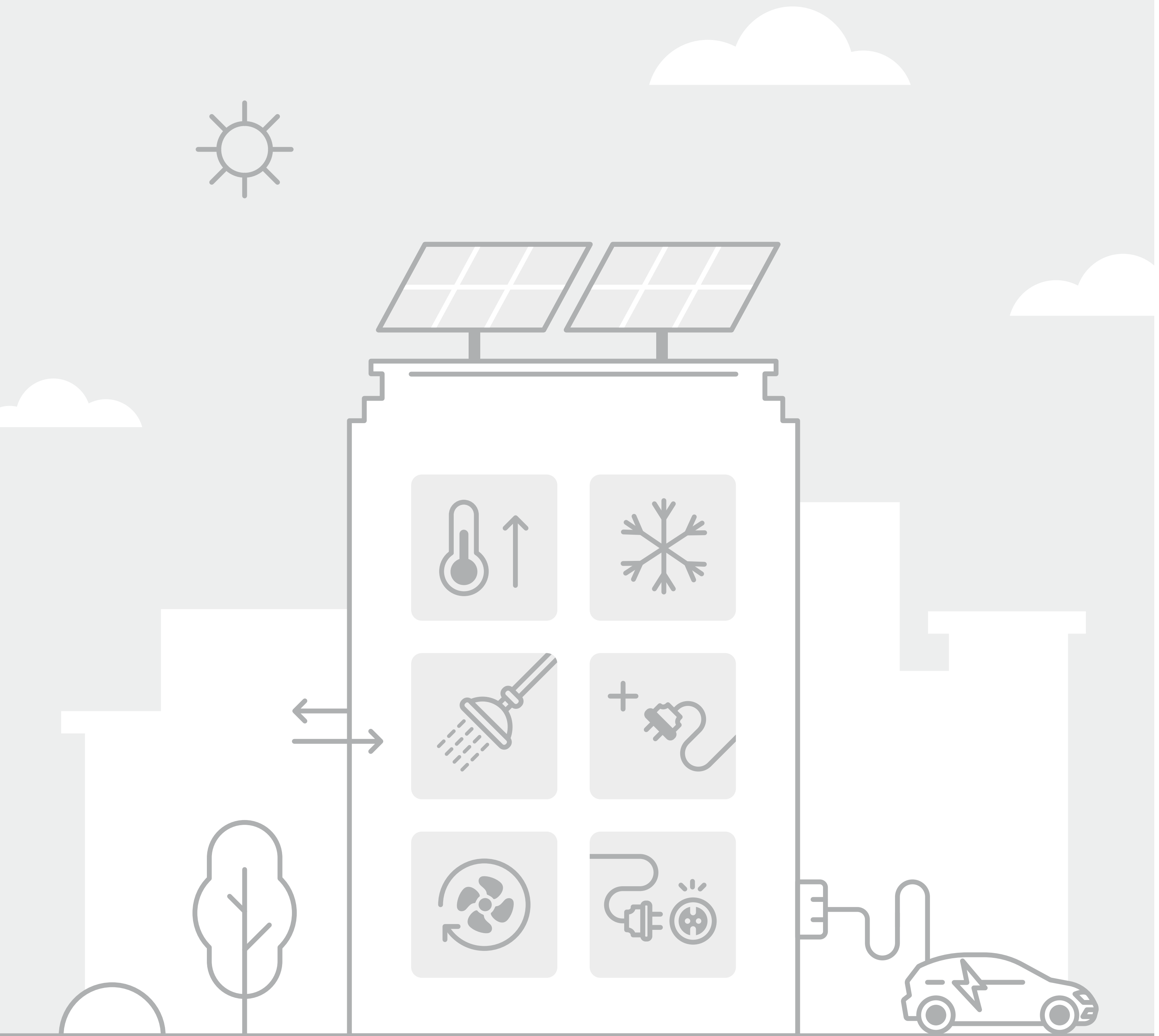
serves as a cornerstone for monitoring and POE, offering structured methodologies for resident engagement and actionable feedback. Survey templates, training modules, and guidelines included in the toolkit can be adapted to meet project-specific needs, ensuring consistency and scalability (see A guiding Toolkit for designing Home Guides for PEBs).

ADDRESSING ANTICIPATED RESIDENT NEEDS

Recognizing the diversity of residents' preferences and behaviors, the strategies outlined above aim to anticipate needs rather than require drastic behavioral changes. While tools such as home guides and surveys provide guidance, their design emphasizes ease of use and minimal effort for residents to engage with the technologies. The intention is to create solutions that are intuitive and self-explanatory, ensuring accessibility for a broad range of users, including those without technical expertise. This approach ensures that PEB systems work seamlessly alongside existing habits, promoting adoption through practicality and convenience rather than requiring significant lifestyle adjustments. By focusing on this balance, PEBs achieve energy efficiency without alienating residents or creating undue complexity.

>> The Cultural-e project checklist provides a simple list of actions and requirements to guide the Plus Energy Buildings implementation.

6. Key technologies



Cultural-E has focused on developing innovative key solutions and concepts aimed at delivering cost-effective packages for Plus Energy Buildings (PEBs). This section highlights the key technologies developed within the project, along with lessons learned and practical tips for their architectural integration. These insights are intended to facilitate the seamless adoption of Cultural-E technologies in the next generation of PEBs.

It is important to note that these guidelines do not aim to mandate the use of these specific technologies as the sole means to achieve Plus Energy targets. Instead, the selection and integration of solutions should be thoughtfully adapted to the local climate, cultural context, and project-specific requirements.

Building on the extensive information gathered throughout the project — including development progress and technical integration strategies for pilot buildings — we have structured this section of the guidelines into eight categories to present the information effectively:

- C1 Architectural integration in the building design
- C2 Overall impact on PEB performance
- C3 User interaction
- C4 Certification /standardisation
- C5 Maintenance and installation
- C6 Costs
- C7 Compatibility with other systems
- C8 Environmental impact

6.1 Active Window System

The Active Window System is a new window system that aims at changing the traditional window concept to an active element that promotes energy efficiency, indoor air quality and user comfort. The Active Window System is based on the following technological pillars:

- Modular wood frame system: The new wood frame design was conceived to be easily adaptable to different configurations, such as different climates, different insulating glazing units (IGU) or integration of different shading devices. It was designed to be easy to manufacture and to install both in-wall and insulated block installation. It is made of natural and recyclable materials.

