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Defining Zero-Emission Buildings

Support for the revision of the Energy Performance of Buildings Directive

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Contents

Abstract

The revision of the Energy Performance of Buildings Directive (EPBD) is essential to set out how the European Union can decarbonise the building stock by 2050. This report presents the work carried out by the JRC during the second half of 2021, supporting the introduction of zero-emission building (ZEB) definition in the revised EPBD. The study identifies the key methodological aspects that a ZEB definition should address (i.e., stages included in the greenhouse gas emissions calculation over building life-time, ambition of reaching zero emissions, calculation methods, metrics, and system boundaries), highlighting the key role of energy efficiency and renewable energy in reducing the operational emissions. Moving towards zero life-cycle emissions, it will be crucial to lower as much as possible the embodied emissions by prioritising low carbon materials, while the calculation and disclosure of global warming potential will guide decision-makers on carbon offset options. Furthermore, the study identifies the main features of a pragmatic definition also considering the interplay with other building-related concepts framed by the EPBD. Finally, the linkage with other EU policies as well as the market readiness to deliver zero-carbon buildings are discussed.

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1 Introduction

The building sector has a high environmental impact not only in terms of energy consumption and greenhouse gas (GHG) emissions, but also in terms of extracted material and waste generation. Besides contributing with 40% to energy consumption and 36% to energy-related GHG emissions, buildings account for about 50% of extracted material (European Commission, 2019). In addition, the construction sector is responsible for more than 35% of the EU's total waste generation (European Commission, 2022a).

The European Commission has therefore identified the building sector and the construction industry as essential fields of action in responding to climate and environmental challenges. The European Green Deal communication (European Commission, 2019) and the following Renovation Wave strategy (European Commission, 2020a) point to the need to build and renovate in an energy and resource efficient way. While stressing the need to at least double the annual renovation rate of the European Union (EU) building stock, it insists on the enforcement of the energy performance of buildings legislation. At the same time, it highlights that the principles of circular economy should guide newly constructed and renovated buildings, while digitalisation and climate-proofing of the building stock should increase.

As an essential legislative tool to support the implementation of the above-mentioned strategies, the revision of the Energy Performance of Buildings Directive (Directive 2010/31/EU) must set out how the EU can achieve a zero-carbon building stock by 2050. Besides the introduction of EU–wide minimum energy performance standards for worst performing buildings, deep renovation definition, renovation passport and mortgage portfolio standards, the revised directive foresees more ambitious concepts for buildings.

This report examines the concept of Zero-Emission Building (ZEB) by identifying the key methodological aspects that a ZEB definition should address: (1) the stages included in the GHG emissions calculation over the building lifetime (operational vs. life-cycle emissions); (2) the ambition dimension of reaching zero emissions (absolute zero vs. net zero) and emission offset options; (3) the calculation methods (static vs. dynamic); (4) the indicators and metrics to be reported by the definition; and finally, (5) the spatial boundary (building level vs. district/city/national/EU level).

These criteria emerge from an overview of existing zero (or very low) emission building definitions worldwide which also highlights the key role of energy efficiency measures, in line with the EU far-reaching guiding principle of "energy efficiency first". Moreover, the criteria is also discussed in relation with concepts currently framed by the EPBD, such as the cost-optimal methodology and nearly-zero energy buildings (NZEBs), presenting their overall interplay. Based on this, the study provides pragmatic features of a possible ZEB definition as well as the main steps to follow for numerical benchmarks derivation.

The report is structured as follows: Chapter 1 lays down the study in the current policy context. Chapter 2 presents an overview of zero carbon building concepts identified in the literature. Chapter 3 discusses the key criteria that a ZEB definition should address. Chapter 4 outlines the decisive role of energy efficiency, while Chapter 5 discusses the essential contribution of renewable energy, followed by a pragmatic definition approach in Chapter 6. Chapter 7 discusses the current state of play in relation with other building concepts and policies and the market readiness. Chapter 8 shows examples of zero-emission buildings and finally, Chapter 9 draws conclusions.

2 Overview of existing zero carbon building concepts

The concept of zero emission buildings has been developed and applied globally in the last two decades, being seen as a main way to decarbonise the building sector. A recent review of such approach indicates year 2006 as the beginning of the gradual increase in research on zero carbon buildings (Ohene et al., 2022).

Table 1 shows definitions for buildings with zero or very low carbon emissions identified in the literature. As observed, only few definitions are given by national legislation, while the majority are conceptual, developed and studied at a theoretical level. A general consensus is that a Zero-Emission Building (ZEB) is an energy efficient building that produces enough renewable energy to compensate for its GHG emissions.

Table 1. Definitions of zero or very low carbon emissions buildings around the world

Name and source	Definition
Zero Emission by The Norwegian Research Centre on Zero Emission Buildings (ZEB, 2022)	A zero emission building produces enough renewable energy to compensate for the building's GHG emissions over its life span. The ZEB research centre has defined different levels of zero emission buildings depending on how many phases of a building's lifespan that are counted in. The 5 most important definitions, in rising ambition level, are: ZEB – O: The building's renewable energy production compensate for greenhouse gas emissions from operation of the building. ZEB – O ÷ EQ: The building's renewable energy production compensate for greenhouse gas emissions from operation of the building minus the energy use for equipment (plug loads). ZEB – OM: The building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials. ZEB – COM: The building's renewable energy production compensate for greenhouse gas emissions from construction, operation and production of building materials ZEB – COMPLETE: The building's renewable energy production compensate for greenhouse gas emissions from the entire lifespan of the building. Building materials – construction – operation and demolition/recycling.
Zero-Carbon-Ready by International Energy Agency (International Energy Agency, 2021a)	A zero-carbon-ready building is highly energy efficient and uses either renewable energy directly or from an energy supply that will be fully decarbonised by 2050 such as electricity or district heat. This means that a zero-carbon-ready building will become a zero-carbon building by 2050, without any further changes to the building or its equipment.
Net Zero Emission by (Good et al., 2015)	In a net zero emission building, all operational and embodied emissions from materials are offset by on-site renewable energy generation. The word "net" indicates that energy can be exported from and imported to the building, and the net energy or emission balance is calculated over a specific period of time, usually a year. In practice, this usually means that the building is connected to the energy grid.
Zero Emission by (Brozovsky et al., 2019)	Zero emission buildings focus on the reduction of GHG emissions and are not targeting energy use as a criterion, at least not primarily. Such building aims to produce enough renewable energy to compensate for the GHG emissions over its life span.
Zero Emission by (Søgnen et al., 2016)	Zero emission buildings should replace fossil fuels with renewable clean energy so that the saved emissions equals the emissions caused by the building's construction, operation and materials.
Zero Emission by (Skaar et al., 2018)	A zero emission building is an energy-efficient building with on-site renewable energy generation that can export enough energy to compensate for the carbon footprint of the building's own energy and material consumption in a life-cycle perspective.
Net Zero Emission by (Ruparathna et al., 2017)	Net zero emission buildings use emission-free energy and supply the energy demand through on-site renewable energy generation.

