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

Position paper for policy-makers showing the impact of PEBs

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Acronym	Description
ADPE	Abiotic depletion potential for non fossil resources
ADPF	Abiotic depletion potential for fossil resources
APA	Acidification potential
CRU	Components for re-use
EEE	Exported electrical energy
EET	Exported thermal energy
EP	Eutrophication potential
FW	Use of net fresh water
GWP	Global warming potential
HWD	Hazardous waste disposed
MER	Material for Energy Recovery
MFR	Materials for recycling
NHWD	Non hazardous waste dispose
NRSF	Use of non renewable secondary fuels
ODP	Depletion potential of the stratospheric ozone layer
PENRE	Non renewable primary energy as energy carrier
PENRM	Non renewable primary energy as material utilization
PENRT	Total use of non renewable primary energy resource
PERE	Renewable primary energy as energy carrier
PERM	Primary energy resources used as raw materials
PERT	Total use of renewable primary energy resources
POCP	Formation potential of tropospheric ozone photochemical oxidants
RSF	Use of renewable secondary fuels
RWD	Radioactive waste disposed
SM	Input of secondary material

Executive summary

The EU H2020 project Cultural-E is going a step beyond the concept of Nearly Zero Energy Buildings (nZEBs), by proposing the concept of Plus Energy Buildings (PEBs). The goal of the project is to account for climatic and cultural differences in the definition of the first generation of European PEBs.

Previous studies have shown how socio-cultural and climatic features can have a significant impact on the building users' everyday practices and energy-related behaviours, as well as on their comfort expectations, preferences and requirements regarding the indoor environment. A great variety of factors play a key role in the process, ranging from climatic differences and personal climatic history to social norms, cultural habituation, contextual boundaries, social dynamics, etc.

These aspects shall be considered and become an integral part of the design process and of the identification of operational strategies. However, they are currently generally neglected, both in common practice and in the guidelines and standards commonly consulted by professionals, leading to a recognised gap in the buildings' performance between the design and the operational phase.

This position paper presents an overview of the Cultural-E definition of PEBs, followed by some project outcomes such as a previous position paper (here integrated) and its possible developments facing the evolution of the EU legislation, as well as two Cultural-E case studies in Germany and Italy showing the advantages of PEBs when compared to nZEBs.

1 Introduction

According to the 2023 Global Status Report for Buildings and Construction, “the buildings and construction sector accounted for around 37% of energy- and process-related CO2 emissions and over 34% of energy demand globally”[1]. Plus, Energy Buildings are key to reaching climate neutrality by 2050 as per the EU Climate Action target. This objective of climate neutrality was enshrined into law in the EU Climate Law, which also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.[2] In this regard, climate and social factors should be taken into account when it comes to mitigating the effects of climate change: both factors are interconnected as the buildings consume energy to achieve a certain level of comfort requested by the occupants.

Furthermore, a Plus Energy Building can be impeccably designed and built, but it will not be enough if occupants of such a building do not take proper measures on energy consumption when inhabiting their homes - for instance, whether occupants poorly manage the technical systems of the buildings, expect an excessive level of comfort, or have behaviour that affects the thermal/ energy balance of the buildings – and this is crucial for the Cultural-E project as the project demo cases are residential buildings.

As the Cultural-E project is running from October 2019 till the end of 2024, the project timeline has been overlapping with the legislative procedure for the revision of the EPBD (figure 1). The Commission’s legislative proposal for a revised directive (December 2021) led to the Cultural-E position paper as proactive feedback on the directive before it was implemented.

[1] https://globalabc.org/our-work/tracking-progress-global-status-report
[2]https://climate.ec.europa.eu/eu-action/european-climate-law_en#:~:text=The%20European%20Climate%20Law%20writes,2030%2C%20compared%20to%201990%20levels.

Figure 1: EPBD timeline from 2021.

SOURCE: EC WEBSITE

2 Towards the EPBD – Cultural-E position paper

The European Commission adopted on 15 December 2021 its legislative proposal for the revision of the Energy Performance of Buildings Directive (EPBD). Back in May 2022, the Cultural-E project welcomed the Commission's aspiration to deliver on the Renovation Wave by improving the energy performance of buildings and promoting the reduction of greenhouse gas emissions from buildings.

For this occasion, the Cultural-E team prepared a **position paper**[3] that was sent as feedback to the EPBD revision. In the position paper, it was stated the following:

*Cultural-E acknowledges the new definition of Zero-Emission Building, proposed by the EU Commission in **Article 2**[4], to become the new standards by 2030: 'A building with a very high energy performance in line with the energy efficiency first principle, and where the very low amount of energy still required is fully covered by energy from renewable sources at the building or district or community level where technically feasible (notably those generated on-site, from a renewable energy community or from renewable energy or waste heat from a district heating and cooling system).'*

Nevertheless, the introduction of the new concept of Zero Emissions Buildings, which will progressively replace the existing Nearly Zero Energy Buildings, will create new requirements for Member States to implement and the sector to adapt to, whereas the logical future step would have been to go beyond and pave the way for Plus Energy Buildings, which have several advantages:

- *producing more energy than they consume and feeding RES-based (renewable energy source) energy to the grid, PEBs represent a key step towards the decarbonization of the building sector and energy independence. In this way, PEBs can support e.g., older/ historic buildings, where the transition to zero energy state would not be possible or cost-efficient.*
- *PEBs contribute to reducing the energy grid congestion by providing a flexible energy asset that allows buildings and energy communities to act as integrated parts of the energy system and exchange energy (electrical, thermal energy, or other future energy carriers) among them or with the grid.*

Furthermore, the Cultural-E project refers to Plus Energy Buildings instead of Positive Energy Buildings, in order to include additional aspects to the positive energy balance relevant for the final users' satisfaction such as accessible, comfortable, and healthy indoor environments.

[3] The position paper was sent to MEP Ciarán Cuffe and submitted on the EC portal: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12910-Energy-efficiency-Revision-of-the-Energy-Performance-of-Buildings-Directive/F2946379_en

[4] Article 2: Zero Emission Buildings; Deep Renovation / Staged Deep Renovation; Mortgage Portfolio Standards.

We strongly promote a paradigm shift from 'less impacting' to 'more providing'. As a result, it is vital to support Plus Energy Buildings with adequate policies such as the EPBD as, besides the direct benefits i.e. energy consumption and GHG emissions reduction, they additionally bring various indirect effects or co-benefits to the district and community. According to Cultural-E, co-benefits are the added positive values that can be obtained, in addition to the direct and measurable impacts which derive from high-efficiency energy buildings or from the energy renovation of existing buildings and their technologies. They can be household co-benefits if they have an effect on the user's well-being and household economy, or community co-impacts if they have wider economic, social and environmental effects.

In this regard, the project's research team has identified various co-benefits that range from the user's wellbeing to the economic sector, the social and environmental sphere, e.g.:

- *public health: local pollution reduction and improved Indoor Environmental Quality (IEQ) leading to reduced costs for public health/ reduced morbidity;*
- *energy security and alleviation of energy poverty: reduced electricity consumption and costs, relief of external grid through contribution to the energy grids, eventually leading to a reduction of dependency on fossil fuels and reduction of import costs;*
- *energy transition: building decarbonization and increased share of electromobility;*
- *sustainability: reduction of CO2 emissions and environmental resource protection, increased resilience to climate change mitigating urban heat island effects.*

Thus, the Cultural-E project would like to put forward the following definition of Plus Energy Buildings to be included in the EPBD:

'A Plus Energy Building is an energy efficient building that produces more final energy than it uses via locally available renewable sources over a time span of one year. Building uses include 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.'

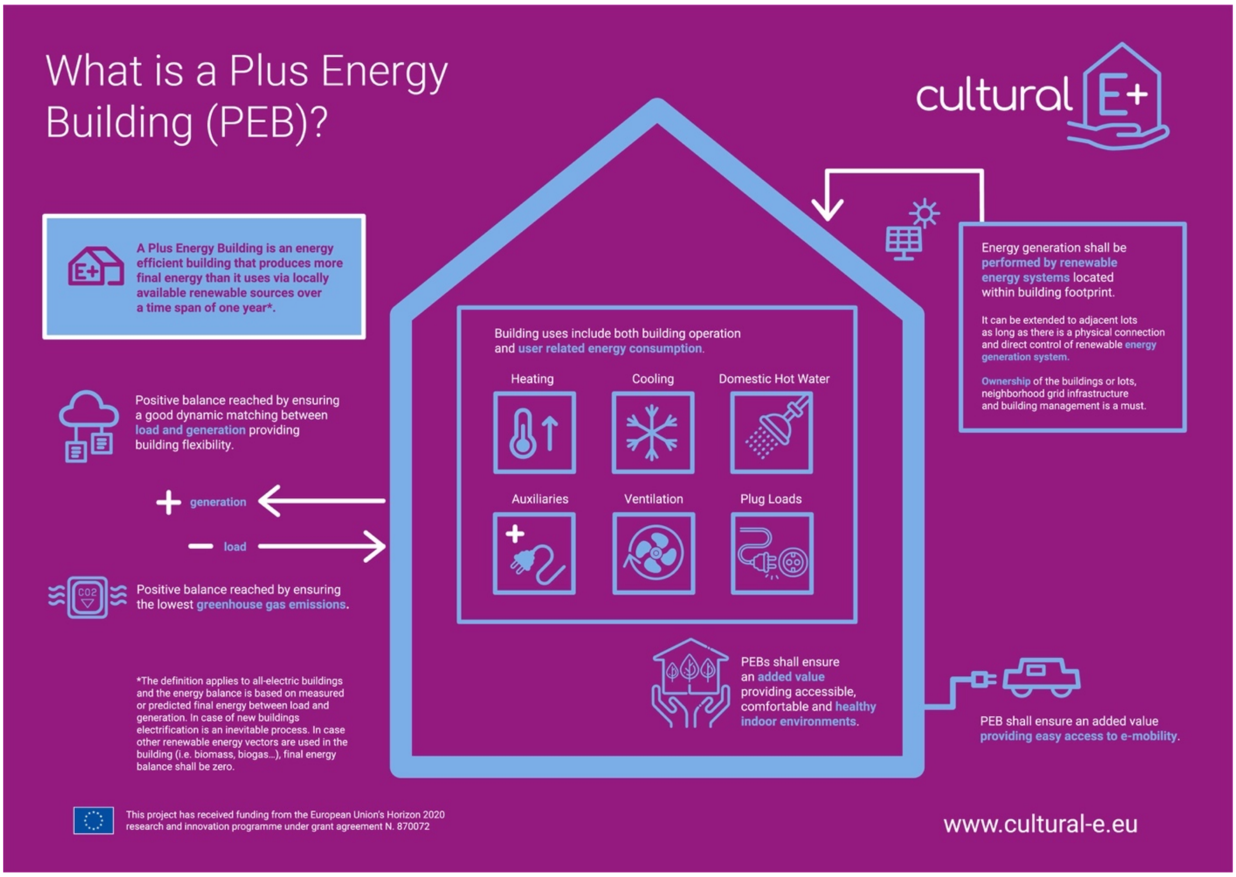


Figure 2: Cultural-E infographic on the definition of Plus Energy Buildings

SOURCE: WWW.CULTURAL-E.EU

The definition applies to all-electric buildings and the energy balance is based on measured or predicted final energy between load and generation[5]*.*

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. 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.

In case of new buildings electrification is an inevitable process. In case other renewable energy vectors are used in the building (i.e., biomass, biogas…), final energy balance shall be zero.This definition is the result of a systematical analysis on the key aspects of the energy

[5] In case of new buildings electrification is an inevitable process. In case other renewable energy vectors are used in the building (i.e., biomass, biogas…), final energy balance shall be zero.

balance definition (metric, period of balance, energy uses included in the balance, type of balance and boundaries) and their practical implications, in particular:

- *Final energy as a metric is directly measurable and predictable, and therefore easier to understand for final users.*
- *Including all energy uses in the balance ensures that the building has an energy production surplus to be shared with other buildings. The full impact of the users is included by considering the plugloads (i.e., the building appliances). This would contribute to empowering building energy endusers to reduce energy consumption and to change the mindset of designers from performance driven to user-centered design.*
- *A time span of one year for energy balance evaluation is the most feasible to evaluate the energy balance and verify the plus energy target.*

Currently investors lack guidelines on how to monetize the co-benefits. In fact, such side effects are generally addressed in a qualitative way, and thus they are neither properly integrated in a comprehensive evaluation of the building's performance nor in business models. A step forward in this direction could in the future significantly support the promotion, acceptance and spread of Plus Energy Buildings among the community. To evaluate in monetary terms the co-benefits from Plus Energy buildings, it is useful to integrate direct costing with stated preference methods, and in particular, with the discrete choice experiment approach. While for some co-benefits a "price tag" can be inferred from their direct or indirect relation with goods and services for which a market exists, some co-benefits are highly subjective and have no market price or substitute goods that can be used to estimate their value: this is the case for instance, for the economic value of improved indoor environmental quality. Such exercise will provide a more comprehensive picture of how people may benefit from Plus Energy Buildings and reduce the risk of biased decisions about the social opportunity of investing in this kind of buildings in terms of their potential to improve public health, increase energy security, alleviate energy poverty, aid in the energy transition, and increase sustainability.