- Movable adaptive shading system: The AWS can integrate different shading systems, such as external shading, electrochromic glass or integrated venetian blinds. In the latter case, the venetian blinds are allocated in a semi-ventilated external chamber in front of the insulating glass unit and protected by an external openable glass. This configuration allows us to easily maintain the system.

- Integrated decentralized ventilation device: The AWS, as a multifunctional window system, allows the integration of decentralized ventilation devices, such as passive trickle vents for assuring certain natural ventilation or active compact mechanical ventilation machines with heat recovery.

- Interaction between shading semi ventilated cavity and decentralized ventilation device: The most advanced configurations of the AWS include the venetian blinds in the semi ventilated cavity and the ventilation device in a way that they collaborate with each other, with the aim of exploiting the shading cavity ventilation for optimizing indoor air quality and energy consumption. This could be done in different ways depending on the type of ventilation device (passive or active) and the season.

Why to use it?

- **Simplified** installation process and reduced installation error risks.
- **Easily adaptable** to each specific case and design requirements.
- **Highly efficient system** from the base configuration to the most advanced ones.
- **Possibility to integrate the shading device in front of the IGU in a protected but accessible semi-ventilated cavity.** This allows to access the shading device for cleaning, maintenance, or replacement in presence of any malfunctioning.
- **Interaction between the ventilation of the shading cavity and the ventilation of the indoor space** to make them collaborate and further improve the thermal performance of the window system.
- **Shading control strategies optimised** between visual/thermal comfort and winter/summer energy savings for different climates, facade orientations and shading types.

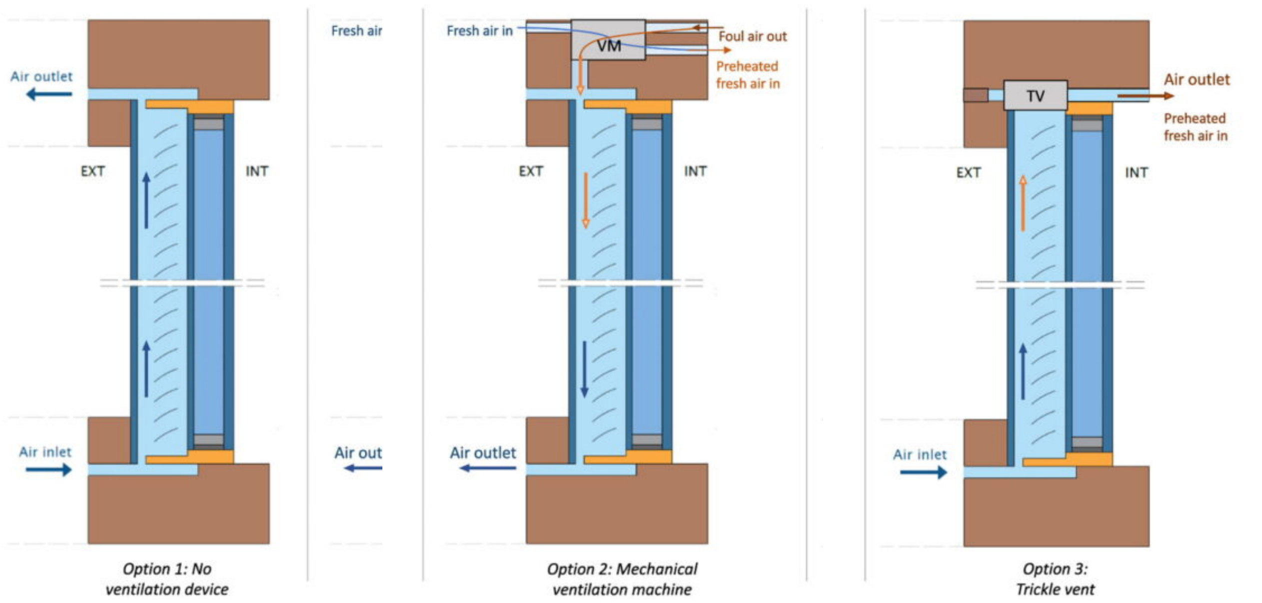


Figure 9. Sketches showing different configuration options for the Active Window System. Source: Eurac Research

Designers are encouraged to explore the Active Window configurator tool as a valuable resource to configu re Active Window System (AWS) for diverse climate conditions, wall orientations and design requirements. This tool enables designers to easily compare different configurations and assess their implications on sy-stemystem behavior.

By using the AWS configurator, designers can evaluate a range of Key Performance Indicators (KPIs) spanning critical domains such as energy performance, thermal comfort, daylighting, and Indoor Air Quality (IAQ). The tool supports analysis of:

- Climate-specific impacts on window frame and glazing thermal characteristics
- Shading solutions, including external shading, integrated shading within the Insulated Glazing Unit (IGU), or electrochromic glazing
- Ventilation options, such as no ventilation, Trickle Vents (TV), or Controlled Mechanical Ventilation (CMV)
- Interactions between ventilation systems and shading strategies

TIPS FROM DESIGNERS TO DESIGNERS	
C1 – Architectural integration	Modularity of the external finishing and protection of the main wooden frame. Account for the combined weight of triple glazing and shading elements when designing the opening system to ensure structural integrity and smooth operation. Ensure the frame is pre-equipped with anti-depth sensors to enhance safety and functionality, especially in automated systems. Address client concerns about potential material overlap by providing physical samples to aid in visualizing the final design and build confidence in the solution. Specify and verify acceptable dimension tolerances for the frame cover to ensure a precise and secure fit during installation. Design with condensation control in mind by selecting appropriate materials, finishes, and ventilation strategies to maintain performance and durability.
C2 – Impact on PEB performance	The inclusion of triple glazing significantly enhances thermal insulation, reduces heat loss, and improves overall energy efficiency, aligning with the energy-positive goals of PEBs. A potential air inlet with an integrated heat exchanger contributes to improved indoor air quality and efficient heat recovery, optimizing the building's HVAC system and energy balance. The modular design of the window system allows it to seamlessly adapt to various architectural and technical requirements, enabling integration with different building systems and technologies. The innovative blind control system provides precise solar shading and daylight management, reducing cooling loads and enhancing occupant comfort while supporting energy efficiency.
C3 – User interaction	The inclusion of triple glazing significantly enhances thermal insulation, reduces heat loss, and improves overall energy efficiency, aligning with the energy-positive goals of PEBs. A potential air inlet with an integrated heat exchanger contributes to improved indoor air quality and efficient heat recovery, optimizing the building's HVAC system and energy balance. The modular design of the window system allows it to seamlessly adapt to various architectural and technical requirements, enabling integration with different building systems and technologies. The innovative blind control system provides precise solar shading and daylight management, reducing cooling loads and enhancing occupant comfort while supporting energy efficiency.
C4 – Certification / standardisation	CE marked[14] Passive House standard

[14] At the moment of the writing of the deliverable, the CE marking for the Active Window System is in progress.