Net Zero Emission by (Torcellini et al., 2006)	A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.
Zero carbon by (Riedy et al., 2011)	A zero carbon building has no net annual Scope 1 and 2 emissions from operation of building-incorporated services. Scope 1 emissions are direct GHG emissions from sources owned or controlled by the occupant. Scope 2 emissions are those from generation of electricity used in the building. Building-incorporated services include all energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope (and associated heating and cooling demand), water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation.
Zero Emission by Australian Government (Pipkorn et al., 2013)	A zero emission house is a detached residential building that does not produce or release any CO_2 or other GHG to the atmosphere as a direct or indirect result of the consumption and utilisation of energy in the house or on the site.
Net Zero Carbon by UK government (UK gov, 2022)	For new buildings and renovation: The amount of carbon emissions associated with a building's product and construction stages up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy. For all buildings in operation: The amount of carbon emissions associated with the building's operational energy on an annual basis is zero or negative. A net zero carbon building is highly energy efficient and powered from on-site and/or off-site renewable energy sources, with any remaining carbon balance offset.

Source: JRC, 2022

3 Methodological aspects of ZEB concepts

The definition must address several key criteria to generate buildings with zero carbon emissions, as listed below. The following sections of the study discuss these criteria.

- System boundary - stages included in GHG calculation over the lifetime of the building (operational vs. life-cycle emissions);
- Emissions balance boundary – ambition dimension of reaching zero emissions (absolute zero vs. net zero) and emissions reduction options;
- Calculation methods (static vs dynamic) and timeframe;
- Indicators and metrics - proper indicators and metrics to be reported in the definition;
- Spatial boundary – the assessment object.

3.1 System boundary

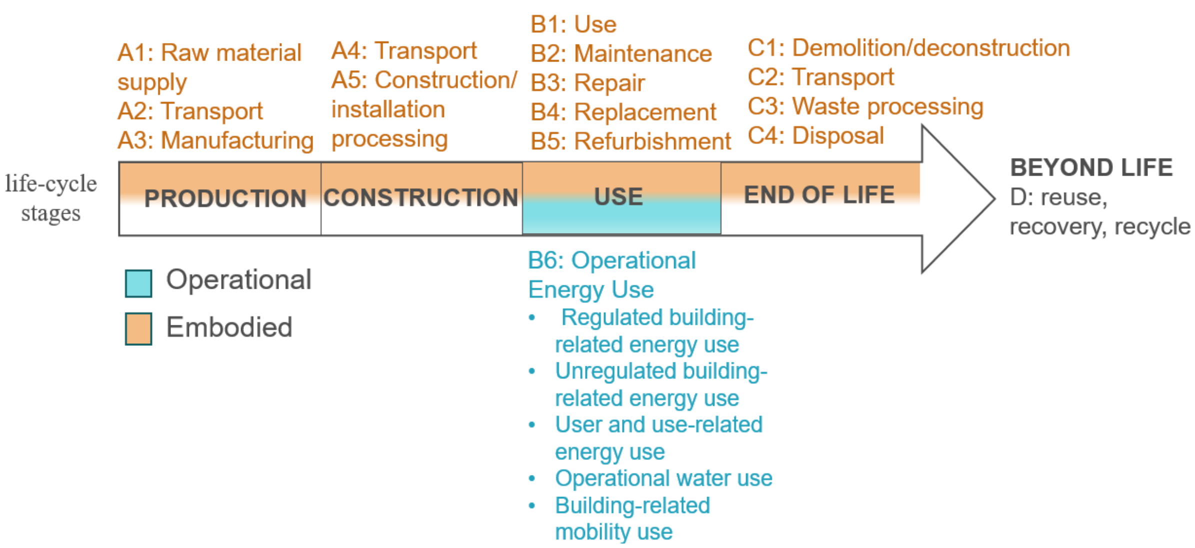
A first main step is setting the system boundaries. A system boundary, as defined by (EN 15978, 2011), represents the interface in the assessment between a building and its surroundings or other products systems. In this case, it means deciding which stages, over the lifetime of a building, are included in the calculation of the GHG.

Commonly, a first disaggregation is dividing the system boundary into two main parts, the operational impact and the embodied impact. The operational part focuses only on the stage at which the building is operated while the embodied impact refers to the stages before and after the operation of the building, such as the product stage, the construction process and the end of life stage. Clearly each of this phases could be further divided to cover all possible emission sources.

It seems that the system boundary outlines the definition of a ZEB. The Norwegian Research centre on Zero Emission Buildings provides five definitions based on the system boundaries (ZEB, 2022), while (Riedy et al., 2011) propose four definitions based on the same approach. Moreover, (Good et al., 2015) consider the full life-cycle emissions in the definition, while (Torcellini et al., 2006) consider only the operational emissions.

Based on (EN 15978:2011) - Assessment of environmental performance of buildings, (Lützkendorf and Frischknecht, 2020) and (Satola et al., 2021) propose a modular structure of the operational emissions, as shown in Figure 1. Such approach is expected to provide transparency regarding the covered operational energy use in the emissions calculation.

Figure 1. System boundaries of a building



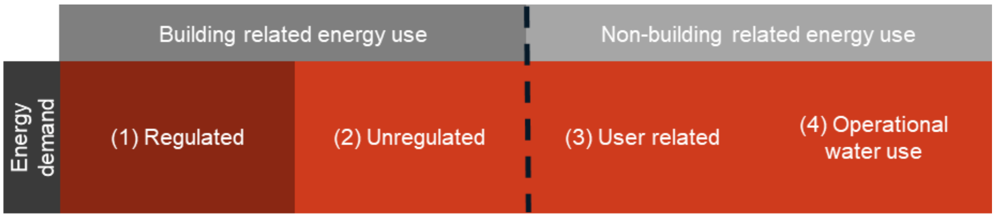
Source: modified from (EN 15978, 2011) and (Lützkendorf and Frischknecht, 2020)

3.1.1 Operational energy and emissions

Most system boundaries focus only on the operational phase of a building. More specifically, the focus is on the regulated energy use, as in the case of Nearly-Zero Energy Building (NZEB) concept, framed by the EPBD. This includes heating, cooling, ventilation, domestic hot water (DHW) preparation, built-in lighting and auxiliary energy.

The unregulated energy use in a building is represented by the energy consumption that is not subject of regulation acts for buildings and it can be building-related or user-related (Birch et al., 2020; Satola et al., 2021). Figure 2 shows the operational energy use disaggregation based on (EN 15978, 2011).