Furthermore, Cultural-E would like to respond to elements relating to Indoor Environmental Quality (IEQ) and the way it is perceived by users as an essential feature of PEBs. Cultural-E supports the various mentioning of the importance of a healthy indoor environment for European citizens ***. We specifically welcome Article 11[6]*** *on technical building systems: 'Member States shall require zero-emission buildings to be equipped with measuring and control devices for the monitoring and regulation of indoor air quality. In existing buildings, the installation of such devices shall be required, where technically and economically feasible, when a building undergoes a major renovation.'*

[6] Article 11: decarbonisation of Technical Building Systems; Monitoring IEQ in new buildings and major renovations

While this attempt goes in a good direction, the project's team recommends ***that IEQ is more strongly acknowledged*** *in the further implementations and more extensively exploited. Moreover, even though indoor air quality is a key share of IEQ -especially recognized after these latest years of pandemic- it is necessary to endorse that it is just one of four parameters necessary for the achievement a healthy indoor environment. In fact, indoor environmental quality is defined by 1) thermal, 2) visual, 3) acoustic, and 4) air quality. As a result, we would welcome a replacement of Indoor Air Quality in the EPBD with Indoor Environmental Quality.*

According to the position paper, the Cultural-E strategic objectives can be summarised as the following:

- **Implement the concept and definition of Plus Energy Building, rather than Zero-Emission Building;**
- **Include the co-benefits – and how to monetise them - in addition to the direct and measurable direct benefits i.e. energy consumption and GHG emissions reduction;**
- **Take into account the IEQ for the health and well-being of PEBs occupiers.**

3 After the adoption of the revised EPBD: where does Cultural-E stand for?

The Cultural-E team considered the revision of the EPBD a unique occasion for a paradigm shift in how the new generations of Plus Energy Buildings are designed and conceived.. The Committee on Industry, Research and Energy (ITRE) of the European Parliament has adopted its stance on the EPBD revision after challenging negotiations. Amendments tabled by the ITRE Committee featured notable changes and more ambitious goals than the recast proposal by the European Commission.

According to the Amendments adopted by the European Parliament on 14 March 2023 on the EPBD, regarding article 11, the '*Measures to improve further the energy performance of buildings should take into account climatic conditions, including adaptation to climate change through green infrastructures, local conditions as well as indoor environmental quality, sufficiency and circularity and energy savings, thus promoting more sustainable, inclusive and innovative ways of living in order to adapt to new needs. Such measures should be implemented in a way that maximises the co-benefits of other requirements and objectives concerning buildings such as accessibility, fire safety and seismic, heating and electrical installation safety and the intended use of the building. Those co-benefits should be monetised in order to realistically determine the cost-optimality of further energy performance improvements. Moreover, they should ensure the improvement of the situation of vulnerable households and people living in social housing*.'

Cultural-E welcomed this amendment proposal as co-benefits are fundamental when designing PEBs and high-performance buildings in general.

In particular, the co-benefit analysis conducted by the Cultural-E team emphasised that PEB buildings can be superior to the reference nZEB in many categories of co-benefits. However, this may not be true for *all* the categories identified. This, on the one hand, hints that the major gains related to PEBs indeed reside more in their primary purpose of existence, i.e. their energy generation potential rather than in their markedly superior or more efficient building characteristics. On the other hand, suggests a particular care in considering the full range of potential co-benefits that are affected to reduce to a minimum, the risk of originating sources of potential negative benefits.

ITRE also proposed the addition of a new Article 11a, which would focus on indoor environmental quality (IEQ) standards for buildings, introducing mandatory requirements for maintaining a healthy indoor climate, including defining indoor target pollutant limits and PM measurement. The ITRE proposal would mandate the Commission to develop a delegated act that would establish a methodology framework on IEQ standards. Overall, the proposed article aims to ensure comprehensive mandatory IEQ indicators for buildings.

Apart from these two draft amendments, which Cultural-E suggested in its position paper, nothing else was mentioned on the adoption of Plus Energy Buildings as a new reference for energy efficiency in construction. Cultural-E considers that Zero Energy Buildings' are not ambitious enough to reach climate neutrality by 2050.

Respect to this, PEB are surely an improvement respect to nZEB. Nonetheless, as mentioned, it is important to iterate that the co-benefit assessment, that however, by construction, does not compare the energy generation potential of the different buildings, showed mixed results as, depending on the co-benefit categories examined, PEB can be either superior or inferior to nZEB. We note that these results are very case specific and of difficult generalization. Eventually, rather than discouraging, they should be used as support to indicate where further improvements are needed.

4 Cultural-E case studies in Italy and Germany

Analysis of the co-benefits that can be associated with a Plus Energy Building (PEB) applying a direct cost methodology to the Italian and German demo cases has been carried out. Co-benefits are "additional positive effects brought by a policy measure that occur regardless of and in addition to the originally predetermined policy goals (AR5, 2014)". Consequently, the assessment does not evaluate the energy generation potential of the PEB, given that this is, indeed, its primary purpose.

Different methodologies are available for co-benefit evaluation. Direct costing method used here associates a straight monetary value to a quantifiable source (i.e. a performance indicator) of co-benefits.

More specifically, co-benefit categories were identified as listed in deliverable Cultural E D5.2 (Bosello et al. 2024); then they were matched to specific co-benefit indicators calculated by the University of Stuttgart (Cultural-E D4.5: Di Bari and Jorji, (2021). That study developed a life-cycle assessment that computes these indicators "per square meter per year" in association to three different types of buildings: PEB A (high rise), PEB B (low rise, smaller), Building C (reference nZEB); monetary evaluations were attributed to each indicator through a literature review; finally co-benefits have been assessed calculating the difference between the two PEBs and the reference nZEB.

The full fiche for both cases can be found in the annexes of this document.

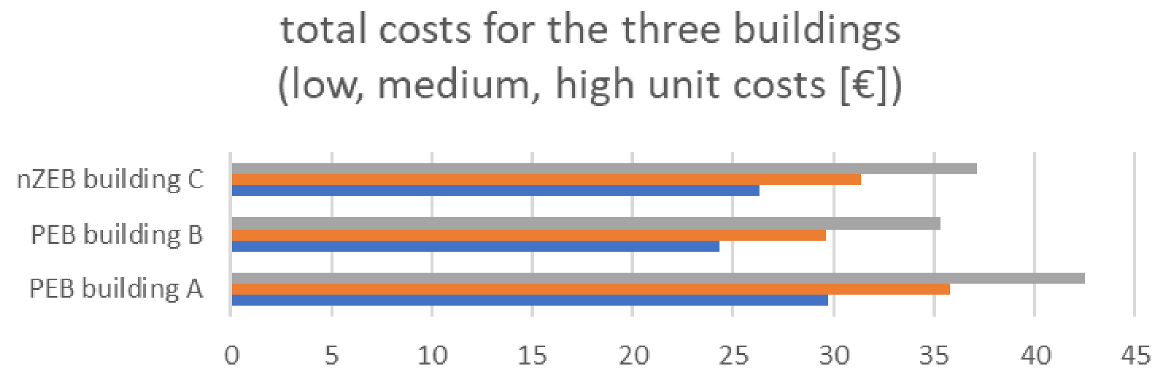
5.1 Italy demo cases

The building types that are contrasted are representative of the Italian context. The buildings chosen have the following characteristics, as described in Cultural-E D6.3 (Leis and di Bari, 2023):

- PEB Building A (high rise) consists of: 3 floors, 7 dwellings, surface area of approximately 75 m²/dwelling, total area of 622 m². Initial investment cost 3003 Euro/m².

- PEB Building B (low rise, smaller) consists of a total area of 520 m². It has the same envelope as Building A. It is equipped with a PV-System of 5,5 kWp per apartment and a battery of 6 kWh per apartment. Furthermore, ceiling fans are installed to increase thermal comfort, Active Window System (AWS) with integrated venetian blinds is installed to control solar gains and the cloud-based House Management System (HMS) will be used to manage the house systems. Initial investment cost 3003 Euro/m²

- nZEB reference Building C. This is the reference case. In accordance with the Cultural-E consortium decision, it is a nZEB. It consists of 4 floors, 9 dwellings, with a total area of 789 m². It has a decentralised air-water Heat pump for heat and DHW production and does not have controlled mechanical ventilation with heat recovery. The electricity produced by the 1,5 kWp per apartment PV system is fed in the grid. Building C is equipped with standard automation. Initial investment cost 3767 Euro/m²



	PEB building A	PEB building B	nZEB building C
high	42.51	35.33	37.14
medium	35.81	29.59	31.36
low	29.73	24.37	26.34

high medium low

Figure 3: Chart of the total cost calculated for each building [€/m2*y]

By "pricing" the indicators identified (see Chart 1) it is possible to associate a cost of:

- 29.73 to 42.51 €/m2*y, to PEB building A,
- 24.37 to 35.33 €/m2*y, to PEB building B,
- 26.34 to 37.14 €/m2*y, to nZEB reference building C.

This implies that, according to all cost estimations, PEB building A is about 12% to 14% "more costly" than nZEB building C, the reference case, while PEB building B always performs better the nZEB building C, i.e. it is about 5% to 7% "less costly". The absolute-value difference across building "costs" provides the direct costing evaluations of the co-benefits. These are, using low-cost estimates:

● 3.40 €/m2*y in the case of PEB building A (which is more costly than nZEB building C and therefore originates in fact negative co-benefits),

● -1.97 €/m2*y in the case of PEB building B (which is less costly than nZEB building C and therefore originates positive co-benefits).

and using high-cost estimates:

● 5.37 €/m2*y in the case of PEB building A (which is more costly than nZEB building C and therefore originates in fact negative co-benefits),

● - 1.81 €/m2*y in the case of PEB building B (which is less costly than nZEB building C and therefore originates positive co-benefits).

The direct costing co-benefit assessment emphasised that the two typologies of PEB considered may, in fact, originate either higher or lower total co-benefits than the nZEB reference. However, looking into the determinants of this result, it also emerges that both the PEB buildings A and B are always superior to the reference in some categories of co-benefit indicators. Namely:

- Total use of renewable primary energy resources (PERT)
- Non-renewable primary energy as material utilisation (PENRM)
- Exported electrical energy (EEE)
- Exported thermal energy (EET)
- Depletion potential of the stratospheric ozone layer (ODP)
- Formation potential of tropospheric ozone photochemical oxidants (POCP)
- Material for Energy Recovery (MER)
- Materials for recycling (MFR)
- Non-hazardous waste dispose (NHWD)
- Use of net fresh water (FW)
- Primary energy resources used as raw materials (PERM).

The fact that in other categories the reference could be superior to the PEB, and that net effects could be favourable to the former, hint that the major gains related to PEBs indeed reside in their energy generation potential rather than in markedly superior or more efficient building characteristics.

This outcome, however, needs some important qualifications:

- Independently upon the net outcome, PEB buildings A and B in fact outperform nZEB reference building C in several cost categories. Nonetheless, the co-benefits stemming from these categories are associated with a lower economic value than other categories.

- In relation to this, it has to be considered that the monetary evaluation of co-benefits is uncertain. For many cost categories, the cost spread between lower and upper values is huge with the latter being more than 1000 times larger than the former. This can highly influence the assessment. This is particularly evident when the use of freshwater is considered. The choice of its pricing determines whether PEB B generates positive co-benefits or not.

- The performance of the PEB buildings A and B respect to the reference nZEB building C in the single indicator types can be used to guide the design of PEB buildings towards improving their co-benefits.

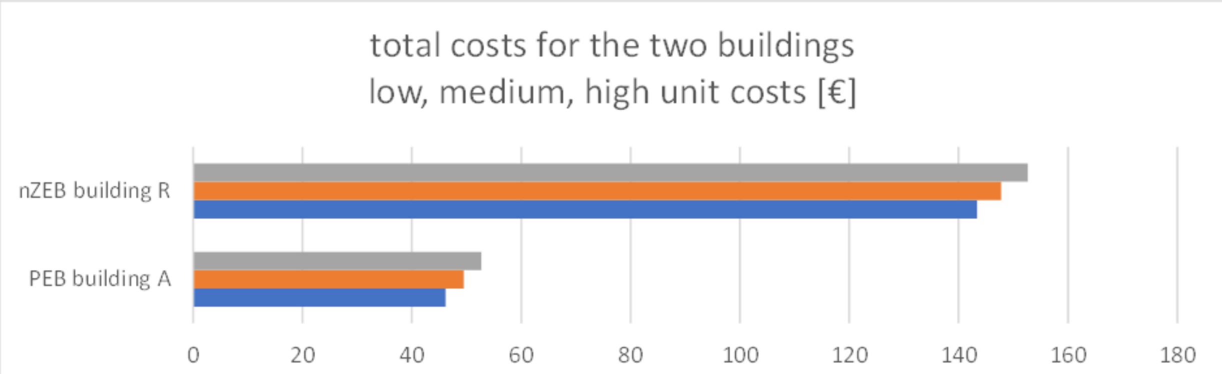
- Finally, it has to be considered that in the present assessment, not all the categories potentially origin of co-benefits has been evaluated.