C5 – Compatibility with other systems	If incorporating ventilation features, ensure they do not conflict with existing or conventional air renewal systems, like centralized ventilation to avoid inefficiencies or performance issues. Consider how the window system can combine with various glass types, shading devices, and other products, ensuring flexibility in meeting diverse architectural and performance requirements. Choose motors that are suitable for the size, weight, and automation needs of the window system. Ensure they are durable, energy-efficient, and capable of operating smoothly over time. Opt for decentralized ventilation systems only if centralized or semi-decentralized solutions are not feasible.
C6 - Costs	n.a.
C7 – Maintenance and installation	Ensure easy access for cleaning glazing and shading systems Make sure the window system can be easily uninstalled or removed if necessary, allowing for flexibility in case of upgrades, repairs, or replacements. In case maintenance requires replacing part of the frame (e.g., the chassis), ensure the process is straightforward. For improved longevity, opt for a wood frame with an aluminum cover instead of wood-to-wood systems, which may require more frequent replacements. Choose exterior materials that are durable and resistant to aging, particularly for high-performance buildings. Ensure the selected joinery withstands environmental factors without the need for frequent corrective work. Plan maintenance access, particularly for outdoor integrations, ensuring safety during repairs. Consider whether an access pod is required for modifications on higher floors and incorporate this into your design. Since the installation process involves two stages, it is more complex than typical installations. Create simple, user-friendly installation layouts and processes, and provide a detailed document for installers to follow for accurate execution.
C8 – Environmental impact	Wooden framed windows have a low environmental impact. Most of the global warming potential lies in its sub-components: the ventilation unit and the shading system integrated in the window system. GWP 275kgCO_{2eq}/m2

6.2 Smart air movement

Air movement is an energy efficient means to provide thermal comfort in warm environments, minimizing or completely avoiding the use of more energy-intensive air conditioning. While the heat generated from a human body does not vary, the forced convection accelerates the heat transfer between the parts of the body skin hit by the air flow and the surrounding thermal environment.

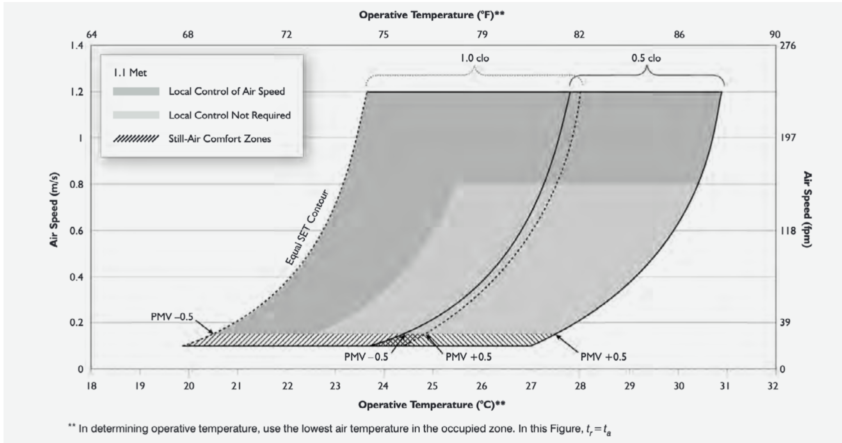


Figure 10. Higher air velocities enable acceptable comfort at elevated temperatures. Comfort zone also depends on clothing levels, with lighter clothing allowing for greater adaptability to warmer conditions. Source: Arens E. et al, 2009. [15]

The Smart Air Movement is a ceiling fan system in which the rotational speed of the fan is driven by measured indoor variables such as temperature and humidity and by people activity level inside the rooms. The generated air movement can provide comfort cooling comparable with a more energy-intensive cooling system source in specific range of temperatures (approximately from 26°C to 32°C).

If fans are available, research has shown that the same level of comfort can be achieved also at higher operating temperatures. Based on this, both ASHARE 55 and EN16798-1 state that an operative temperature correction can be applied for buildings equipped with fans or personal systems providing building occupants with personal control over air speed at occupant level. This means that a higher cooling set-point can be used depending on the assumed average air speed, namely 1.2 °C higher for 0.6 m/s, 1.8 °C for 0.9 m/s, and 2.2 °C for 1.2 m/s.

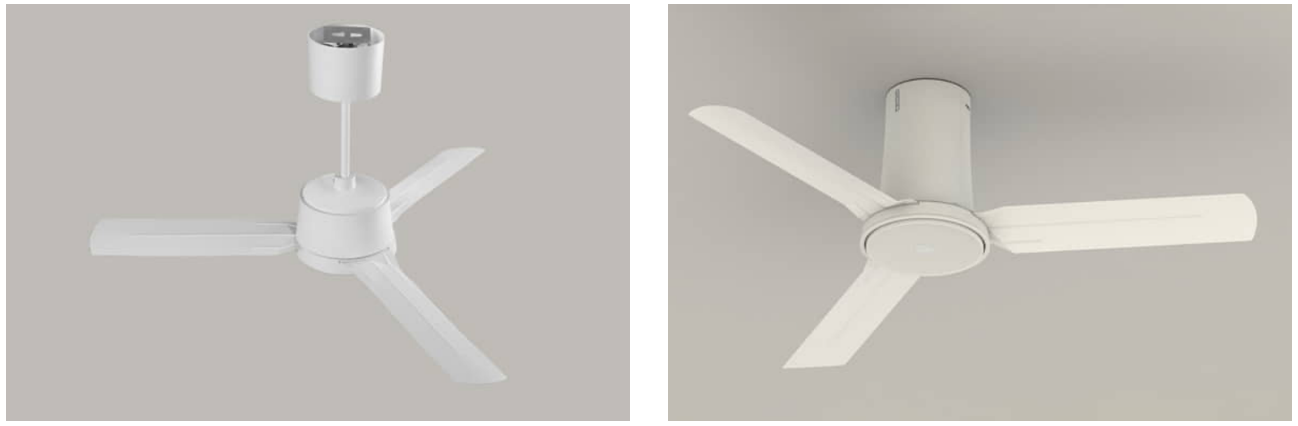


Figure 11. Vortice Nordik eco ceiling fan before (left) and after (right) the redesign. Without jeopardizing the fans' performances (i.e. air flow generated), the blade-to-ceiling height was reduced to 30cm to enable the installation of the ceiling fans also in rooms with internal height down to 260cm, which is a common situation in recent and brand-new residential buildings in Europe.