Figure 2. Operational energy use in buildings



Source: modified from (EN 15978, 2011)

Building-related energy use:

(1) Regulated: heating, cooling, ventilation, DHW, lighting and auxiliary energy for pumps, control and automation:

(2) Unregulated: energy consumed by lift, elevators, escalators, automatic doors, safety and security systems, communications systems and any other technical systems needed for the proper functionality of the building;

Worldwide, elevators are responsible for 2% – 10% from the total energy consumption of a building whilst during peak hours the share could reach at 40% (Brown et al., 2012). Moreover, across the EU, in 2008, elevators and escalators accounted for a share of 0.7% in the total electricity consumption (De Almeida et al., 2012).

Non-building-related energy use:

(3) User-related: energy consumed by plug-in appliances (TV, refrigerators, IT equipment, etc.) and production related energy and any other energy use generated by the building's user;

On the other hand, this category generates heat gains, therefore having a positive contribution on the energy performance of buildings by decreasing the heating need. However, worldwide, the use of IT devices is associated with 3% electricity demand and 2% of the GHG emissions (Brown et al., 2012).

(4) Operational water use: includes all water used by building integrated water consuming processes such as: drinking water, water for sanitation, irrigation of green area integrated in the building, water used by the HVAC systems, pools, fountains and any other specific water use;

Some national project approaches for the assessment of a building's operational emissions include the energy use for the provision of drinking water (France, Sweden, UK, USA, and Australia).

Also, some projects (Norway, Switzerland, Lithuania) investigate emissions associated with building-induced mobility, such as emissions triggered by the daily commute of inhabitants (Lausselet et al., 2019; Satola et al., 2021). In addition, it should be discussed whether the electricity used to recharge electric vehicles should also be included in the system boundaries. Since this consumption is actually attributable to the transport sector rather than to the building sector, it is proposed to monitor it separately and not to account for it in the building assessment.

A study on the life-cycle of 60 buildings concluded that the operating energy represents by far the largest share in the lifecycle of a building and measures to reduce the energy demand in the operational phase are crucial to achieve energy efficient buildings throughout their lifetime (Sartori and Hestnes, 2007a). However, more recent studies demonstrate the growing importance of embodied energy and emissions, both in absolute terms and in relative contribution to life-cycle impacts of highly energy efficient buildings.

3.1.2 Embodied energy and emissions

The embodied energy and emissions are linked to the phases before and after the operation phase of a building. Together with the operational emissions, the embodied emissions give life-cycle GHG emissions of a building. The life-cycle stages include the extraction and processing of the raw materials, manufacturing of materials and equipment, transport to the site, the construction process of the building, the installations of equipment as well as demolition process and transport and disposal of waste (Riedy et al., 2011). It is also important to consider the maintenance, repair and replacements. Special attention should be given to the embodied emissions associated to replacement, since many technical systems (e.g. PVs) require replacements during the lifetime of a building, which could comparable with the construction embodied emissions (Satola et al., 2021).

Currently, the energy efficiency measures mainly target the reduction of the operational energy use and operational GHG emissions while the incorporated energy and GHG emissions are overlooked. However, the embodied emissions across the building stock contribute about 11% of the total GHG emissions (WGBC, 2019).

Nearly-zero energy buildings and highly energy efficient buildings imply the use of a higher amount of materials (notably insulation materials) compared to conventional ones, the installation of more complex technical systems and, in case of renovation, the removal and treatment of old materials (Castellani et al., upcoming), leading to higher embodied impacts of buildings.

As operational emissions are being reduced, the importance of the embodied emissions rises dominating the life-cycle emissions of a building. (Röck et al., 2020) noted that while earlier studies used to consider negligible in a building environmental impact those factors beyond operational energy use and emissions, more recent studies demonstrate the growing importance of embodied energy and emissions, both in absolute terms and in relative contribution to life-cycle impacts.

It is estimated that the upfront carbon emissions (emissions released before the use of the building) will represent about 50% in the life-cycle emissions of a new buildings in the next decades (WGBC, 2019). Therefore, several studies highlight the risk of potential burden shifting (in terms of energy consumption and/or GHG emissions) from the use phase to the production and construction phase of a building life-cycle (e.g. Asdrubali et al., 2019; Chastas et al., 2016; Cusenza et al., 2022; Röck et al., 2020).

Despite the fact that a growing body of literature acknowledges the importance to assess buildings energy and emission performance from a life-cycle perspective, very few studies focus on achieving net-zero life-cycle primary energy or GHG emissions.

In response to this research gap, (Stephan and Stephan, 2020) demonstrated the technical feasibility of achieving net zero life-cycle primary energy and GHG emissions in an apartment building in a Mediterranean area, but observed that the feasibility of achieving net zero life-cycle GHG emissions buildings depends to a great extent on the emission intensity of the electricity grid. Analysing a detached house in Rome tailored to be net zero energy in the use phase, (Cusenza et al., 2022) observed that while different configurations of building envelope insulation material and integration of PV system could deliver net-zero energy performance in the use phase, none of them achieves the target of life-cycle zero impact in any of the energy impact categories; the authors hence highlighted the importance to follow a life-cycle approach to quantify the embodied impacts in low energy buildings and thus increase the efficiency of the actions implemented.

Evaluating the embodied emissions gives a complete figure on the emissions during the life-cycle of building and enables the possibility of planning a major emission reduction with the greatest impact on the built environment. However, calculating the embodied emissions is a complex process. For instance, data for the incorporated materials in existing buildings may not be available and thus a complete evaluation of the embodied emission is not always possible.

3.2 Emission balance boundary

This section discusses the boundaries in the emission calculation which reflect the ambition level of zero-emission buildings. Two main possibilities are presented: net zero emissions and absolute zero emissions (Lützkendorf and Frischknecht, 2020; Satola et al., 2021).

3.2.1 Net zero emissions

Net zero emissions implies that the emissions balance over a period of time, typical a year, is zero. Several options for allowable emissions reduction are identified in the literature (Lützkendorf and Frischknecht, 2020; Riedy et al., 2011; Sartori et al., 2010; Sartori and Hestnes, 2007a; Satola et al., 2021; Torcellini et al., 2006). A common understanding is that in a net zero approach the building imports energy from the grid and exports renewable energy to the energy grid. Most ZEB definitions in the literature allow grid connection and count on it to counterbalance the emissions.

However, while most studies discuss the importance to reduce the energy need through energy efficiency measures as the main step in achieving zero emissions, other studies focus on emissions balancing options which are not all necessarily aligned with the "energy efficiency first principle". Concrete approaches for emissions compensation are presented below.