5.2 Germany demo cases

The building types that are contrasted are representative of the German context. The buildings chosen have the following characteristics, as described in Cultural-E D6.3 (Leis and di Bari, 2023):

- PEB Building A consists of: 4 above ground floors and one basement level. The ground floor accommodates 560 m2 of commercial use, whereas the top three floors contain 21 rental apartments with a usable area of 1570 m2, all equipped with balconies and terraces. Approx. 40 parking places will be provided in the basement. The total gross building area is 4125 m2 including the basement level. The total building height is 13 m. The structure is a wood/concrete hybrid: the basement level and building core housing the vertical circulation is designed in reinforced concrete, whereas the remaining load-bearing structure above ground is envisioned in wood. The roof provides approx. 550 m2 of area for the installation of PV-panels.

- nZEB reference Building C. This is the reference case. In accordance with the Cultural-E consortium decision it is a nZEB. It consists of: 4 floors, total floor area of 2363 m², net floor area 1986 m². The structure is mixed, primarily reinforced concrete. It has a decentralized ventilation, floor heating, centralized heating with a condensing boiler, and lift.



	PEB building A	nZEB building R
high	52,67	152,61
medium	49,46	147,79
low	46,15	143,35

Figure 4: Chart of the total cost calculated for each building [€/m2*y]

By "pricing" the categories listed in Table 1 (see Chart 2), it is possible to associate a cost of:

- 46.1 to 52.7 €/m2*y, to PEB building A,
- 143.3 to 152.6 €/m2*y, to nZEB building C.

This implies that PEB building A is 65 to 68% cheaper (in terms of co-damages production, the dual of co-benefit) than the reference. The absolute-value difference across building "costs" provides the direct costing evaluations of the co-benefits. These are positive and total:

- 97.2 €/m2*y using "low-cost estimates".
- 99.9 €/m2*y using "high-cost estimates".

The direct costing co-benefit assessment emphasised that, in the German case, the PEB considered may, in fact, originate substantively positive net co-benefits compared with the nZEB reference. This is an additional advantage on top of its energy generation potential.

This outcome, however, needs some important qualifications:

- Independently upon the net outcome, the nZEB in fact outperforms the PEB in several cost categories, most notably the use of secondary materials. The co benefits stemming from these categories are however associated with a lower economic value than the other categories.

- The monetary evaluation of co-benefits is uncertain. For many cost categories, the cost spread between lower and upper values is huge with the latter more than 1000 times larger than the former. This can highly influence the assessment. In the specific German case study however, this variability is less of an issue given that the largest spread in cost assessment is linked with the use of freshwater resources that is limited in both types of buildings.

- Finally, it has to be considered that in the present assessment, not all the categories potentially origin of co-benefits have been evaluated.

5 Conclusions

With its case studies, this position paper has shown that PEBs can and should guide future EU policies—hence overcoming nZEBs—to decarbonise the EU building stock and make the building environment more liveable.

It is advised that the key points addressed in this position paper, particularly those relating to co-benefits, should be incorporated into the implementation of the EPBD at the national level, as Member States have the ability to go beyond the minimum requirements set out in the directive - as it has been done in the past. And because the EPBD did not reform the Energy Performance Certificates (EPC), Member States have more leadership when it comes to choosing their metrics for energy performance standards, meaning that it is indeed possible to aim at the design and construction of Plus Energy Buildings at national level and tackle the points the EPBD has not addressed.

Overall, the Cultural-E team believes that the current attention of EU policy on the built environment, represents a significant opportunity to drive positive change in the energy performance of buildings across the EU. By adopting the recommendations put forward in this position paper and working together to implement them at the national level, we can create more sustainable residential buildings for future generations.

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Annex 1: Assessing co-benefits of PEB. Applying a direct cost assessment – Italian case study

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1. Introduction

As part of task 5 of the Cultural-E project the following "fiche" reports the evaluation of the co-benefits that can be associated with a Plus Energy Building (PEB) applying a direct cost methodology to the Italian case study.

As defined in Cultural-E D5.2. co-benefits are "additional positive effects brought by a policy measure, that occur regardless of and in addition to the originally predetermined policy goals (AR5, 2014)." Consequently, the current assessment does not evaluate the energy generation potential of the PEB, given that this is, indeed, its primary purpose.

Different methodologies are available for co-benefit evaluation. Direct costing (see D5.2) here described attempts to associate a straight monetary value to a quantifiable source (i.e. a performance indicator) of co-benefits.

This can be more easily feasible when co-benefits can be linked to a "use" in turn, associated with material aspects transiting through "market transactions". A typical example is a higher or lower use of say "building materials" commonly bought and sold in standard markets. This can be however possible also for "materials" not directly "priced" by demand and supply interactions. A typical example is the emission of pollutants in the atmosphere, whose damage can be monetised applying different methodologies to quantify external costs (see e.g.: Rennert & Kingdon, 2019)

Following this methodology, we hereby evaluate the co-benefits associated with a PEB representative of the Italian context.

2. The methodology

To apply the direct cost methods the following steps have been followed:

1. co-benefit categories were identified as listed in deliverable Cultural-E D5.2 (Bosello et al. 2024) Table 4. They are reported in table 1 below (first column);
2. co-benefit categories were matched to specific environmental indicators calculated by University of Stuttgart (Cultural-E D4.5: Di Bari and Jorgji, 2021, table 1 second column) based on EN 15804 +A1. The study, consisting in a life-cycle assessment, computes a list of indicators "per square meter per year" of three different types of buildings (see below).

3. Monetary evaluations were attributed to each indicator through a literature review (list of money reference is here while the source literature is reported at the end of this document). Whenever possible, ranges, (low to high cost estimations) for the monetary values have been reported, to communicate the uncertainty beyond the assessment and test its robustness. In the cases of materials for recycling, disposal of radioactive wastes, disposal of hazardous and non-hazardous wastes only one cost reference has been found.
4. The final evaluations of co-benefits were performed comparing (calculating the difference between) three building types: Building A (high rise), Building B (low rise, smaller), Building C (reference nZEB), see below Charts 1-4 and table 2.

As anticipated, it is worth stressing that not all potential co-benefits are directly linkable to direct economic values. Furthermore, the unavailability of specific co-benefit indicators, can prevent the assessment of co-benefits even though economic evaluations are in principle available. Specifically (see table 1), due to a lack of information, in the present assessment it was not possible to quantify indicators of:

- operation and maintenance activity,
- employment creation,
- air pollution.

Accordingly, the potential co-benefits associated to these categories were not computed.
Furthermore, no data were available to measure changes in energy poverty.

Table 1: List of co-benefits, indicators, and money metric for the direct cost assessment (Deliverable D5.2 - Guidelines to assess the co-benefits of Plus Energy Buildings)

Note: indicators' acronym **XXX** taken from mappe1.xlsx and other Pivot tables for Fabbricato A, Fabbricato B, Fabbricato C (reference)

Co-benefit	Indicator	Direct cost assessment
Reduction of construction material and demolition waste.	Difference quantities of the various waste categories over lifetime of PEB compared to NZEB. **HWD**	A standard Waste Treatment Cost from the literature. [Vázquez-López et al, 2020]
Lower operational and maintenance costs.	Difference in the operational and maintenance hours over the lifetime of the PEB compared to NZEB. **Not available**	Average market value of those services.
Mitigation of climate change.	Difference in the total quantity of CO2 emissions over the lifetime of PEB compared to NZEB. **GWP**	The social cost of carbon. [Rennert & Kingdon, 2019]
Employment creation.	Number of additional jobs created as a result of the construction of a PEB compared to a NZEB. **Not available**	The average wage in the relevant industry.
Improvement of social welfare.	Total energy savings over the lifetime (MWh) of the PEB compared to a NZEB.	Reduction in energy poverty. Demonstrating the effect of energy savings on the financial situation of the lowest income decile. **Not available**
Reduction of air pollution.	Difference in physical emissions (kg) of particulate matter over the lifetime of the PEB compared to a NZEB. **Not available**	The external or social cost of PM10 emissions or equivalent, €39.2. [CE Delft, 2018]
Reduced ozone depletion.	Difference in emissions of CFC equivalent substances over the lifecycle phases of a PEB compared to the reference case NZEB **ODP**	The external or social cost of emitting additional kg of CFC or equivalent, €30.40. [CE Delft, 2018]
Reduced formation potential of tropospheric ozone photochemical oxidants.	The difference in kg of Ethen equivalent emissions over the life cycle of a PEB compared to a NZEB. **POCP**	The external or social cost of Photochemical oxidant formation is given as €1.15 per kg of non-methane volatile organic compounds (NMVOC) emitted. [CE Delft, 2018]

Reduced acidification potential.	Difference in emissions of kg of phosphate equivalent over the life cycle of a PEB compared to a NZEB. **AP**	The external or social cost of a unit of sulphur dioxide emissions is €4.97 per kg. [CE Delft, 2018]
Reduced eutrophication potential.	Difference in emissions of kg of phosphate equivalent over the life cycle of a PEB compared to a NZEB. **EP**	The external or social cost of freshwater eutrophication is given as €1.86 per kg of phosphate equivalent. [CE Delft, 2018]
Reduced abiotic depletion potential for non-fossil resources.	Difference in emissions of kg of Sb (Antimony) equivalent over the life cycle of a PEB compared to a NZEB. **ADPE**	The external or social cost of resource use, minerals and metals is given as €1.64 per kg of Sb equivalent. [Trinomics, 2020]
Reduced Abiotic depletion potential for fossil resources.	The difference in energy (Mj) related over the life cycle of a PEB compared to a NZEB. **ADPF**	The external or social cost of fossil resource use is given as €0.0013 per Mj.[Trinomics, 2020]
Reduced water use.	The difference in net fresh water use over the life cycle of a PEB compared to a NZEB. **FW**	The external or social cost of water use is given as €0.00499 per m3 of water equivalent. [Trinomics, 2020]

3. The case study

The building types that are contrasted are representative of the Italian context. The buildings chosen have the following characteristics, as described in Cultural-E D6.3 (Leis and Di Bari, 2023):

- Building A (high rise) consists of: 3 floors, 7 dwellings, surface area of approximately 75 m²/dwelling, total area of 622 m².
  Initial investment cost 3003 Euro/m²
- Building B (low rise, smaller), consists of: total area of 520 m². It has the same envelope as Building A. It is equipped with a PV-System of 5,5 kWp per apartment and a battery of 6 kWh per apartment. Furthermore, ceiling fans are installed to increase thermal comfort, Active Window System (AWS) with integrated venetian blinds is installed to control solar gains and the cloud-based House Management System (HMS) will be used to manage the house systems.
  Initial investment cost 3003 Euro/m²
- Building C. This is the reference case. In accordance with the Cultural-E consortium decision it is a nZEB. It consists of: 4 floors, 9 dwellings, total area of 789 m². It has a decentralized air-water Heat pump for heat and DHW production and does not have controlled mechanical ventilation with heat recovery. The electricity produced by the 1,5 kWp per apartment PV system is fed in the grid. Building C is equipped with standard automation.

Initial investment cost 3767 Euro/m²

4. Results

Table 2 reports extensively the calculation done, while Charts 1-4 visualize the results of the procedure.