[15] Arens E., S. Turner, H. Zhang, and G. Paliaga. 2009. Moving air for comfort. ASHRAE Journal, May 51 (25), 8 – 18. https://escholarship.org/uc/item/6d94f90b

The key technological step forwards are **better integration of the ceiling fan within the HVAC system** and hence building energy concept, and the **improvement of the ceiling fan body** to reduce the blade-to-ceiling distance and integrate a sensor for automatically estimating the occupants' activity level.

The **ceiling fan is fully integrated with the HVAC system** to unleash energy savings potential in the summer season while ensuring a stable and high level of thermal comfort, and it will learn from the occupant's control preferences and coordinate its action with cooling and ventilation systems for an energy efficient, comfortable and healthy indoor environment. Further development of the fan unit was focused on embedding a **movement sensor** to enable the automatic identification of the activity level which otherwise must be manually selected by the user. In any case, a complete manual operation of the fan is always possible (i.e. rotational speed and flow direction directly chosen by the user overriding the automatic control logic).

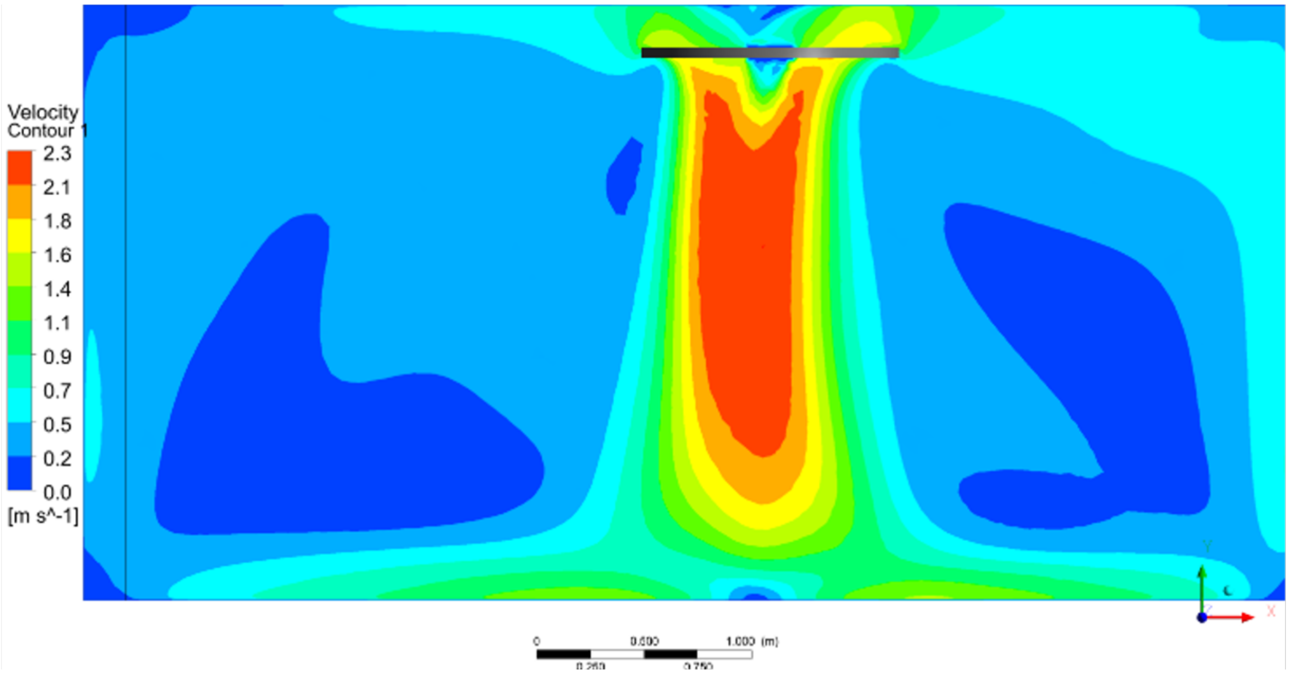


Figure 12. Air speed field generated by direct flow mode (scale from 0.0 m/s to 2.3 m/s). Source: Babich et al., 2021. [16]

Why to use it?

- Less operational costs for cooling than active cooling systems.
- Provide comfort cooling comparable with a more energy-intensive cooling system source in specific range of temperatures (approximately from 26°C to 32°C).
- Improve user adaptation.
- Saving space for cooling systems.
- Less maintenance needed compared to active cooling system.

[16] Source: Babich F. et al, 2021. Babich, F., Pasut, W., & Belleri, A. (2021). The use of ceiling fans in reverse-flow mode for comfort cooling: physiological aspects and relationship with internal standards, ASHRAE virtual annual conference, ASHARE Transactions Virtual Vol. 127, Pt. 2