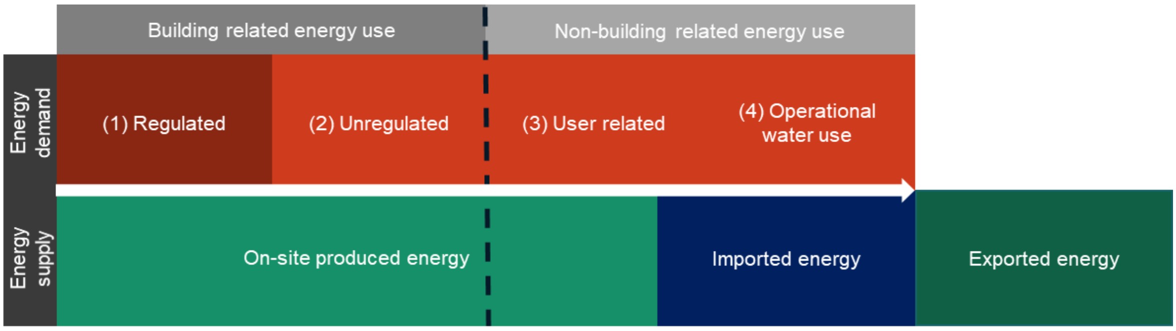
- **Net balance approach**

The net balance approach implies that the building produces and exports renewable energy to the grid and the potential benefits are attributed to it. The operational energy demand and the on-site renewable energy production are calculated and the balance is assessed by attributing to the building the benefits of avoiding GHG emissions caused by exporting energy to the grid.

The approach is in line with “energy efficiency first principle” as it is feasible for energy efficient buildings with low energy use and capacity to produce renewable energy.

The energy produced on-site is assumed to cover first the building-related energy use and then the energy use not related to the building operation (EN 15978, 2011). Figure 3 represents the priorities in allocating the energy generated on-site.

Figure 3. Priorities in allocation of on-site produced energy



Source: modified from (EN 15978, 2011)

- **Economic approach**

In the economic approach the operational emissions or the whole life-cycle emissions are offset by purchasing CO_2 emission certificates. Although, it is a straightforward approach, only financial compensation does not lead to zero emissions so this approach should be combined with other options to counterbalance the emissions.

- **Technical approach**

The technical approach is based on technologies to extract and store the GHG from the atmosphere. Basically after the operational or the life-cycle emissions are evaluated, technical measures are employed to extract the equivalent amount of emissions from the atmosphere. Some of the available negative emissions technologies are afforestation and reforestation, land management to increase and fix carbon in soil and bioenergy production with carbon capture and storage (Courvoisier et al., 2018). Although, the approach gives a real reduction of GHG, many aspects in this technologies are still under discussion, such as geopolitical aspects, long-term costs and liabilities as well as the risk of CO_2 leakage or release.

3.2.2 Absolute zero emissions

An absolute zero-emission building is a building that has zero emissions associated to fuel or electricity to cover the energy use in the operational phase. In addition, if considering the whole life-cycle emissions, the building materials should be from zero emissions supply sources and the transport of the materials and the construction process should be characterized by zero emissions.

While absolute zero emissions during the operation phase of buildings would be possible with high energy efficiency measures and on-site renewable energy, currently it is not the case of absolute zero life-cycle emission buildings.

3.3 Calculation methods and timeframe

Buildings are long-lasting products, built to last at least 50-60 years. Over time, we can expect changes in climate conditions, user behaviour, and the energy mix. The changing climate will likely have an impact on operational energy, leading to lower heating demand and higher cooling demand. The demand for air conditioning in summer is expected to increase 3.14% per year, mainly in Central and Southern European countries (68% of total EU demand) (Pardo et al., 2012). Changes in awareness and in occupants' behaviour, together with the implementation of new technologies may also influence operational energy. Therefore, to ensure the achievement of zero emissions during the lifetime of a building it is important to consider these changes.

To evaluate the operational energy balance of a building and then the associated emissions, two type of calculation methods are commonly used: steady-state (static) methods and dynamic methods. In the steady state methods the calculation is performed in a stationary approach overlooking the real dynamic behaviour of the building. The heating and cooling season have fixed lengths. On the other hand, the dynamic methods take into account the actual dynamic behaviour of the environment, the variability of heat gains, the ventilation and infiltration rate as well as the mass capacity of the building. Of course, a dynamic approach is more time consuming and requires additional digitalisation and costs. Additionally, it can be used only in a later stage of the energy performance design when all needed parameters all known. However, based on accurate input data, the results are a truthful representation of the real behaviour of the analysed building.

Moreover, a dynamic approach is also considered important when dealing with the carbon intensity of the energy mix, which changes over the years. The use of GHG emissions factors with a more detailed time scale provides a more precise and reliable accounting of GHG emissions by including in the assessment scope the significant variation in GHG emissions in the energy mix over time. As pointed out by (Stephan & Stephan, 2020) the decreasing GHG intensity of electricity grids can make it harder to displace the initial embodied GHG emissions of a building. For a theoretical fully decarbonised energy grid, the initial embodied emissions are no longer displaced by exporting renewable energy to the grid. In addition, sensitivity analyses to simulate changes in the electricity mix are seen necessary to accurately assess renovation scenarios of buildings with electricity-based heating systems (Van de moortel et al., 2022).

In addition, the GHG emission intensity of the electricity mix can be considered on an annual, seasonal, monthly, daily, or hourly basis. The use of hourly and regionally specific (marginal) GHG emissions factors are deemed important for a reliable and accurate representation of the benefits related to the implementation of GHG emission reduction strategies, such as on-site renewable energy systems (Satola et al., 2021).

3.4 Indicators and metrics

The choice of indicators and metrics to measure the environmental performance of a building depends on the environmental objective(s) and the protection goal. For a long time, the consideration of the resource use, and the use of non-renewable primary energy resources, dominated the discussion as a single indicator/metric by which to assess and benchmark buildings' environmental performance (Satola et al., 2021). With the increasing attention to climate protection and the need to pursue ambitious climate goals, GHG emissions are becoming the main performance indicator, and requirements for climate neutrality both in operations and in life-cycle are being introduced.

The operational part of a life-cycle assessment is based on the calculation of the final energy demand for the operation of the building, generally including heating, cooling, hot water supply, ventilation or air conditioning, auxiliary energy for pumps, and fixed lighting, or sometimes also covering occupants' use of plug-in appliances (so-called plug loads). Using primary energy factors (PEF), it is possible to determine the primary non-renewable energy demand. Using emission factors, information on the final energy demand of a building can be converted into GHG emissions (Satola et al., 2021).

Energy demand is often considered as a proxy for carbon emissions and several building assessment frameworks use energy demand to measure the performance of buildings with respect to climate change. However, the relation between energy demand and carbon emissions is not so straightforward in an energy system which is becoming more and more decarbonised.

The EPBD defines the primary energy as energy from renewable and non-renewable sources which has not undergone any conversion or transformation process. For fossil fuels, the definition of primary energy is based on the thermal energy that can be realised, usually by combustion, which is then converted into an energy carrier such as electricity, incurring losses in the process (Hitchin, 2019). In the case of fossil primary energy, the PEF gives an indication of the detrimental effect of such energy consumption on resource levels. Applying this principle to renewable energy is less intuitive as the initial source is not so easily identifiable (Parkin et al., 2020).