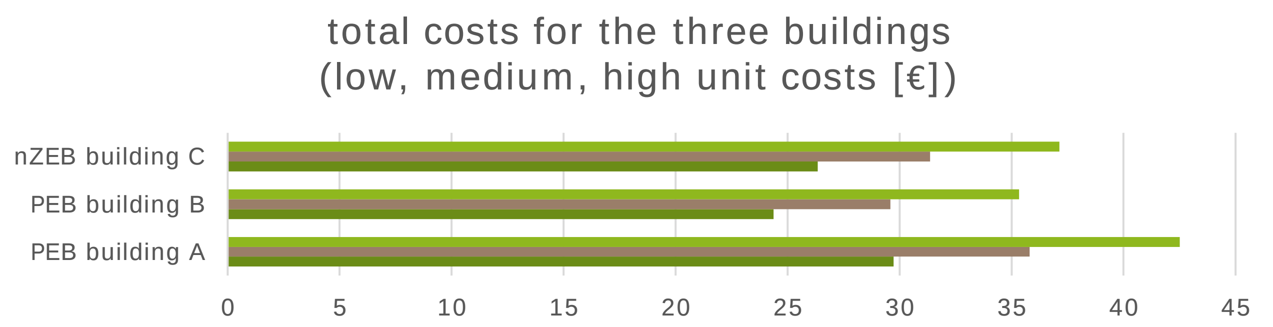
Table 2a: Unit costs and sources

	unit cost					
Indicator	**low**	**medium**	**High**	**impact/m²*y Unit**	**Price Unit**	**Source**
Total use of renewable primary energy resources (**PERT**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Total use of non renewable primary energy resource (**PENRT**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Global warming potential (**GWP**)	0.04 €	0.28 €	0.53 €	kg CO2-Eq	$2022/kg CO2	Tol, 2023
Depletion potential of the stratospheric ozone layer (**ODP**)	22.10 €	30.40 €	45.70 €	kg R11-Eq	€2015/kg CFC-eq.	CE Delft, 2018
Acidification potential (**AP**)	0.53 €	4.97 €	5.66 €	kg SO2-Eq	€2015/kg SO2-eq.	CE Delft, 2018
Eutrophication potential (**EP**)	0.25 €	1.86 €	2.11 €	kg Phosphat-Eq	€2015/kg P-eq.	CE Delft, 2018
Formation potential of tropospheric ozone photochemical oxidants (**POCP**)	0.84 €	1.15 €	1.84 €	kg Ethen-Eq	€2015/kg NMVOC-eq.	CE Delft, 2018
Abiotic depletion potential for non fossil resources (**ADPE**)	0.00 €	1.64 €	6.53 €	kg Sb-Eq	€2018/kg Sb eq	Trinomics, 2020
Abiotic depletion potential for fossil resources (**ADPF**)	0.00 €	0.00 €	0.01 €	MJ	€2018/MJ	Trinomics, 2020
Material for Energy Recovery (**MER**)	-0.32 €	-0.43 €	-0.55 €	kg	€/MJ	Our computation*
Materials for recycling (**MFR**)	2.83 €	2.83 €	2.83 €	kg	€/kg	Vázquez-López et al., 2020
Radioactive waste disposed (**RWD**)	4.00 €	4.00 €	4.00 €	kg		enea, 2023
Non hazardous waste dispose (**NHWD**)	0.03 €	0.03 €	0.03 €	kg	€/kg	Vázquez-López et al., 2020
Hazardous waste disposed (**HWD**)	0.08 €	0.08 €	0.08 €	kg	€/kg	Vázquez-López et al., 2020
Use of net fresh water (**FW**)	0.00 €	0.00 €	0.24 €	m3	€/m3	Trinomics, 2020
Use of non renewable secondary fuels (**NRSF**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Use of renewable secondary fuels (**RSF**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Input of secondary material (**SM**)	2.83 €	2.83 €	2.83 €	kg	€/kg	Vázquez-López et al., 2020
Renewable primary energy as energy carrier (**PERE**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Primary energy resources used as raw materials (**PERM**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Non renewable primary energy as energy carrier (**PENRE**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Non renewable primary energy as material utilization (**PENRM**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Exported electrical energy (**EEE**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Exported thermal energy (**EET**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*

* Description of the methodology can be found in appendix

Table 2b: Calculation of costs

Indicator	PEB Building A				PEB Building B				nZEB Building C			
	impact/m²*y	A - low	A - medium	A - high	impact/m²*y	B - low	B - medium	B - high	impact/m²*y	C - low	C - medium	C - high
PERT	38.199	0.69 €	1.24 €	1.79 €	38.362	0.69 €	1.24 €	1.80 €	47.462	0.85 €	1.54 €	2.22 €
PENRT	188.450	2.58 €	2.62 €	2.66 €	155.137	2.13 €	2.16 €	2.19 €	176.897	2.42 €	2.46 €	2.49 €
GWP	18.174	0.73 €	5.13 €	9.54 €	14.609	0.58 €	4.13 €	7.67 €	13.412	0.54 €	3.79 €	7.04 €
ODP	0.000	0.00 €	0.00 €	0.00 €	0.000	0.00 €	0.00 €	0.00 €	0.000	0.00 €	0.00 €	0.00 €
AP	0.035	0.02 €	0.17 €	0.20 €	0.030	0.02 €	0.15 €	0.17 €	0.029	0.02 €	0.14 €	0.16 €
EP	0.005	0.00 €	0.01 €	0.01 €	0.004	0.00 €	0.01 €	0.01 €	0.004	0.00 €	0.01 €	0.01 €
POCP	0.006	0.00 €	0.01 €	0.01 €	0.006	0.00 €	0.01 €	0.01 €	0.011	0.01 €	0.01 €	0.02 €
ADPE	0.000	0.00 €	0.00 €	0.00 €	0.000	0.00 €	0.00 €	0.00 €	0.000	0.00 €	0.00 €	0.00 €
ADPF	174.894	0.00 €	0.23 €	1.19 €	145.556	0.00 €	0.19 €	0.99 €	171.853	0.00 €	0.22 €	1.17 €
MER	0.000	0.00 €	0.00 €	0.00 €	0.000	0.00 €	0.00 €	0.00 €	0.108	-0.03 €	-0.05 €	-0.06 €
MFR	0.002	0.00 €	0.00 €	0.00 €	0.001	0.00 €	0.00 €	0.00 €	0.027	0.08 €	0.08 €	0.08 €
RWD	0.005	0.02 €	0.02 €	0.02 €	0.004	0.01 €	0.01 €	0.01 €	0.002	0.01 €	0.01 €	0.01 €
NHWD	1.269	0.04 €	0.04 €	0.04 €	1.162	0.04 €	0.04 €	0.04 €	1.871	0.06 €	0.06 €	0.06 €
HWD	0.003	0.00 €	0.00 €	0.00 €	0.002	0.00 €	0.00 €	0.00 €	0.001	0.00 €	0.00 €	0.00 €
FW	0.079	0.00 €	0.00 €	0.02 €	0.079	0.00 €	0.00 €	0.02 €	0.623	0.00 €	0.00 €	0.15 €
NRSF	8.415	0.12 €	0.12 €	0.12 €	7.915	0.11 €	0.11 €	0.11 €	7.538	0.10 €	0.10 €	0.11 €
RSF	4.554	0.08 €	0.15 €	0.21 €	10.946	0.20 €	0.35 €	0.51 €	3.599	0.06 €	0.12 €	0.17 €
SM	7.801	22.07 €	22.07 €	22.07 €	6.244	17.67 €	17.67 €	17.67 €	6.613	18.71 €	18.71 €	18.71 €
PERE	37.951	0.68 €	1.23 €	1.78 €	38.274	0.69 €	1.24 €	1.79 €	35.725	0.64 €	1.16 €	1.67 €
PERM	0.666	0.01 €	0.01 €	0.01 €	0.595	0.01 €	0.01 €	0.01 €	12.626	0.17 €	0.18 €	0.18 €
PENRE	175.064	2.40 €	2.43 €	2.47 €	142.110	1.95 €	1.98 €	2.00 €	140.842	1.93 €	1.96 €	1.99 €
PENRM	17.611	0.24 €	0.24 €	0.25 €	17.827	0.24 €	0.25 €	0.25 €	46.942	0.64 €	0.65 €	0.66 €
EEE	0.739	0.01 €	0.02 €	0.03 €	0.503	0.01 €	0.02 €	0.02 €	1.944	0.03 €	0.06 €	0.09 €
EET	1.832	0.03 €	0.06 €	0.09 €	1.216	0.02 €	0.04 €	0.06 €	4.604	0.08 €	0.15 €	0.22 €
TOTAL		**29.73 €**	**35.81 €**	**42.51 €**		**24.37 €**	**29.59 €**	**35.33 €**		**26.34 €**	**31.36 €**	**37.14 €**



	PEB building A	PEB building B	nZEB building C
high	42.51	35.33	37.14
medium	35.81	29.59	31.36
low	29.73	24.37	26.34

high medium low

Chart 1: Total cost calculated for each building [€/m2*y]

By "pricing" the categories listed in table 1 (see Chart 1) it is possible to associate a cost of:

- 29.73 to 42.51 €/m^2*y, to building A,
- 24.37 to 35.33 €/m^2*y, to building B,
- 26.34 to 37.14 €/m^2*y, to building C.

This implies that, according to all cost estimations, PEB building A is about 12% to 14% "more costly" than nZEB building C, the reference case, while PEB building B always performs better the nZEB building C, i.e. it is about 5% to 7% "less costly". The absolute-value difference across building "costs" provides the direct costing evaluations of the co-benefits. These are, using low-cost estimates:

- 3.40 €/m^2*y in the case of PEB building A (which is more costly than nZEB building C and therefore originates in fact negative co-benefits),
- -1.97 €/m^2*y in the case of PEB building B (which is less costly than nZEB building C and therefore originates positive co-benefits).

and using high-cost estimates:

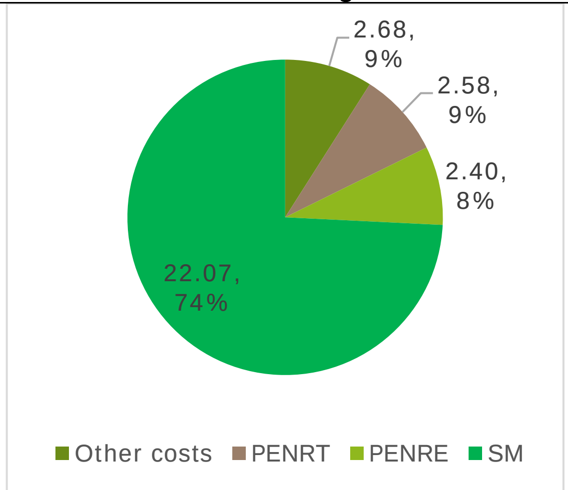
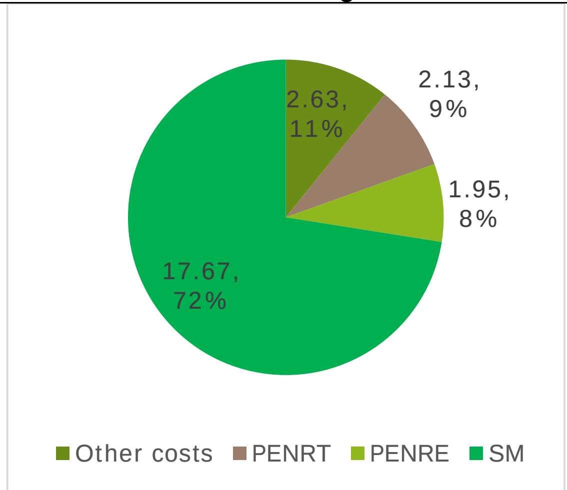
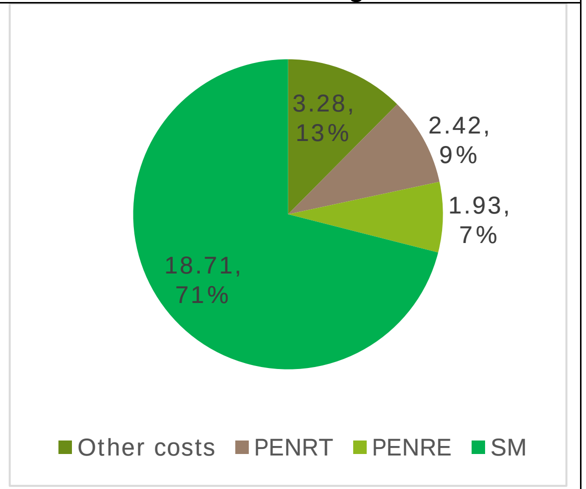
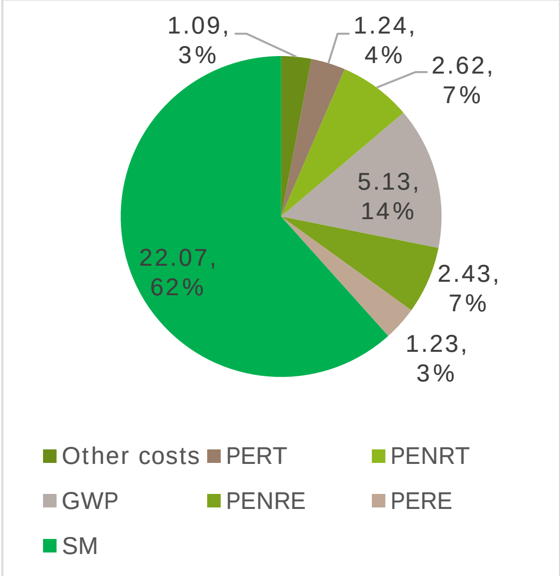
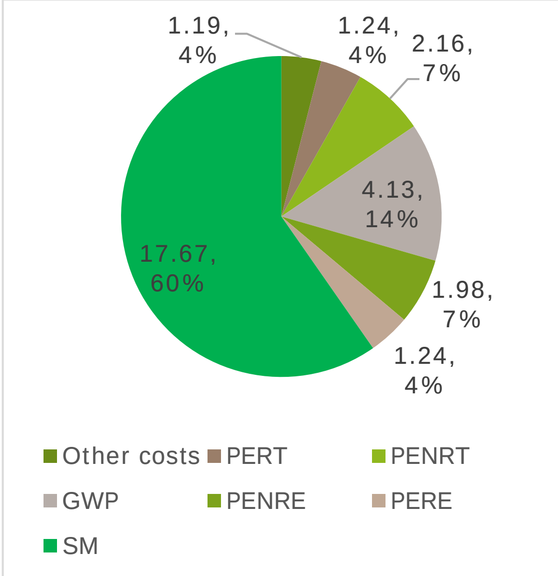
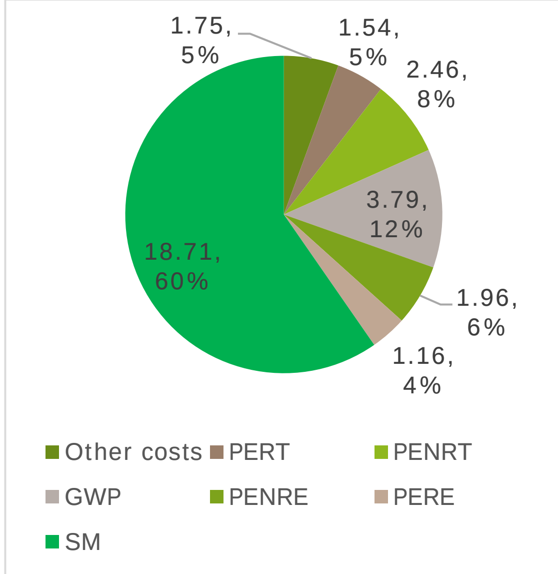
- 5.37 €/m^2*y in the case of PEB building A (which is more costly than nZEB building C and therefore originates in fact negative co-benefits),
- - 1.81 €/m^2*y in the case of PEB building B (which is less costly than nZEB building C and therefore originates positive co-benefits).