TIPS FROM DESIGNERS TO DESIGNERS	
C1 – Architectural integration	blade-to-floor distance must always be 230cm or more for safety purposes. Ideally, install the ceiling fan at the center of the room to ensure even air distribution across the entire space. Lighting has similar requirements. Putting rotating blades close to lights would cause light flickering; thus, the ceiling fans can host light on the stem to solve this issue.
C2 – Impact on PEB performance	Dynamic building simulations performed within the project provided a detailed understanding of the impact of ceiling fans on building energy performance across different climates. In the **Mediterranean climate**, space cooling is reduced by 40% for low-rise residential buildings and 58% for high-rise residential buildings. In the **Oceanic climate**, the reduction is 55% for low-rise residential buildings and 35% for high-rise residential buildings. For both **Continental** and **Sub-Arctic climates**, ceiling fans delay the space cooling demand, contributing to energy efficiency. Ceiling fans also reduce the electrical consumption of the HVAC system. In the **Mediterranean climate**, HVAC consumption is reduced by 18% for low-rise residential buildings and 53% for high-rise residential buildings. In the **Continental** climate, the reduction is 9% for low-rise buildings and 20% for high-rise buildings. In the **Oceanic climate**, the reductions are 23% and 21%, respectively, while in the **Sub-Arctic climate**, HVAC system consumption decreases by 5% for low-rise buildings and 4% for high-rise buildings.
C3 – User interaction	Automated control of ceiling fans was proved to guarantee 90% of user satisfaction for temperatures up to 29.5 °C and still managing to guarantee satisfaction higher than 85% at higher temperatures. Ceiling fans can work in direct flow or reverse flow mode, but reverse flow is not perceived as effective as direct flow mode by users
C4 – Certification / standardisation	EMC test approval RED conformity Certificate
C5 – Compatibility with other systems	Ceiling fans can be effectively integrated in the HVAC system to enable to use a higher cooling set-point (and thus lower energy use) thanks to the generated air movement. The ceiling fans allow to reduce the utilization of the radiant panels, thus reducing the risk of condensation's formation on the floor. Moreover, the air motion created by the ceiling fans further reduces the risk of condensation's formation.
C6 – Costs	Limited cost if compared to an active cooling system.
C7 – Maintenance and installation	Easy installation and no maintenance needed, except cleaning the blades from dust.
C8 – Environmental impact	GWP 75 $kgCO_{2eq}$/item Most of its global warming potential lies in the electronics systems, in which is included also the Control Unit with Wi-Fi systems. Alternatives to such materials are at the moment hardly available.

6.3 Decentralized packed heat pump system

All-in-one solution with compact dimensions, providing balanced ventilation, hot water and comfort by using exhaust air as a source of energy, combined with a high efficiency heat pump and intelligent connected controls. Actively adapting to each individual home, the system provides outstanding energy performance at a manageable cost.

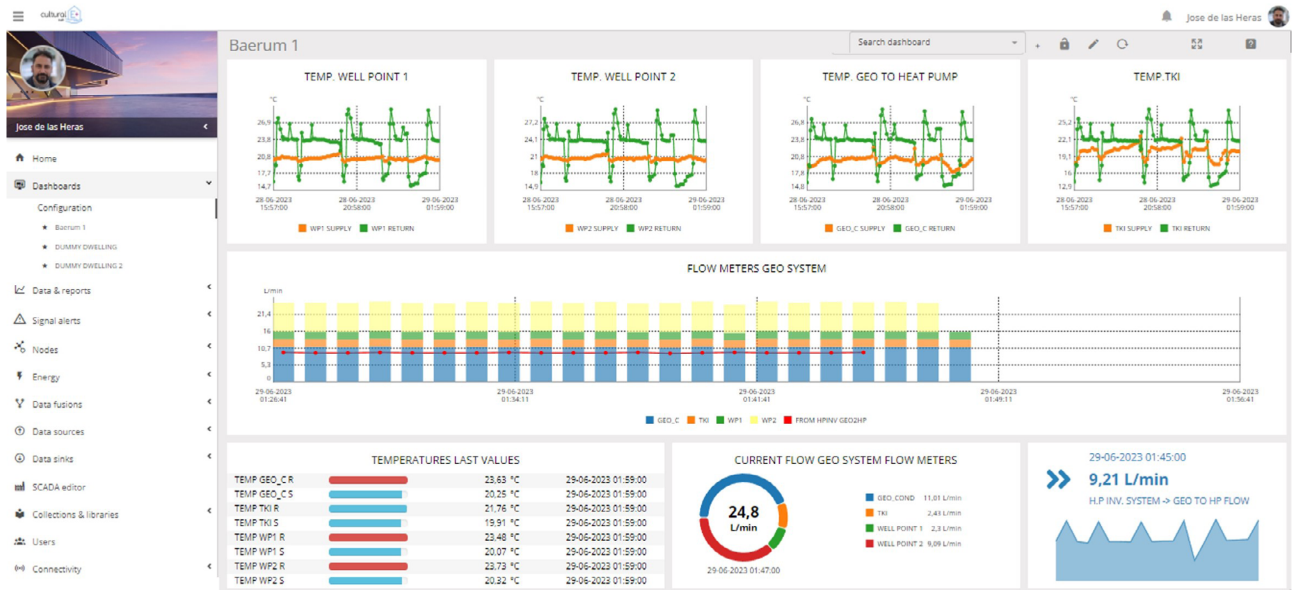
Why to use it?

- Low emission and low energy.
- Better air quality - fresh air delivered to rooms, no mixing of stale air.
- Can suit users' needs. Performance optimized to suit occupancy.
- Can be connected to the cloud system for real-time performance monitoring and proactive maintenance.
- Increased comfort as quickly responds to users' needs; Winter heat recovery to keep your house warm and summer cooling to avoid overheating.
- Compact size and easy to install.

TIPS FROM DESIGNERS TO DESIGNERS	
C1 – Architectural integration	Decentralized heat pumps can be installed inside or outside the apartment (i.e. on balconies or technical room in the staircase). Indoor installation is recommended to reduce thermal dispersion. Evaluate and mitigate the visual impact of heat pump components on the building façade. Consider aesthetic solutions like integration into existing structures or using design elements that blend with the building's appearance. Target is individual housing units, making it an ideal choice for retrofit or decentralized heating projects. Decentralized systems can be an attractive alternative to centralized solutions to avoid the need for collective domestic hot water pipes maintained at high temperatures (e.g., 60°C) and to overcome barriers related to pipe length restrictions. Provide noise insulation solutions for closets or technical rooms to minimize noise impact, specifying wall and door types to reduce sound transmission. Specify antivibration mounts with references to minimize operational vibrations, ensuring a quiet and stable installation.
C2 – Impact on PEB performance	The cooling fluid is critical in the CO_2 LCA of the building. Lower impact refrigerants are recommended.
C3 – User interaction	Provide a dynamic thermostat with app-based controls, enabling users to easily monitor and adjust system settings, also remotely. Include a comprehensive list of system data and operational information accessible to facility managers, ensuring efficient monitoring and maintenance of the system.
C4 – Certification / standardisation	CE mark, kiwa
C5 – Compatibility with other systems	It has its own controller and management system but can send data to the general house management system to show status parameters and settings.
C6 – Costs	Consider building size: For buildings with many apartments, a centralized heat pump system is often more economical and practical. In countries like Italy, owning more than six apartments classifies one as a legal entity, incurring higher taxes. This may make centralized systems more appealing for landlords. Social landlords (e.g., social housing companies) often prefer centralized systems due to their responsibility for operation and maintenance, which centralization simplifies. Decentralized systems can be fairer for occupants, as only those with inefficient energy usage are directly impacted by higher costs, fostering responsible behavior. Decentralized systems can be an attractive concept for project owners (like real estate promoters), who want tenants to bear their individual heating and cooling expenses, maintenance included. The compactness of the system allows to optimize spaces.
C7 – Maintenance and installation	For multi-owned residential buildings, consider individual maintenance contracts for each dwelling rather than one for the whole building. While centralized systems may work for social housing, ensure a clear, validated contractual framework is in place for shared systems. Clearly outline the terms of the maintenance contract, including responsibilities, frequency of servicing, and expected costs. Define who is responsible for replacing faulty components and supplying spare parts, ensuring transparency and accountability. Rely on local or national contact points for installation and maintenance to ensure efficient support and reduce downtime.
C8 – Environmental impact	Heat pump: GWP 702 $kgCO_{2eq}$/item Heat storage: GWP 51 $kgCO_{2eq}$/item High Global Warming Potential due to the metal parts of the system.