The standard on the energy performance of buildings EN ISO 52000-1:2017 categorises the PEFs as follows (Hogeling, 2018):

- **non-renewable PEF** considering only non-renewable energy overheads of delivery to the point of use, excluding renewable energy overheads and primary energy components;
- **renewable PEF** considering only renewable energy overheads of delivery to the point of use, excluding non-renewable energy overheads and primary energy components;
- **total PEF** which represents the sum of the non-renewable and renewable PEF, respectively.

Moving from PEF to carbon emissions coefficients, there is a strong link between these coefficients and PEFs for non-renewable energy sources such as fossil fuels. However, this link becomes weaker for energy sources that are less clearly defined as non-renewable. Hitchin (Hitchin, 2019) noted that there is no consensus on the PE basis for energy sources such as renewable energy, biomass, nuclear energy and the combustion of waste material.

The standard on Reporting of Primary Energy Factors and CO_2 emission coefficient (prEN 17423) provides a transparent framework to reporting the choices to determine PEFs and carbon emission coefficients for energy delivered- to and/or exported-by the buildings as described in ISO 52000-1:2017 (Zirngibl, 2020).

For existing buildings, the standard on sustainability in buildings and civil engineering works – Carbon metric of an existing building during use stage, part 1 (ISO 16745-1:2017) and part 2 (ISO 16745-2:2017), provides a set of methods for the calculation, reporting, communication and verification of a collection of carbon metrics for GHG emissions arising from the measured energy use during the activity of the building, the measured user-related energy use, and other relevant GHG emissions and removals. The carbon metric used is the sum of annual GHG emissions and removals, expressed as CO_2 equivalents, associated with the use stage of a building.

3.5 Spatial boundary

Another mandatory step in defining a ZEB is to set up the assessment object from a geometrical perspective. Generally, it could be a single construction, a group, a neighbourhood, a city or even the whole national building stock (Satola et al., 2021).

Most of the case studies identified in the literature focus on a single building. Several large scale zero energy projects address also the GHG reduction. (Sandberg et al., 2021) modelled the energy performance of the Norwegian building stock under two ZEB scenarios and found out a potential of 23 and 36 TWh energy savings in the total estimated delivered energy by 2050. However, although it is clear that having broader spatial boundaries implies more substantial impact in emission reduction, a more complex methodology is needed and it should be built on a clear zero-emission concept at building level.

ZEBs should cover different types of buildings, new and existing, residential and non-residential as their energy need, the applicable energy efficiency and RES measures as well as the possibilities to reduce the GHG emissions could differ significantly. New buildings can be modelled testing different geometry, orientation and envelope. The energy need can be supplied through low energy technologies and renewable sources. For existing buildings, the energy efficiency level is subject to technological feasibility and what it can be achieved at a cost optimal level. Another key difference in existing buildings compared to new buildings is the implementation of renewable energy sources especially in crowded urban areas where the on-site renewable energy generation might be limited.

In addition, the focus on the main renewable energy sources is triggered by the dominant energy need in a building, either thermal or electric need, which in turn is triggered, among others, by the type of the building (residential, administrative, school, hospital etc.).

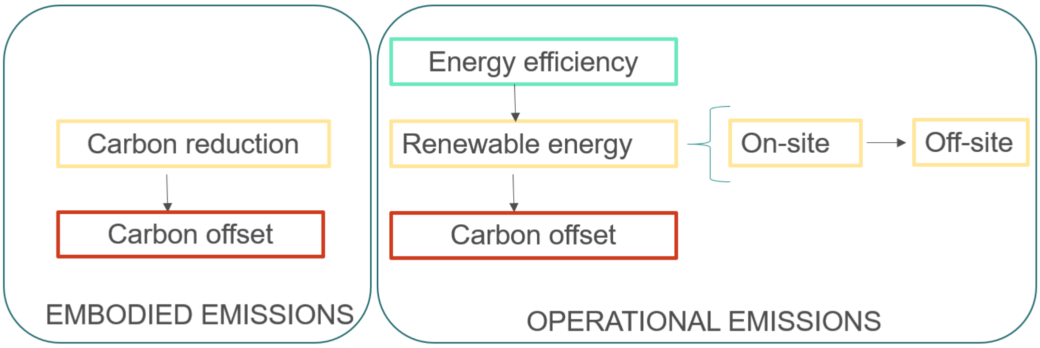
4 Energy efficiency first

Energy efficiency first principle (EE1st) is a key pillar to meet the climate objectives and to reduce dependence on fossil fuels from abroad, increasing security of supply and stimulating the use of renewable energy (European Parliament and Council, 2018a). The principle should ensure that only the energy needed is produced and that investments in stranded assets are avoided in the pathway to achieve the climate goals (European Commission, 2021a). In zero carbon buildings, measures to reduce the energy need are crucial to prevent energy generation that can been avoided with cost-effective energy efficiency measures. Therefore, a logical approach in scheming the ZEB definition is to reduce the energy needs as much as possible through implementation of energy efficiency measures before the implementation of renewable energy technologies.

The operational energy use represents the largest share during the life-cycle of a building while the rest is associated to the embodied energy. It is clear that energy efficiency measures still represent a key way to zero carbon buildings due do their contribution in effectively reducing the operational energy use thus reducing the life-cycle energy consumption of buildings. Achieving zero emission buildings without having energy efficiency requirements would mean supplying large quantities of energy from renewable sources which generally is not feasible nor cost effective.

Figure 4 illustrates the logical priorities in achieving zero emissions in buildings. In the design phase of a building, the operational and embodied emissions can be minimized through energy efficiency measures and the use of low carbon materials. The use of renewable energy further decreases the operational emissions. On-site renewable energy is prioritized, although purchasing off-site renewable energy remains an option where the on-site production is limited. Finally, for the residual emissions, both embodied and operational, offset options have to be considered and implemented.

Figure 4. Priorities in achieving ZEBs



Source: modified from (WRI, 2020)

Although energy efficiency measures can significantly reduce a building's operational energy to almost zero or even zero, they could also lead to an increase in the embodied energy if little attention is paid to the whole life-cycle behaviour of the building. Nevertheless, studies show that high energy efficient buildings perform better over their life-cycle compared to conventional buildings (Sartori and Hestnes, 2007b).

However, in the case of self-sufficient buildings, the situations appear somewhat different. Several studies highlighted that zero energy buildings consume more energy than low carbon buildings considering the whole life-cycle of the buildings. The reason is higher embodied energy due to extra energy efficiency measures. Researchers concluded that the excessive use of passive and active features may be ineffective (Ramesh et al., 2010; Sartori and Hestnes, 2007a).

In conclusion, reducing the energy demand should be a top priority closely followed by assessing and reducing the embodied energy in the design phase of the building. Especially in buildings connected to grids with high carbon electricity mix, the reduction in the operational energy demand is mandatory to achieve life-cycle zero-emission buildings (Moschetti et al., 2019). In addition, in high energy efficient buildings the operational energy need is dominated by user unregulated energy (such as electric appliances, cooking) compared to traditional buildings where the energy need for heating and cooling are leading in the energy balance of a building (Blengini and Di Carlo, 2010).