Decomposing the determinants of this result, it can be noted (table 2) that the higher unit costs, which also present high spread between low and high unit costs estimates, are associated to the emissions of ozone depleting substances (ODP), to the acidification potential (AP) and to the abiotic depletion potential generated by the use of non-fossil resources (ADPE). The largest spread between low and high unit cost estimates are demonstrated by Eutrophication potential (EP).

However, the final determination of co-benefits also depends on the emitted/used quantity of the single substances. Therefore, compounding cost measures with quantity data, it emerges that (Chart 2), in the low-cost case, co benefits are mostly associated with the three categories of: input of secondary material (SM), total use of non-renewable primary energy resource (PENRT), non-renewable primary energy as energy carrier (PENRE). Also, in the high-cost case input of secondary material (SM) emerges as the largest contributor to the co-benefit determination. This is then followed by global warming potential (GWP), non-renewable primary energy as energy carrier (PENRE), total use of non-renewable primary energy resource (PENRT), total use of renewable primary energy resources (PERT), renewable primary energy as energy carrier (PERE), and abiotic depletion potential for fossil resources (ADPF).

Focusing on the single indicators enables to describe with more detail the contribution to co-benefits of the PEB buildings with respect to nZEB building C (Chart 3):

- PEB building A performs better than the reference case in 11 out of 24 co-benefit indicators: PERT, ODP, POCP, MER, MFR, NHWD, FW, PERM, PENRM, EEE, EET;
- PEB building B outperforms the reference case in 15 out of 24 indicators: PERT, PENRT, ODP, EP, POCP, ADPF, MER, MFR, NHWD, FW, SM, PERM, PENRM, EEE, EET.

	PEB building A	PEB building B	nZEB building C
LOW			
MEDIUM			

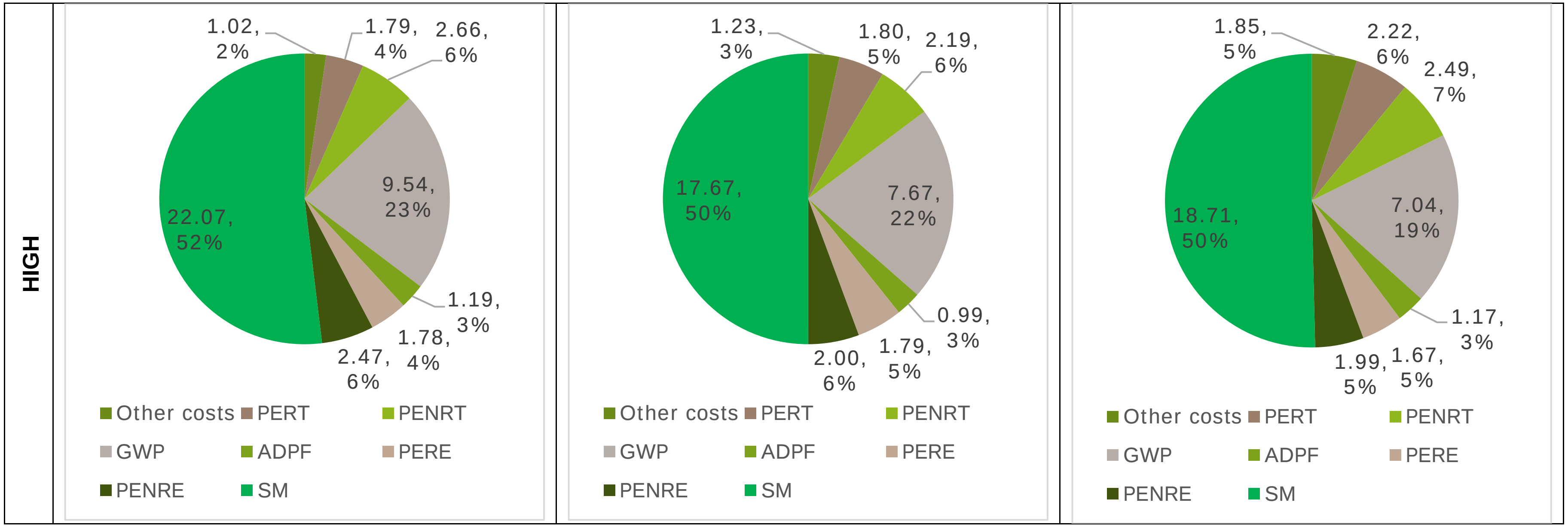
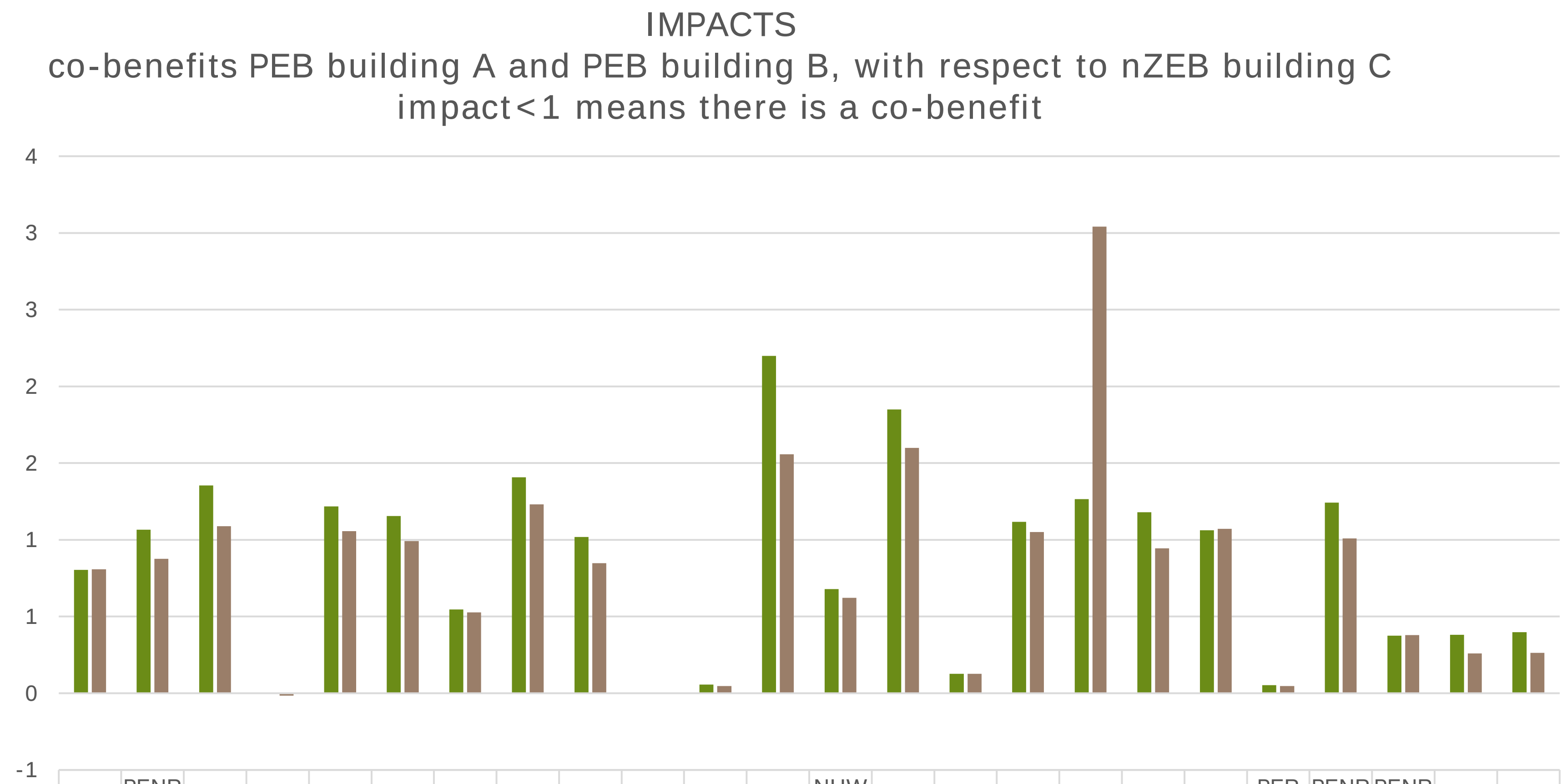


Chart 2: Cost shares associated with different co-benefit indicators for each building in the low, medium, high costs cases [€]



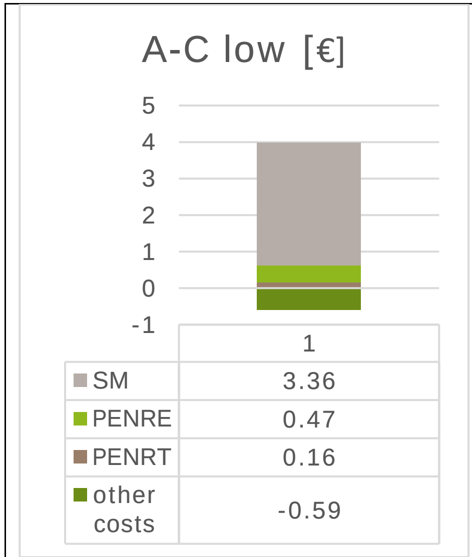
	PERT	PENRT	GWP	ODP	AP	EP	POCP	ADPE	ADPF	MER	MFR	RWD	NHWD	HWD	FW	NRSF	RSF	SM	PERE	PERM	PENRE	PENRM	EEE	EET
A/C impacts	0.80	1.07	1.36	0.00	1.22	1.15	0.55	1.41	1.02	0.00	0.06	2.20	0.68	1.85	0.13	1.12	1.27	1.18	1.06	0.05	1.24	0.38	0.38	0.40
B/C impacts	0.81	0.88	1.09	-0.0	1.06	0.99	0.53	1.23	0.85	0.00	0.05	1.56	0.62	1.60	0.13	1.05	3.04	0.94	1.07	0.05	1.01	0.38	0.26	0.26

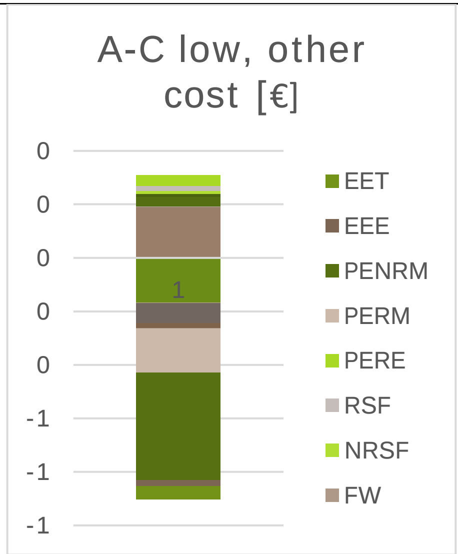
Chart 3 enables a deeper comparison across the different building types

The worse aggregated performance of PEB building A compared with the reference nZEB building C (Chart 4), is always mostly due to the higher costs associated with use of secondary material (SM), Non-renewable primary energy as energy carrier (PENRE), Total use of non-renewable primary energy resource (PENRT). When the medium-cost estimates are used, in addition Renewable primary energy as energy carrier (PERE) and global warming potential (GWP) become a relevant source of co-benefit loss; and when the high-cost estimates are used, in addition Abiotic depletion potential for fossil resources (ADPF) becomes a relevant source of co-benefit loss. These cost items build about 80% of the (negative) co-benefits of A (for low, medium high costs).

Considering the total co-benefits associated with all the items the nZEB reference building C outperforms the PEB building A by 3.4 and 5.4 €/m^2*y in the low and high-cost cases respectively.

The aggregated performance of PEB building B is always better than that of the nZEB reference building C independently upon the cost estimates used: PEB building B outperforms nZEB reference building C by 2 and by 1.8 €/m^2*y in the low and high-cost cases respectively.