6.4 House Management System

The cloud-based House Management System (HMS) is a smart solution that optimizes the energy performance and comfort of buildings by integrating data from various sources and controlling different technologies. It is compatible with existing equipment and can be accessed by different users through a web portal and an app.



Dashboard of the cloud-based management system. Source: image courtesy of Advanticsys

The cloud-based HMS is a breakthrough in the field of smart buildings, as it enables not only tenants or end users but also owners and facility managers to be in full control of their building and subsystems.

Why to use it?

- It balances energy supply and demand, minimizes consumption and carbon emissions, and ensures optimal indoor comfort, by leveraging data from indoor and outdoor sensors, renewable energy systems, storages, web services, grid signals, and other buildings.
- It has a user-friendly interface that informs and guides the users on how to interact with the systems and adopt energy-efficient behaviors.
- It is a non-intrusive system that adapts to the building characteristics and user preferences.
- It is a cost-effective solution that requires no maintenance and can be easily integrated with existing equipment.

TIPS FROM DESIGNERS TO DESIGNERS	
C1 – Architectural integration	Take into account the physical dimensions of additional hardware components during the design phase to ensure proper accommodation. Plan for integration with electrical cabinets to determine if the system can be incorporated into a traditional electrical cabinet. If so, design the cabinet layout to accommodate the house management system components efficiently while maintaining compliance with safety and accessibility standards.
C2 – Impact on PEB performance	Enhance building flexibility and energy efficiency of the building overall and potentially in connection with a REC. Engage occupants by encouraging sustainable behaviours.
C3 – User interaction	Provide tenants with clear, engaging, and educational information about energy use and sustainability. Enhance comfort and user satisfaction implementing occupancy-based controls and responding to real-time usage patterns. User interface is intuitive and user-friendly for both younger and older occupants and includes customizable settings.
C4 – Certification / standardisation	ISO 52120-1:2021 [17] "Energy performance of buildings — Contribution of building automation, controls and building management". Smart Readiness Indicator
C5 – Compatibility with other systems	Select an HMS with high capacity and modularity to allow for future scalability. Clarify the specific services offered by the system to ensure they align with project goals and operational needs. Verify where and how user data is stored, processed, and protected. Ensure the system complies with GDPR regulations by confirming data storage locations, usage policies, and the provider's data protection commitments. Specify the use of open protocols (e.g., KNX) in system requirements to guarantee interoperability with other building systems. This approach allows flexibility for future upgrades and prevents vendor lock-in.
C6 – Costs	Depends on the services/packages needed
C7 – Maintenance and installation	Choose an HMS that offers comprehensive monitoring features to track system performance and energy usage. Ensure sensors and monitoring tools are easily accessible for maintenance and upgrades. Select systems with open API capabilities to enable seamless data collection and integration with other smart devices or building management systems. This flexibility simplifies future expansions and system updates. Anticipate long-term maintenance needs by securing a service contract that outlines regular system checks, updates, and potential repair costs. This helps manage expenses and ensures consistent system performance over the building's lifespan. Ensure the provider offers robust technical support and long-term service continuity to minimize downtime. Clearly define the responsibilities of technology providers regarding system failures or malfunctions. Include warranty terms and liability coverage in contracts to protect against unexpected costs or damages.
C8 – Environmental impact	n.a.

[17] https://www.iso.org/standard/65883.html

7. Case Studies

Thanks to Cultural-E project 4 demonstration cases were designed and built as PEBs and are meant as early adopters who pave the way for PEBs' wider uptake.

Information on Cultural-E demonstration cases and other inspirational case studies are collected in an online repository: https://energyefficientbuilding.eurac.edu/en/pebhub/.

The **PEB HUB**, is designed for all kinds of practitioners, as a repository of PEBs that aspires to become a community powered by Plus Energy Building professionals and to provide support on multifamily-residential buildings design by reporting other designers' experiences on PEB design.

Join the community and discover real cases of buildings that produce more energy than they consume!

8. Key References and useful links

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[13] Dallapiccola M, Barchi G, Adami J, Moser D. The Role of Flexibility in Photovoltaic and Battery Optimal Sizing towards a Decarbonized Residential Sector. Energies. 2021; 14(8):2326. https://doi.org/10.3390/en14082326

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9. Appendix

9.1 Post-Occupancy Evaluation Survey for POEs in CULTURAL-E

This survey is designed to assess residents' experiences in Plus Energy Buildings (PEBs), focusing on indoor environmental quality (IEQ), user interaction with installed technologies, and overall comfort. The data collected helps evaluate the real-world performance of PEBs and informs improvements in building design and operation.

The survey is structured into five sections:

1. General Information – Collects demographic and household data.
2. Indoor Environmental Quality (IEQ) – Assesses occupant satisfaction with temperature, air quality, lighting, and acoustics.
3. User Interaction with Installed Technologies – Evaluates ease of use, controllability, and effectiveness of technologies such as Active Windows, Heat Pumps, and the House Management System (HMS).
4. Social Compatibility – Explores how the building fits within residents' lifestyles and expectations.
5. General Comments – Provides space for open-ended feedback.

The survey is recommended to be administered twice per year, once in winter and once in summer, to capture seasonal variations in comfort and building performance. The results will contribute to refining Home Guides, energy-saving strategies, and user engagement tools for future PEB projects. The survey is translated into the languages of each country where there is a demo case.

(See the full survey below.)