5 Renewable Energy role

In line with the "energy efficiency first principle", a ZEB should be designed to minimize the energy needs. Residual emissions associated with the low amount of energy still required by the building could be offset by renewable energy produced by the building and exceeding its needs.

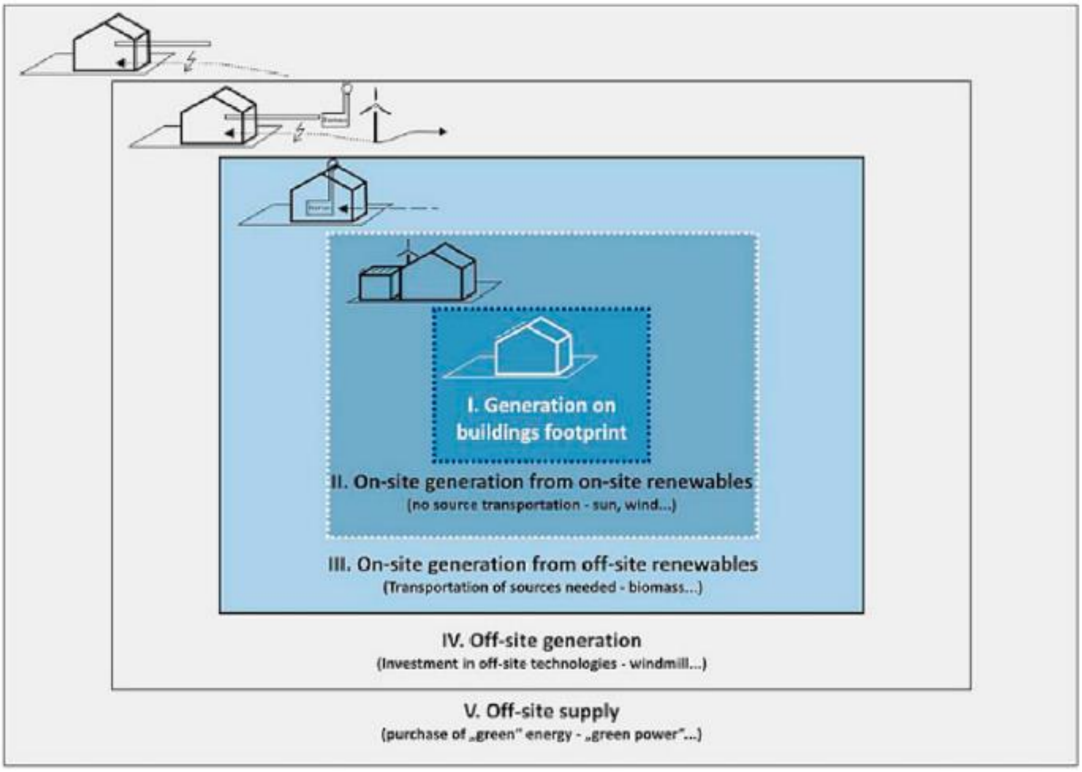
5.1 Methodological boundaries for renewables

However, not all buildings can access enough on-site renewable energy sources; in these cases, the users should be allowed to rely on off-site sources to meet the renewable energy requirements (Edelson, 2019). Consequently, a key aspect that should be taken into consideration in the definition of a ZEB is which type of renewable energy generation can be attributed to the building and within which system boundaries (Satola et al., 2021).

Various options exist concerning renewable energy supply. Figure 5 presents the different options applied in international energy calculation methodologies, ordered following the location of the energy supply option with respect to the building:

- Option I refers to energy generation from RES installed on the building, such as PV and solar thermal installed on the rooftop or on building facades;
- Option II refers to the use of renewable energy sources available at the site (e.g. PV on parking lots);
- Option III refers to the use of renewable energy sources available off site to generate energy on site (e.g. biomass or wood pellets that can be imported);
- Option IV refers to the investments in off-site renewable energy production;
- Option V refers to the purchase of green energy

Figure 5. Overview of possible renewable supply options



Source: (Marszal et al., 2011)

Option V includes also the possibility to purchase renewable heat supplied to the building via a district heating network, generated with geothermal, solar (PV or thermal) and biomass. In addition, some local gas suppliers offer the possibility to their customers to purchase gas certified as low-emission or renewable. This might become increasingly relevant with the blending of biogas and, in future, of hydrogen in the natural gas grid, thus leading to lower emission factors for natural gas.

It must be stressed that the above classification does not represent a hierarchical ranking from the most preferred option to the least preferred one.

Some authors (Panwar et al., 2011) suggest that exported electricity outside the system boundary can compensate the GHG emissions associated with energy used by the building. Other authors suggest presenting the benefits of exported energy as additional information, in line with the ISO 16475 standard. For example (Lützkendorf and Frischknecht, 2020) state that *attributing these benefits solely to the building relies on the uncertain scenario that exported electricity avoids the average grid mix production of today. It also bears the real risk of double-counting of emission reductions with both the producer (the building) and the user (purchaser of exported energy).*

5.2 On-site vs off-site generation

Several building assessment frameworks allow balancing (life-cycle) GHG emissions with emissions avoided thanks to renewable energy from both on-site and off-site generation. However, only focusing on on-site generation appears suitable mainly for new and relatively small buildings, therefore various compensation options should be allowed (Satola et al., 2021). Nevertheless, there seems to be a general consensus that on-site renewable generation should be prioritized.

A possible approach could be to focus on the **ownership** of the renewable energy installation, rather than on its location. In any case, the approach should be designed carefully, with a view to avoiding the risk of double counting (i.e. counting avoided emissions both in the balance sheet of the building and in the balance sheet of the purchaser of exported energy). In this respect, (Satola et al., 2021) point to a recommendation from the US Energy Agency, 2018 aimed at preventing double counting of environmental benefits in the case of exchanging renewable energy in the form of renewable energy certificates, by retiring certificates just after making an official environmental claim.

In terms of RES technologies, in the Mediterranean climates, benefitting from greater solar radiation, the more convenient sources are solar thermal and PV, while in colder climate countries in northern Europe heat pumps (geothermal energy) and biomass used in heating systems are more common (Magrini et al., 2020).

In addition to traditional roof-installed PV, building-integrated photovoltaic systems (BIPV) can be a key player both in existing and new buildings (Skandalos et al., 2022). PV could provide the electricity needed to power a heat pump, responsible for the heating, cooling and domestic hot water production. A secondary generation system, such as a biomass boiler, could support the heat pump in the winter months, while remaining a renewable energy source. A study on replacing fossil fuels boilers (namely heating oil, LPG and natural gas) with biomass boilers in multi-family buildings in Spain estimated a CO_2 emissions decrease by 90% to 94% (Las-Heras-Casas et al., 2018).