A-C low [€]
5
4
3
2
1
0
-1
1
SM 3.36
PENRE 0.47
PENRT 0.16
other costs -0.59


A-C low, other cost [€]
0
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-1
-1
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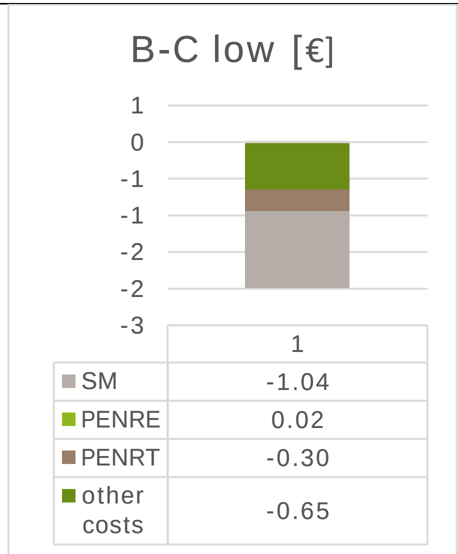
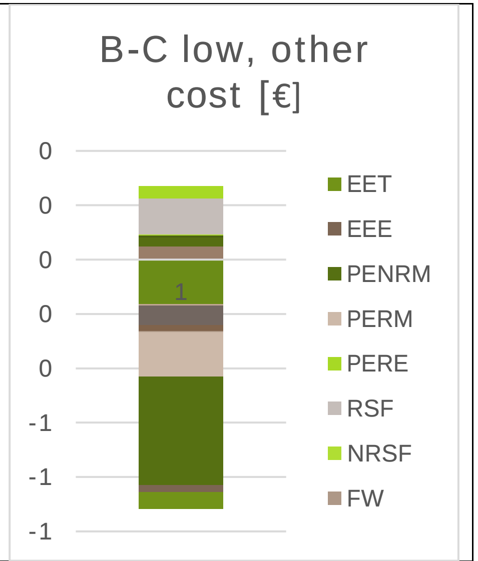
1
EET
EEE
PENRM
PERM
PERE
RSF
NRSF
FW


B-C low [€]
1
0
-1
-1
-2
-2
-3
1
SM -1.04
PENRE 0.02
PENRT -0.30
other costs -0.65


B-C low, other cost [€]
0
0
0
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0
-1
-1
-1
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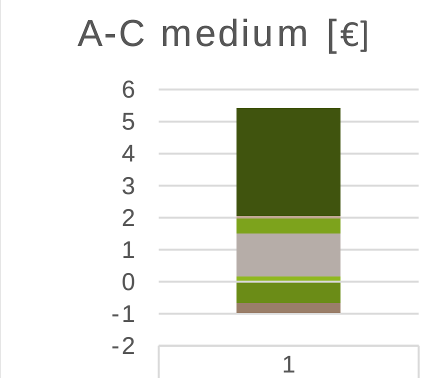
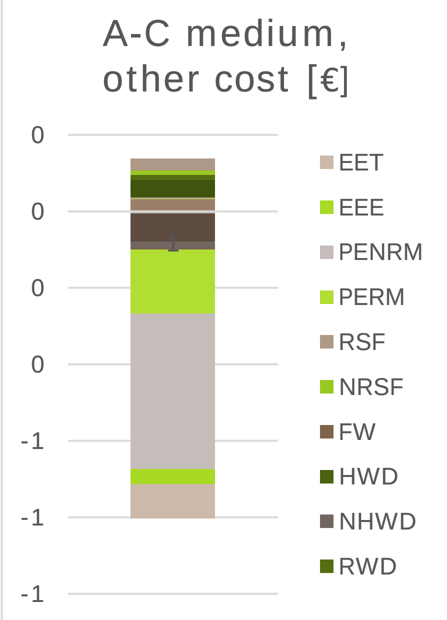
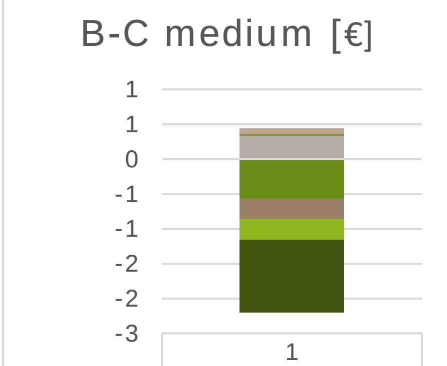
PERE
RSF
NRSF
FW

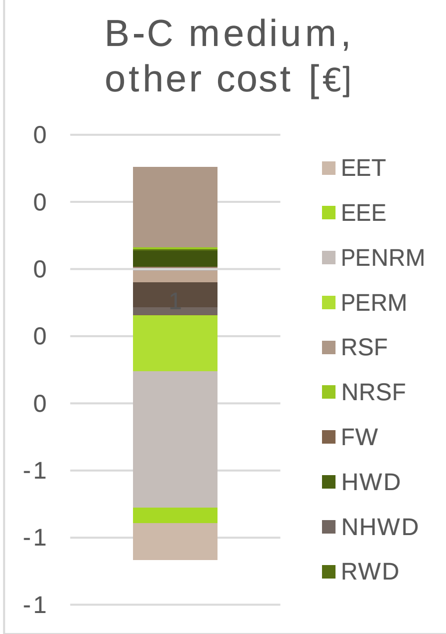


	1
SM	3.36
PERE	0.07
PENRE	0.48
GWP	1.35
PENRT	0.16
PERT	-0.30
other costs	-0.67





	1
SM	-1.04
PERE	0.08
PENRE	0.02
GWP	0.34
PENRT	-0.30
PERT	-0.29
other costs	-0.56



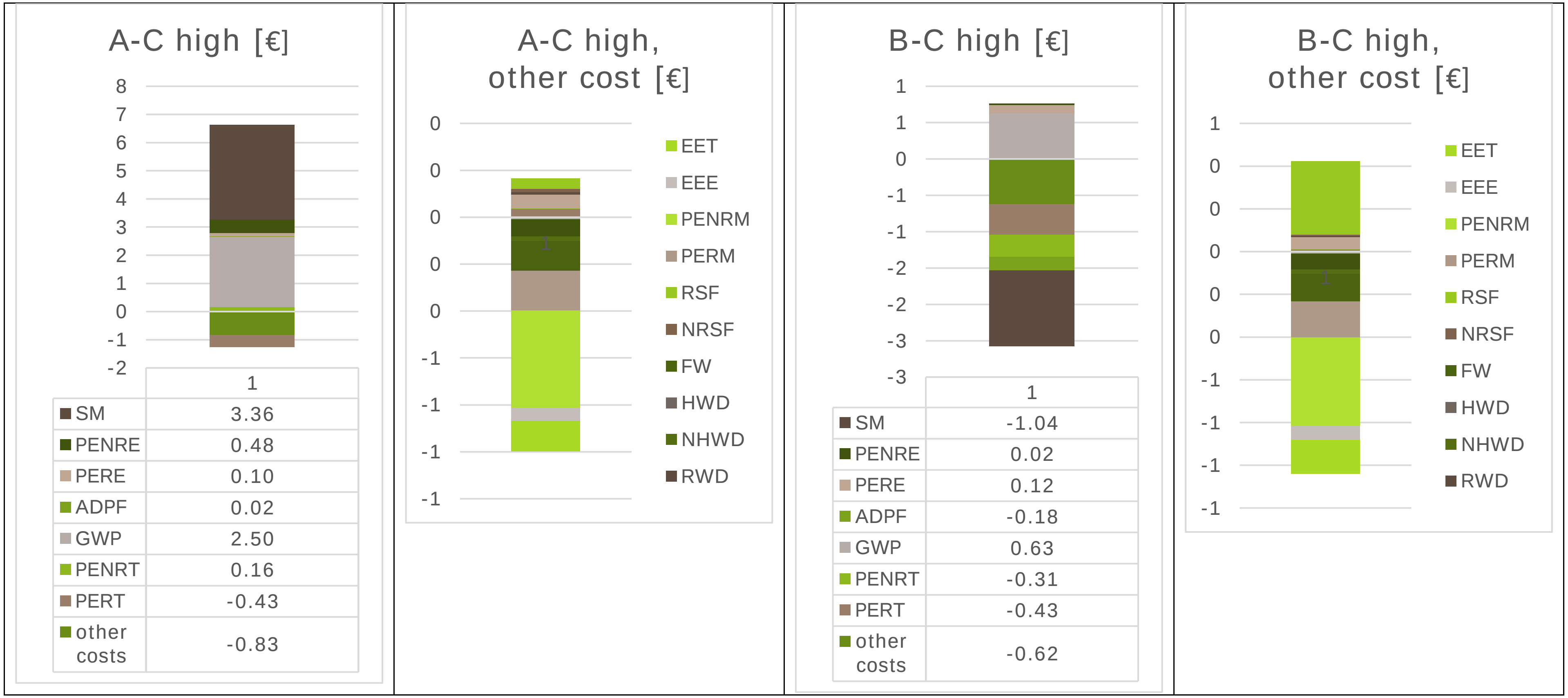


Chart 4: Contribution to performance in absolute values [€]

5. Conclusions

The direct costing co-benefit assessment emphasized that the two typologies of PEB considered may, in fact, originate either higher or lower total co-benefits than the nZEB reference. However, looking into the determinants of this result, it also emerges that both the PEB buildings A and B are always superior to the reference in some categories of co benefit indicators. Namely:

- Total use of renewable primary energy resources (PERT)
- Non renewable primary energy as material utilization (PENRM)
- Exported electrical energy (EEE)
- Exported thermal energy (EET)
- Depletion potential of the stratospheric ozone layer (ODP)
- Formation potential of tropospheric ozone photochemical oxidants (POCP)
- Material for Energy Recovery (MER)
- Materials for recycling (MFR)
- Non hazardous waste dispose (NHWD)
- Use of net fresh water (FW)
- Primary energy resources used as raw materials (PERM).

The fact that in other categories the reference could be superior to the PEB, and that net effects could be favourable to the former, hint that the major gains related to PEBs indeed reside in their energy generation potential rather than in markedly superior or more efficient building characteristics.

This outcome however needs some important qualifications:

- Independently upon the net outcome, PEB buildings A and B in fact outperform nZEB reference building C in several cost categories. Nonetheless, the co-benefits stemming from these categories are associated with a lower economic value than other categories.
- In relation to this, it has to be considered that the monetary evaluation of co-benefits is uncertain. For many cost categories, the cost spread between lower and upper values is huge with the latter more than 1000 times larger than the former. This can highly influence the assessment. This is particularly evident when the use of freshwater is considered. The choice of its pricing determines whether PEB B generates positive co-benefits or not.
- The performance of the PEB buildings A and B respect to the reference nZEB building C in the single indicator types can be used to guide the design of PEB buildings towards improving their co-benefits.
- Finally, it has to be considered that in the present assessment, not all the categories potentially origin of co-benefits has been evaluated.

Annex 2: Assessing co-benefits of PEB. Applying a direct cost assessment – German case study

Valentina Giannini, CMCC, Francesco Bosello, University of Venice

1. Introduction

As part of task 5 of the Cultural-E project the following "fiche" reports the evaluation of the co-benefits that can be associated with a Plus Energy Building (PEB) applying a direct cost methodology to the German case study.

As defined in Cultural-E D5.2. co-benefits are "additional positive effects brought by a policy measure, that occur regardless of and in addition to the originally predetermined policy goals (AR5, 2014)." Consequently, the current assessment does not evaluate the energy generation potential of the PEB, given that this is, indeed, its primary purpose. (The assessment is however reported in an appendix of this fiche).

Different methodologies are available for co-benefit evaluation. Direct costing (see D5.2) here described, attempts to associate a straight monetary value to a quantifiable source (i.e. a performance indicator) of co-benefits.

This can be more easily feasible when co benefits can be linked to a "use" on its turn associated to material aspects transiting through "market transactions". A typical example is a higher or lower use of say "building materials" commonly bought and sold in standard markets. This can be however possible also for "materials" not directly "priced" by demand and supply interactions. A typical example is the emission of pollutants in the atmosphere, whose damage can be monetized applying different methodologies to quantify external costs (see e.g.: Rennert & Kingdon, 2019)

Following this methodology, we hereby evaluate the co-benefits associated with a PEB representative of the Italian context.

2. The methodology

To apply the direct cost methods the following steps have been followed:

a) co-benefit categories were identified as listed in deliverable Cultural E D5.2 (Bosello et al. 2024) Table 4. They are reported in Table 1 below (first column);
b) co-benefit categories were matched to specific environmental indicators calculated by University of Stuttgart (Cultural-E D4.5: Di Bari and Jorgji, 2021, table 1 second column) based on EN 15804 +A1. The study, consisting in a life-cycle assessment,

computes a list of physical indicators "per square meter per year" of two different types of buildings (see below).

c) Monetary evaluations were attributed to each indicator through a literature review (list of money reference is here while the source literature is reported at the end of this document). Whenever possible, ranges, (low to high cost estimations) for the monetary values have been reported, to communicate the uncertainty beyond the assessment and test its robustness. In the cases of materials for recycling, disposal of radioactive wastes, disposal of hazardous and non-hazardous wastes only one cost reference has been found.
d) The final evaluations of co-benefits were performed comparing (calculating the difference between) two building types: Building A (demo PEB), Building C (reference nZEB), see below Charts 1-4 and Table 2.