One-off questionnaire (for PEBs)

The one-off questionnaire for PEBs will be structured into five sections: general information, IEQ, user interaction with the installed technology, social compatibility, and general comments. The one-off questionnaire will be administered twice, once during winter and once during summer.

Section 1: general information

S1.1. ID: _________

S1.2. Genre:

- Male
- Female
- Other
- Prefer not to say

S1.3. Age:

- 18 or less
- 8-30
- 31-50
- 51-70
- Over 70
- Prefer not to say

S1.4. Weight:

- 40 kg or less
- 41-60 kg
- 61-80 kg
- 81- 100 kg
- More than 100 kg
- Prefer not to say

S1.5. Height:

- 150 cm or less
- 151- 170 cm
- 171-190 cm
- More than 190 cm
- Prefer not to say

S1.6. Higher education level achieved:

- Less than primary education
- Primary education
- Lower secondary education
- Upper secondary education
- Bachelor's or equivalent
- Master's or equivalent
- Doctoral or equivalent
- Other (please, specify: _________)
- Prefer not to say

S1.7. How often do you consume coffee?

- Never or almost never
- One to 3 times a day
- 4 or more times a day
- Prefer not to say

S1.8. How often do you drink alcohol?

- Never or almost never
- One to 3 times a week
- 4 ore more times
- Prefer not to say

S1.9. How often do you drink energy drinks?

- Never or almost never
- One to 3 times a week
- 4 or more times
- Prefer not to say

S1.10. How many cigarettes do you smoke on average in a week?

- None or almost none
- Up to 20 cigarettes
- 20 cigarettes or more
- Prefer not to say

S1.11. During the past month(s), how would you rate your overall sleep quality?

....

S1.12. If you wake up at night, what is usually the main reason?
.....

Section 2: Indoor Environmental Quality (IEQ)

The following questions assess user satisfaction regarding Indoor Environmental Quality (IEQ).

S2.1. Are you generally satisfied with your dwelling's comfort?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.1. Are you generally satisfied with your dwelling's comfort?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.3a. How would you best describe the source of discomfort during summertime? (check all that apply)

- Humidity too high (damp)
- Humidity too low (dry)
- Air movement too high
- Air movement too low
- Incoming sun
- Hot/cold floor surfaces
- Hot/cold ceiling surfaces
- Hot/cold wall surfaces
- Draft from vents
- Cooling system does not respond quickly enough to the thermostat

S2.2b. During wintertime, are you generally satisfied with the temperature in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.3b. How would you best describe the source of discomfort during wintertime? (check all that apply)

- Humidity too high (damp)
- Humidity too low (dry)
- Air movement too high
- Air movement too low
- Incoming sun
- Hot/cold floor surfaces
- Hot/cold ceiling surfaces
- Hot/cold wall surfaces
- Draft from vents
- Cooling system does not respond quickly enough to the thermostat

S2.4. In this moment, are you satisfied with the temperature in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.4. Overall, are you satisfied with the air quality in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.5. How would you best describe the source of air quality dissatisfaction? (multiple choice available)

- The air smells bad (odours)
- Tobacco smoke
- Food smell
- Carpet or furniture
- Wall painting
- Outside sources
- Air is stuffy/ stale
- Air too dry
- Air too humid
- Others (please, specify)

S2.6. In this moment, are you satisfied with the air quality in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.7. Overall, are you satisfied with the air ventilation in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.8. Overall, are you satisfied with the level of natural light in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.9. If, in the previous question, you answered that you are dissatisfied with the natural light in the space. Which of the following aspects contribute to your dissatisfaction? (multiple choice available)

- Too dark
- Too bright
- Not enough daylight
- Too much daylight
- Reflection issues
- Glare issues

S2.10. Overall, are you satisfied with the view from your windows?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.11. To what extent do you see the following elements from the windows of your dwelling?

Vegetation

-3	-2	-1	0	+1
Not at all	A little	Moderately	A lot	Completely dominating

Sky

-3	-2	-1	0	+1
Not at all	A little	Moderately	A lot	Completely dominating

Other buildings

-3	-2	-1	0	+1
Not at all	A little	Moderately	A lot	Completely dominating

S2.12. Overall, are you satisfied with the level of artificial lighting in your dwelling?

-3	-2	-1	0	+1	+2	+3
Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied

S2.14. If, in the previous question, you said that you are dissatisfied with the acoustic quality of your household. Which of the following aspects contributes to this problem? (multiple choice available)

- Noise from mechanical systems (heating, cooling and ventilation)
- Noise from lighting equipment
- Excessive echoing of voices or other sounds
- Outdoor traffic noise
- Other outdoor noise
- Noises coming from neighbours
- It is too much quiet

Section 3: user interaction with the installed technology (Just for PEB, not reference building)

The following questions are used to assess the users' interaction (in terms of: controllability, feedback, and system interoperability) with the installed Cultural-E technologies: Active Window System (AWS), Packed Heat Pump (PHP), Ceiling fan, House Management System (HMS). The rating scale is the same for all the questions:

0	+1	+2	+3	+4	+5
Not applicable	Poor	Barely satisfactory	Satisfactory	Good	Best

S3.1. "How do you evaluate the controllability of the installed Active Windows?"

S3.2. "How do you evaluate the controllability of the installed Packed Heat Pump?"

S3.3. "How do you evaluate the controllability of the installed ceiling fan?"

S3.3. "How do you evaluate the controllability of the overall House Management System?"

S3.4. "How do you evaluate the feedback provided by the overall House Management System?"

S3.5. "How do you evaluate the system interoperability of operations provided by the overall House Management System?"

Section 4: social compatibility

The following questions aim to evaluate how much the building solutions fit people's frame of mind.

S4.1. How many people, including yourself, currently live in your same dwelling? ______

S4.2. Are there any elderly individuals (65 years or older) living in your dwelling?

- Yes
- No
- Prefer not to say

S4.3. Do you have any children (under 13 years old) living with you?

- Yes
- No
- Prefer not to say

S4.4. For how long have you been living in this Country?

- Less than 6 months
- From 6 months to 1 year
- From 2 years to 5 years
- From 5 years to 10 years
- From when I was born
- Prefer not to say

S4.5. Which Country are you originally from? __________

S4.6. For how long have you been living in this dwelling?

- Less than 1 month
- From 1 month to 6 months
- From 6 months to one year
- More than one year
- Prefer not to say

S4.7. Which were the reasons that prompted you to buy and/or rent a new energy-efficient dwelling? (multiple choice allowed)

- Cost savings
- Improved comfort
- Sustainability
- Other (please specify)
- Prefer not to say

S4.8. How would you define the typology of your previous dwelling?