However, some reflections are needed on how to account for the emissions associated with the use of biomass. Biomass use for energy production is often considered to be 'carbon neutral' because the combustion of biomass is assumed to release the same amount of CO_2 as was captured by the plant during its growth. Nevertheless, the environmental impact of bioenergy can vary considerably depending on several factors, such as the feedstock used, the accounting rules and systems boundaries within the life-cycle analysis, the feedstock transport distances (Amponsah et al., 2014). Accordingly, the estimates of GHG mitigation potentials can vary by over an order of magnitude. In addition, during the biomass conversion into energy some low pollutants are emitted (Carlini et al., 2013).

5.3 Emission factor for grid-supplied electricity

The mix of fuels used to generate electricity changes over time, in response to national and international climate change mitigation policies. Therefore with respect to climate change, the value of using electricity from the grid and/or offsetting grid electricity with renewable electricity (e.g. from PV) is not the same across different countries and is changing with time.

Two different concepts are generally used to describe the electricity mix (Satola et al., 2021):

- The "average electricity" principle presents the statistical average emissions generally expressed in gCO_2-eq/kWh from the entire electricity mix and usually containing several interconnected regional zones.

- The “marginal electricity” principle is defined as marginal changes in GHG emissions caused by changes in non-baseload electricity generation due to daily or hourly variation in the electricity consumption profile. This principle takes into account the local and actual effects of different actions on the power grid.

In most of the building assessment approaches analysed by (Satola et al., 2021), the “average electricity” principle is employed. Two approaches present a hybrid use of the average and marginal electricity mix factor: the emission factor for the average supply mix is used for estimating the GHG emissions from electricity use in the building; the marginal emission factor approach is employed to determine the environmental benefits from locally produced electricity exported to the grid.

The emission factors proposed in the building assessment approaches significantly influence assessing the performance of zero-carbon buildings and the choice of optimal design strategies. A building situated in a country/region characterised by a low carbon intensity of the electricity mix (e.g. with a large share of electricity coming from renewables or from nuclear) in principle could achieve a zero-emission performance more easily than a building in a country/region with a high carbon intensity of the grid. This is particularly true if the building energy demand is mainly satisfied by electricity and if the assessment approach only accounts for operational emissions. If instead the building also has a residual consumption of fossil fuels, a low carbon intensity of the grid may result in a low value of offsetting grid electricity with renewable energy.

Some authors (Georges et al., 2015; Stephan and Stephan, 2020) highlighted the strong dependency between the emission factors and the possibility to balance embodied emissions: they noted that an overall emission balance including both operational and embodied energy is difficult to realise and would be unobtainable in a scenario of low-carbon electricity from the grid.

Parkin (Parkin et al., 2020) observed that where the offsetting value of PV electricity is high, because the carbon intensity of the electricity grid is high, excess generation creates a large carbon credit that can offset carbon emissions from heat demand, and embodied carbon. However, where electricity demand is likely to exceed PV generation, and the electricity grid has a high carbon intensity, this translates into a significant carbon debt which is unlikely to be offset entirely by any negative embodied carbon in the building fabric.

The choice of the emission factor for electricity therefore influences the counting of the potential benefits caused by energy produced on-site and sold to the grid.

6 Towards a pragmatic ZEB definition

The ZEB concept should be based on a clear and transparent methodology and coordinated with the cost-optimal approach. The methodology should clearly state the components and the components' boundaries included in the definition. In addition, the methodology should give flexibility to reflect various climate across Europe, the building typologies and configurations, the energy systems and technologies, the available energy sources as well as the heterogeneity of the building stock in case of renovation.

Based on the information presented in the above sections of this report, below are summarized the main features of a possible Zero Emissions Building definition in the EPBD.

- An annual operational net zero emissions ambition is set by applying a net balance approach, i.e. the balance of the primary energy or the CO_2 emissions over a year, are zero. This allow the building to import energy from the grid and export renewable energy to the energy grid;
- The definition targets both new and existing buildings;
- New buildings have to comply with numerical benchmarks more stringent that the NZEB level;
- The ZEB level in existing buildings may be derived in case-by-case approach using the cost-optimal methodology, but going beyond the NZEB level for existing buildings;
- The numerical benchmark could be designed in terms of (1) total and non-renewable primary energy demand (kWh/m^2/year) thresholds as in the case of NZEBs recommendations and adding (2) CO_2-equivalent thresholds (kgCO_2-eq/ m^2/year);
- In addition, the definition asks for embodied emissions report to raise awareness on the building's carbon footprint and help decide on possibilities and priorities to further off-set the embodied emissions moving towards a zero emission life-cycle.

6.1 Operational energy and emissions

This section provides suggestions on possible grouping of energy uses and associated emissions for the calculation of a ZEB, as well as the steps to derive numerical benchmarks for the operational energy.

6.1.1 Uses coverage

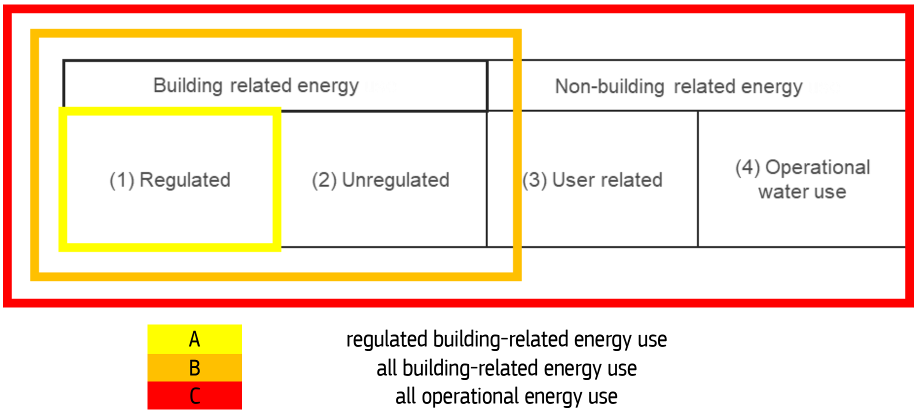
So far, only the building-related energy use for heating, cooling, ventilation, DHW, lighting and auxiliary energy is regulated to a certain extent by the current EPBD (within the cost-optimal methodology and the NZEB definition) while the inclusion of building-related unregulated energy, the user-related energy as well as the energy for the operational water use is decided at a national level.

However, (EN 15978, 2011) suggest that the operational energy use shall include energy used by all building-integrated technical systems during the normal use of the building. If the energy use not related to the building use is also considered, this have to be reported separately.

Figure 6 illustrates a proposal for possible groups of energy uses to be considered in the ZEB definition.

- Group A includes the calculation of the regulated building-related energy use and the associated GHG emissions. Practically it covers the same uses as the cost-optimal methodology and generally as the NZEB definitions across the EU.
- Group B considers, in addition to the regulated energy use, the energy use by other technical systems needed for the proper functionality of the building.
- Group C encompasses all types of operational energy use identified in a building and described in (EN 15978, 2011).