As anticipated, it is worth stressing that not all potential co-benefits are directly linkable to direct economic values. Furthermore, the unavailability of specific co-benefit indicators, can prevent the assessment of co-benefits even though economic evaluations are in principle available. Specifically (see Table 1), due to a lack of information, in the present assessment it was not possible to quantify indicators of:

- operation and maintenance activity,
- employment creation,
- air pollution.

Accordingly, the potential co-benefits associated to these categories were not computed. Furthermore, no data were available to measure changes in energy poverty.

Table 1: List of co-benefits, indicators, and money metric for the direct cost assessment (Deliverable D5.2 - Guidelines to assess the co-benefits of Plus Energy Buildings)

Note: indicators' acronym **XXX** taken from mappe1.xlsx and other Pivot tables for Fabbricato A, Fabbricato B, Fabbricato C (reference)

Co-benefit	Indicator	Direct cost assessment
Reduction of construction material and demolition waste.	Difference quantities of the various waste categories over lifetime of PEB compared to NZEB. **HWD**	A standard Waste Treatment Cost from the literature. [Vázquez-López et al, 2020]
Lower operational and maintenance costs.	Difference in the operational and maintenance hours over the lifetime of the PEB compared to NZEB. **Not available**	Average market value of those services.
Mitigation of climate change.	Difference in the total quantity of CO2 emissions over the lifetime of PEB compared to NZEB. **GWP**	The social cost of carbon. [Rennert & Kingdon, 2019]
Employment creation.	Number of additional jobs created as a result of the construction of a PEB compared to a NZEB. **Not available**	The average wage in the relevant industry.
Improvement of social welfare.	Total energy savings over the lifetime (MWh) of the PEB compared to a NZEB.	Reduction in energy poverty. Demonstrating the effect of energy savings on the financial situation of the lowest income decile. **Not available**
Reduction of air pollution.	Difference in physical emissions (kg) of particulate matter over the lifetime of the PEB compared to a NZEB. **Not available**	The external or social cost of PM10 emissions or equivalent, €39.2. [CE Delft, 2018]
Reduced ozone depletion.	Difference in emissions of CFC equivalent substances over the lifecycle phases of a PEB compared to the reference case NZEB **ODP**	The external or social cost of emitting additional kg of CFC or equivalent, €30.40. [CE Delft, 2018]
Reduced formation potential of tropospheric ozone photochemical oxidants.	The difference in kg of Ethen equivalent emissions over the life cycle of a PEB compared to a NZEB. **POCP**	The external or social cost of Photochemical oxidant formation is given as €1.15 per kg of non-methane volatile organic compounds (NMVOC) emitted. [CE Delft, 2018]

Reduced acidification potential.	Difference in emissions of kg of phosphate equivalent over the life cycle of a PEB compared to a NZEB. **AP**	The external or social cost of a unit of sulphur dioxide emissions is €4.97 per kg. [CE Delft, 2018]
Reduced eutrophication potential.	Difference in emissions of kg of phosphate equivalent over the life cycle of a PEB compared to a NZEB. **EP**	The external or social cost of freshwater eutrophication is given as €1.86 per kg of phosphate equivalent. [CE Delft, 2018]
Reduced abiotic depletion potential for non-fossil resources.	Difference in emissions of kg of Sb (Antimony) equivalent over the life cycle of a PEB compared to a NZEB. **ADPE**	The external or social cost of resource use, minerals and metals is given as €1.64 per kg of Sb equivalent. [Trinomics, 2020]
Reduced Abiotic depletion potential for fossil resources.	The difference in energy (Mj) related over the life cycle of a PEB compared to a NZEB. **ADPF**	The external or social cost of fossil resource use is given as €0.0013 per Mj.[Trinomics, 2020]
Reduced water use.	The difference in net fresh water use over the life cycle of a PEB compared to a NZEB. **FW**	The external or social cost of water use is given as €0.00499 per m3 of water equivalent. [Trinomics, 2020]

3. The case study

The building types that are contrasted are representative of the German context. The buildings chosen have the following characteristics, as described in Cultural-E D6.3 (Leis and di Bari, 2023):

- PEB Building A consists of: 4 above ground floors and one basement level. The ground floor accommodates 560 m^2 of commercial use, whereas the top three floors contain 21 rental apartments with a usable area of 1570 m^2, all equipped with balconies and terraces. Approx. 40 parking places will be provided in the basement. The total gross building area is 4125 m^2 including the basement level. The total building height is 13 m. The structure is a wood/concrete hybrid: the basement level and building core housing the vertical circulation is designed in reinforced concrete, whereas the remaining load-bearing structure above ground is envisioned in wood. The roof provides approx. 550 m^2 of area for the installation of PV-panels.

nZEB Building C. This is the reference case. In accordance with the Cultural-E consortium decision it is a nZEB. It consists of: 4 floors, total floor area of 2363 m^2, net floor area 1986 m^2. The structure is mixed, primarily reinforced concrete. It has a decentralized ventilation, roof collector, floor heating, centralized heating with a condensing boiler, and lift.

4. Results

Table 2 reports extensively the calculation done, while Charts 1-4 visualize the results of the procedure.

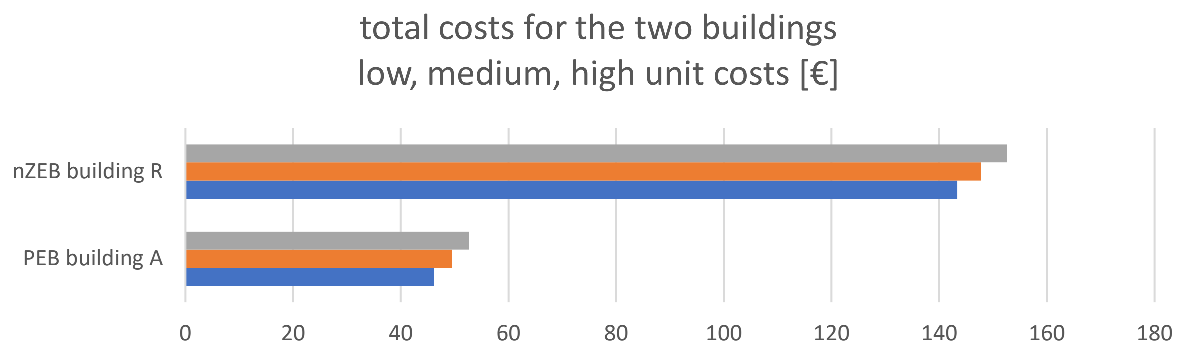
Table 2a: Unit costs and sources

	unit cost					
Indicator	**low**	**medium**	**High**	**impact/m²*y Unit**	**Price Unit**	**Source**
Total use of renewable primary energy resources (**PERT**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Total use of non renewable primary energy resource (**PENRT**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Global warming potential (**GWP**)	0.04 €	0.28 €	0.53 €	kg CO2-Eq	$2022/kg CO2	Tol, 2023
Depletion potential of the stratospheric ozone layer (**ODP**)	22.10 €	30.40 €	45.70 €	kg R11-Eq	€2015/kg CFC-eq.	CE Delft, 2018
Acidification potential (**AP**)	0.53 €	4.97 €	5.66 €	kg SO2-Eq	€2015/kg SO2-eq.	CE Delft, 2018
Eutrophication potential (**EP**)	0.25 €	1.86 €	2.11 €	kg Phosphat-Eq	€2015/kg P-eq.	CE Delft, 2018
Formation potential of tropospheric ozone photochemical oxidants (**POCP**)	0.84 €	1.15 €	1.84 €	kg Ethen-Eq	€2015/kg NMVOC-eq.	CE Delft, 2018
Abiotic depletion potential for non fossil resources (**ADPE**)	0.00 €	1.64 €	6.53 €	kg Sb-Eq	€2018/kg Sb eq	Trinomics, 2020
Abiotic depletion potential for fossil resources (**ADPF**)	0.00 €	0.00 €	0.01 €	MJ	€2018/MJ	Trinomics, 2020
Material for Energy Recovery (**MER**)	-0.32 €	-0.43 €	-0.55 €	kg	€/MJ	Our computation*
Materials for recycling (**MFR**)	2.83 €	2.83 €	2.83 €	kg	€/kg	Vázquez-López et al., 2020
Radioactive waste disposed (**RWD**)	4.00 €	4.00 €	4.00 €	kg		enea, 2023
Non hazardous waste disposed (**NHWD**)	0.03 €	0.03 €	0.03 €	kg	€/kg	Vázquez-López et al., 2020
Hazardous waste disposed (**HWD**)	0.08 €	0.08 €	0.08 €	kg	€/kg	Vázquez-López et al., 2020
Use of net fresh water (**FW**)	0.00 €	0.00 €	0.24 €	m3	€/m3	Trinomics, 2020
Use of non renewable secondary fuels (**NRSF**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Use of renewable secondary fuels (**RSF**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Input of secondary material (**SM**)	2.83 €	2.83 €	2.83 €	kg	€/kg	Vázquez-López et al., 2020
Renewable primary energy as energy carrier (**PERE**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Primary energy resources used as raw materials (**PERM**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Non renewable primary energy as energy carrier (**PENRE**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Non renewable primary energy as material utilization (**PENRM**)	0.01 €	0.01 €	0.01 €	MJ	€/MJ	Our computation*
Exported electrical energy (**EEE**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*
Exported thermal energy (**EET**)	0.02 €	0.03 €	0.05 €	MJ	€/MJ	Our computation*

* Description of the methodology can be foun in appendix

Table 2b: Calculation of costs

	PEB Building A				nZEB Building C			
Indicator	**impact/m²*y**	**A – low**	**A - medium**	**A – high**	**impact/m²*y**	**C - low**	**C – medium**	**C – high**
PERT	93.81	1.69 €	3.04 €	4.39 €	28.45	0.51 €	0.92 €	1.33 €
PENRT	21.19	0.29 €	0.29 €	0.30 €	116.36	1.59 €	1.62 €	1.64 €
GWP	3.84	0.15 €	1.08 €	2.01 €	13.31	0.53 €	3.76 €	6.99 €
ODP	0.00	0.00 €	0.00 €	0.00 €	0.00	0.00 €	0.00 €	0.00 €
AP	0.02	0.01 €	0.10 €	0.11 €	0.02	0.01 €	0.12 €	0.13 €
EP	0.00	0.00 €	0.01 €	0.01 €	0.00	0.00 €	0.01 €	0.01 €
POCP	0.00	0.00 €	0.01 €	0.01 €	0.01	0.00 €	0.01 €	0.01 €
ADPE	0.00	0.00 €	0.00 €	0.00 €	0.00	0.00 €	0.00 €	0.00 €
ADPF	35.67	0.00 €	0.05 €	0.24 €	109.81	0.00 €	0.14 €	0.75 €
MER	5.75	-1.81 €	-2.48 €	-3.16 €	0.06	-0.02 €	-0.03 €	-0.03 €
MFR	9.54	26.99 €	26.99 €	26.99 €	45.59	128.98 €	128.98 €	128.98 €
RWD	0.00	-0.02 €	-0.02 €	-0.02 €	0.00	0.01 €	0.01 €	0.01 €
NHWD	8.20	0.26 €	0.26 €	0.26 €	24.77	0.78 €	0.78 €	0.78 €
HWD	0.00	0.00 €	0.00 €	0.00 €	0.00	0.00 €	0.00 €	0.00 €
FW	-0.68	0.00 €	0.00 €	-0.16 €	0.04	0.00 €	0.00 €	0.01 €
NRSF	1.01	0.01 €	0.01 €	0.01 €	0.49	0.01 €	0.01 €	0.01 €
RSF	7.05	0.13 €	0.23 €	0.33 €	0.12	0.00 €	0.00 €	0.01 €
SM	5.74	16.23 €	16.23 €	16.23 €	3.06	8.66 €	8.66 €	8.66 €
PERE	90.70	1.63 €	2.94 €	4.24 €	25.27	0.45 €	0.82 €	1.18 €
PERM	1.78	0.02 €	0.02 €	0.03 €	3.13	0.04 €	0.04 €	0.04 €
PENRE	24.14	0.33 €	0.34 €	0.34 €	106.85	1.46 €	1.49 €	1.51 €
PENRM	3.64	0.05 €	0.05 €	0.05 €	8.38	0.11 €	0.12 €	0.12 €
EEE	2.93	0.05 €	0.09 €	0.14 €	3.05	0.05 €	0.10 €	0.14 €
EET	6.74	0.12 €	0.22 €	0.32 €	7.08	0.13 €	0.23 €	0.33 €
TOTAL		**46.15 €**	**49.46 €**	**52.67 €**		**143.35 €**	**147.79 €**	**152.61 €**



	PEB building A	nZEB building R
high	52,67	152,61
medium	49,46	147,79
low	46,15	143,35

Chart 1: Total cost calculated for each building [€/m2*y]

By “pricing” the categories listed in Table 1 (see Chart 1) it is possible to associate a cost of:

- 46.1 to 52.7 €/m^2*y, to PEB building A,
- 143.3 to 152.6 €/m^2*y, to nZEB building C.

This implies that PEB building A is 65 to 68% cheaper (in terms of co-damages production, the dual of co-benefit) than the reference. The absolute-value difference across building “costs” provides the direct costing evaluations of the co-benefits. These are positive and total:

- 97.2 €/m^2*y using “low-cost estimates”.
- 99.9 €/m^2*y using “high-cost estimates”.