- Historical building
- Traditional building
- Low-energy building
- Net zero energy building (NZEB)
- Zero energy building (ZEB)
- Plus energy building (PEB)
- None of the above
- Prefer not to say

S4.9. Compared to your previous dwelling, are you more satisfied with the overall building experience?

-1	0	+2
No	Neither No or Yes	Yes

S4.10. Compared to your previous dwelling, what advantages does living in this dwelling have for you? (multiple choice allowed)

- Cost savings
- Improved comfort/quality of life
- Increase of control of the technologies in the home
- Decrease of control of the technologies in the home
- Contributing to sustainability goals
- Others (please specify)

S4.11. Over which of these elements do you have control? (multiple choice available)

- Operable windows
- Ventilation system
- External shadings
- Internal shadings
- Heating system
- Portable heater
- Cooling system
- Ceiling fan
- Standing fan
- Other (please specify)
- None of the above

S4.12. How do you evaluate your control of comfort parameters at the moment?

-1	0	+2	+1
Very low control	Low Control	Little Control	High control

S4.13. How often do you open the windows in the living area of your dwellings? (multiple choices available)

- Rarely
- One time in the early morning
- One time in the afternoon
- One time in the evening
- From time to time, during the day
- From time to time, during the night
- I keep the windows open most of the time
- Other (open question)

S4.14. How often do you open the windows in the sleeping area of your dwellings? (multiple choices available)

- Rarely
- One time in the early morning
- One time in the afternoon
- One time in the evening
- From time to time, during the day
- From time to time, during the night
- I keep the windows open most of the time
- Other (open question)

S4.15. Would you recommend a Plus Energy House to a friend of yours?

-2	-1	0	+1	+2
Highly advise against	Advise against	Neither recommend nor advise against	Recommend	Highly recommend

Section 5: general comments

This section will contain open questions used to collect open feedback from the occupants.

9.2 A Guiding Toolkit for designing Home Guides for PEBs

A Guiding Toolkit

Developing User-Centric Home Guides

This toolkit offers practical guidance for creating engaging Home Guides tailored to residents' needs, supporting designers and building managers in promoting energy-saving behaviors and user acceptance.

To address the most commons user needs, we propose structuring Home Guides around the following:

1. **Focus on residents's needs: prioritize practical, actionable content over technical jargon.**

2. **Organize content around needs:**
   - identify the 10 most frequent resident needs;
   - for each need, include these four subsections:

   1. Tips - practical advice for addressing the need;
   2. HMS Guidelines - clear instructions for interacting with the House Management System
   3. Technology involved - overview **of technologies related to the need;**
   4. Energy savings - quantify how specific behaviours can reduce energy use.

Best Practices for Home Guide Design

Concise Format
Limit guides to a maximum of 20 pages of readability.

Use Visuals
Incorporate diagrams, infographics, and images to simplify complex concepts.

Interactive Features
Add QR Codes linked to video or online resources.

Develop short video tutorials for key functionalities.

Cultural Adaptation
Tailor content to the cultural and social practices of residents in each region

9.3 Checklist for Plus-Energy Buildings implementation

DESIGN PHASE	
1	Implement bio-climatic design and innovative technologies in the early stages considering their maintenance, and life cycle.
2	Ensure early-stage collaboration between the design team (architects and engineers) to ensure the best possible integration between bio-climatic design and the building services technologies.
3	Design anticipating and prioritising user comfort and needs over most efficient use of technologies.
4	Engage at early-stage socio-technical professionals who can provide information on user needs and habits driven by local cultural and social-economic features. These boundaries conditions will inform the calibration of the building services technologies.
5	Assess energy consumption using energy simulations considering the local climatic conditions and the building archetype.3
6	Integrate energy storage solutions like thermal storage and batteries
7	Design and size Heat, Ventilation and Air Conditioning (HVAC) system considering passive solutions, users' habits, controllability at building scale and adaptability.
8	Design an integrated user-centred system controls and dashboard for data sharing with different access privileges.
9	Optimise Photovoltaic (PV) panel design considering load profile and price dynamics and battery system possible capacity. Architectural design considers the integration of PV panels in the roof and façade.
10	Integrate into design Electrical Vehicle charge points.
11	Improve communication strategy between the design team at different levels for a clear understanding of the new building services technologies and use.
12	Define the type of data collection: continuous monitoring or spot measurements.

DESIGN PHASE	
1	Adapt the contract or create a new type of contract that focus on collaboration and coordination between the design and construction team to deliver the building service system with all technologies integrated and fully functional.
2	Adopt a performance-based procurement that focus on the desire performance and end result rather than process and inputs.

CONSTRUCTION PHASE	
1	Training on-site construction workers on the new technologies to be implemented on site to reduce risks of delay and cost-raising potential.
2	Consider in large scale projects, the engagement of 'intermediary actors' to bridge, and a lean construction management ensuring achievement of the goals and schedule.

COMMISSIONING PHASE	
1	Adapt the commissioning contract or create a new type of commissioning contract that focus on collaboration and coordination between the commissioning teams to deliver the building service system with all technologies integrated and fully functional.
2	Provide information on the maintenance of the new technologies and system for a better installation and follow up.
3	Engage an independent commissioner to ensure the correct installation and functioning as per design.
4	Plan the commission of large-scale projects in phases. Implement and complete the commission process in few units and replicate the process for the other units.

MONITORING AND POST-OCCUPANCY EVALUATION (POE)	
1	Include specifications on communication protocols, sensors, and signals in the monitoring system architecture.
2	Implement a cloud-based system to integrate the technologies and monitoring information.
3	Collect data on indoor environmental quality parameters such as temperature, relative humidity, CO_2 levels, and pollutants.
4	Monitor parameters via continuous monitoring or spot measurements.
5	Maximize self-consumption by adopting predictive control strategies for energy storage management to mitigate the mismatch between energy consumption and production
6	Gather building user feedback through surveys, focus groups, semi-structured interviews, etc.
7	Plan feedback and collection of monitoring data at several points in the year in different seasonal conditions.
8	Providing information to building users for better use of the building system to ensure a healthy and comfortable indoor environment with minimal energy use. The information format should be adapted according to the local conditions and circumstances and could be printed or online home guides and training in person or online training, how-to-do videos, etc.