Decomposing the determinants of this result, it can be noted (Table 2a) that the higher unit costs are associated to the emissions of ozone depleting substances, the disposal of non-hazardous wastes and to the abiotic depletion potential generated by the use of non-fossil resources. The largest spread between low and high-cost estimates are demonstrated by the use of freshwater, the abiotic depletion from fossil and non-fossil resources, the global warming potential and acidification. However, the final determination of co-benefits also depends on the emitted/used quantity of the single substances. Therefore, compounding cost with quantity data, it emerges that (Table 2b and Chart 2) co benefits are dominated by materials for recycling and input of secondary materials. The latter, in particular, builds the bulk of the difference across the German PEB and nZEB showing much better performance of the first building type.

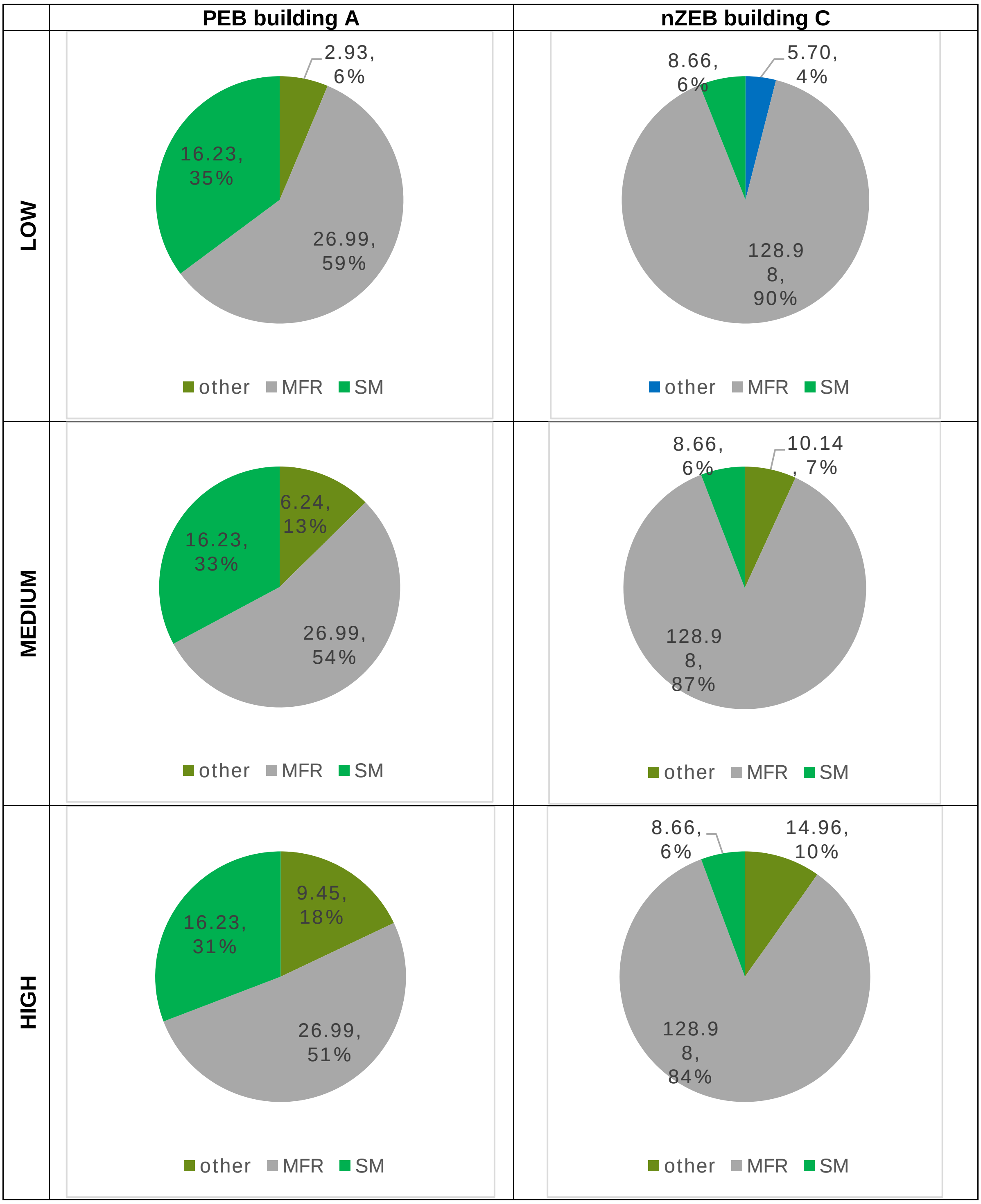


Chart 2: Cost shares associated to different co-benefit indicators for each building for low, medium, high costs [€]

Focusing on the single indicators, enables to describe with more detail the contribution to co-benefits of the PEB building A with respect to nZEB building C (Chart 3):

- PEB building A performs better than the reference case in 15 out of 21 co-benefit indicators: PENRT, GWP, ODP, AP, EP, POCP, ADPF, MFR, RWD, NHWD, PERM, PENRE, PENRM, EEE, EET;

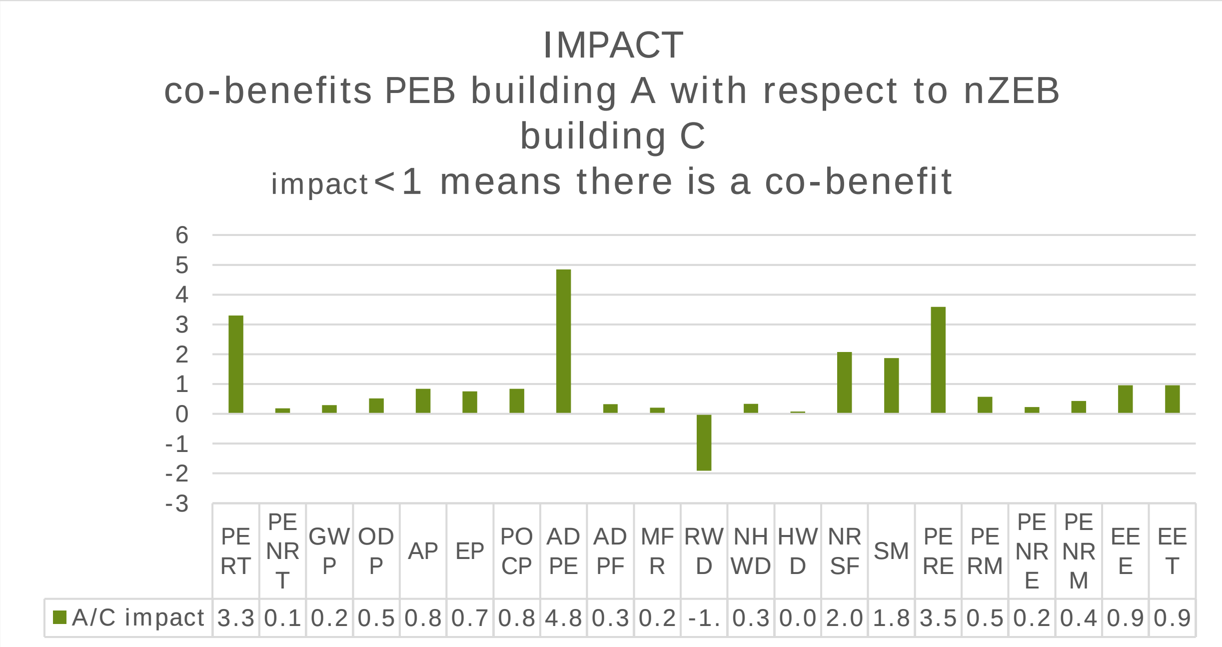


Chart 3: enables a deeper comparison across the two buildings.

As mentioned, the best aggregated performance of the PEB building A compared with the reference nZEB building C, is almost entirely due to the lower costs associated with material for recycling (MFR) (see Chart 4). On the contrary, examining the use of secondary materials (SM), the use of renewable resources as energy carriers (PERE), the use of renewable primary energy resources (PERT) and the use of renewables secondary fuels (RSF) the nZEB reference slightly outperforms the PEB. However, the lower co-benefits associated with these items are much smaller that the positive co-benefits from material for recycling. Altogether they build a co benefit value of roughly 2.5 to 6 €/m^2*y against more than 100 €/m^2*y deriving from the material from recycling.

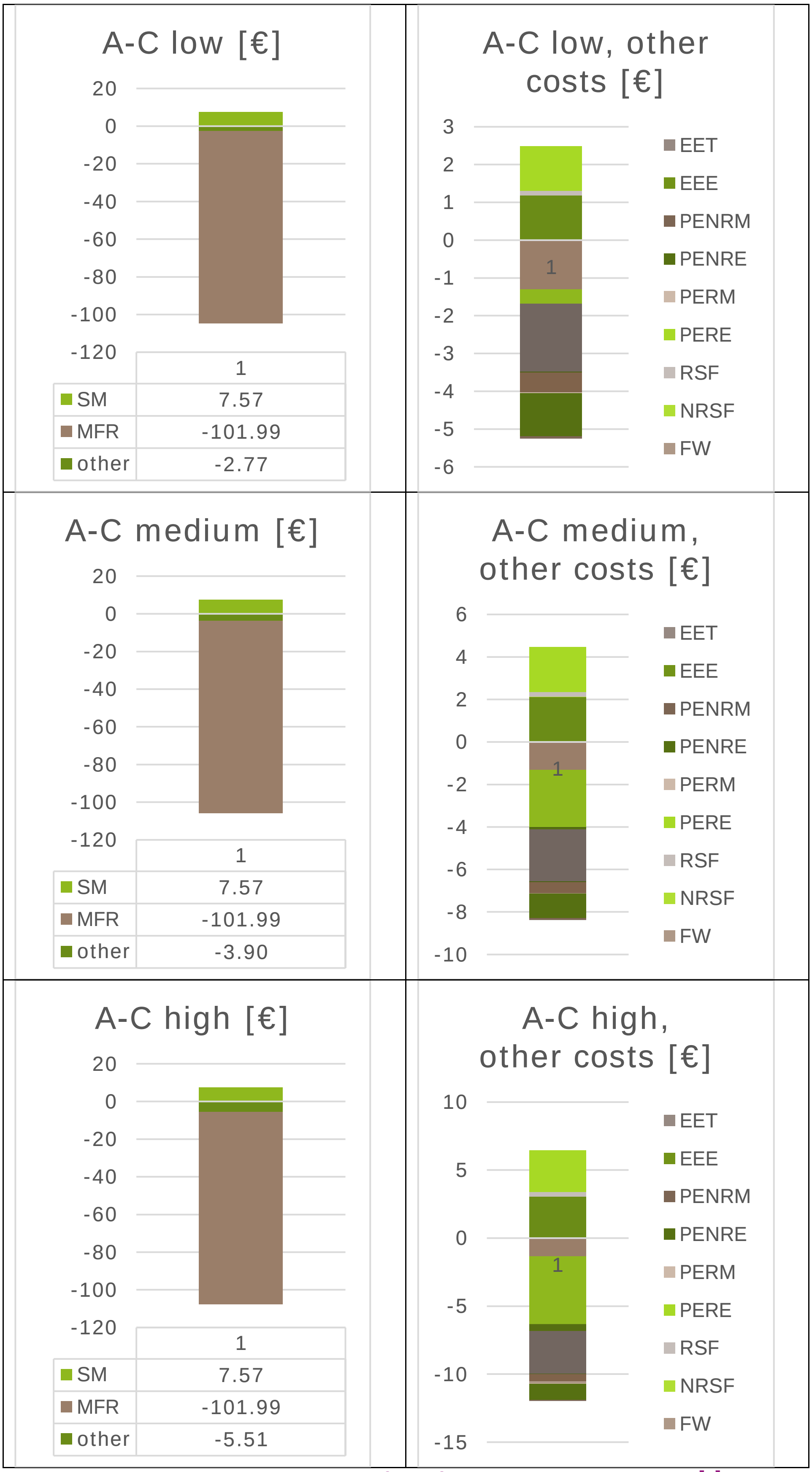


Chart 4: Contribution to co benefit performance in absolute values [€]

5. Conclusions

The direct costing co-benefit assessment emphasised that, in the German case, the PEB considered may, in fact, originate substantively positive net co-benefits compared with the nZEB reference. This is an additional advantage on top of its energy generation potential.

This outcome however needs some important qualifications:

- Independently upon the net outcome, the nZEB, in fact, outperforms the PEB in several cost categories, most notably the use of secondary materials. The co-benefits stemming from these categories are, however, associated with a lower economic value than the other categories.
- The monetary evaluation of co-benefits is uncertain. For many cost categories, the cost spread between lower and upper values is huge with the latter more than 1000 times larger than the former. This can highly influence the assessment. In the specific German case study however, this variability is less of an issue given that the largest spread in cost assessment is linked with the use of freshwater resources that is limited in both types of buildings.
- Finally, it has to be considered that in the present assessment, not all the categories potentially origin of co-benefits have been evaluated.