Figure 6. Proposed grouping of energy uses



Source: JRC, 2022

However, given the complexity of accounting for unregulated and non-building-related energy use at the design stage of the building, it would make sense that an initial ZEB definition focuses on the already regulated energy use. Member States could voluntary go beyond this boundary in a more ambitious approach until clear synergies between policies on buildings and appliances and other technical systems used in buildings are defined.

6.1.2 Methodology to derive numerical benchmarks

The calculation direction starts with assessing the building energy needs, energy use, delivered energy, primary energy and CO_2 emissions (from needs to the source) for various scenarios.

The thermal services (mainly heating, cooling, DHW) and the electrical services (mainly ventilation, lighting, auxiliary) are considered separately, but the effect of heat gains generated by the electrical services on the thermal needs.

The thermal need of a building represents the energy need for heating, cooling, humidification and dehumidification and preparation of hot water. The energy use for cooling, heating and preparation of hot water represents the energy input to the heating, cooling or hot water system, including the auxiliary energy, to satisfy the energy need for heating, cooling (including dehumidification) or hot water respectively.

The energy use for lighting and ventilation represents the electrical energy input to the lighting systems and ventilation system respectively. The energy use covers both non-renewable and renewable energy produced on-site.

The delivered energy is the energy delivered (by carrier) to the technical systems through the system boundary, to satisfy the uses taken into calculation (heating, cooling, ventilation, DHW, lighting, appliances and others) or to produce electricity.

The primary energy is the form of energy that has not been subjected to any kind of conversion process. The primary energy (E_p) includes non-renewable and renewable energy and it is calculated from the delivered and exported energy using conversion factors and it given by the equation:

$$E_P = \sum (E_{del,i} f_{P,del,i}) - \sum E_{exp,i} f_{P,exp,i}$$

$E_{del,\,i}$ is the delivered energy for energy carrier i;
$E_{exp,\,i}$ is the exported energy for energy carrier i;
$f_{P,del,i}$ is the primary energy factor for the delivered energy carrier energy i;
$f_{P,exp,i}$ is the primary energy factor for the exported energy carrier energy i;

The CO_2 emissions coefficient is calculated for a given carrier and represents the quantity of CO_2 emitted into the atmosphere per unit of delivered energy (equivalent emissions of other GHG can be included) (EN 15603, 2008).

The GHG emissions expressed in kg of CO_2 equivalent (mCO_2-eq) associated with the energy use of a building calculated based on the delivered energy for each carrier plus the energy produced on-site according to (ISO 16745-1:2017, 2017):

$$m\,CO_{2-eq} = \sum \left(\left(E_{del,ci} \times K_{del,ci} \right) + \left(E_{site,ci} \times K_{site,ci} \right) \right)$$

$E_{del,\,ci}$ is the delivered energy for energy carrier del,ci;
$E_{site,\,ci}$ is the energy produced on-site for the energy carrier site,ci;
$K_{del,\,ci}$ is the GHG emission coefficient for delivered energy carrier del,ci;
$K_{site,\,ci}$ is the GHG emission coefficient for on-site energy carrier site,ci.

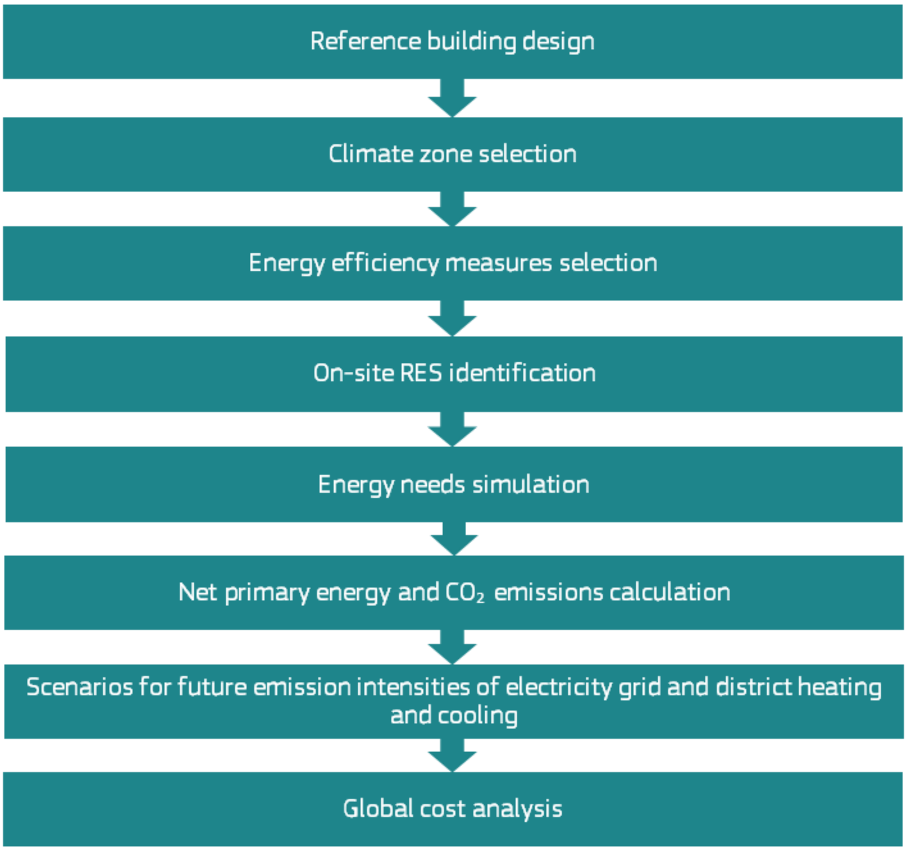
The GHG emissions (mCO_2-eq) associated with the exported energy produced on-site are given by the following equation (ISO 16745-2:2017, 2017):

$$m\,CO_{2-eq} = \sum \left(E_{exp,ci} \times K_{exp,ci} \right)$$

$E_{exp,\,ci}$ is the exported energy for energy carrier exp, ci;
$K_{exp,\,ci}$ is the GHG emissions coefficient for exported energy carrier exp,ci.

The main steps in deriving numerical benchmarks are illustrated in Figure 7.

Figure 7. Main steps for deriving numerical benchmarks



Source: JRC, 2022

6.2 Life-cycle energy and emissions

The Level(s) framework published by the European Commission in December 2020 sets out indicators and guidance for reporting on use stage energy consumption, embodied carbon and operational carbon emissions, amongst other sustainability aspects.

The embodied emissions associated with different stages in the life-cycle of a building could be assessed and reported following the *Level(s) indicator 1.2 Life-Cycle Global Warming Potential (GWP)* (Dodd et al., 2021) and aims to quantify the carbon footprint of a building in terms of equivalent annual CO_2 emissions per useful floor area ($kgCO_2$-eq/m^2/year). The reference standard for the calculation procedure is (EN 15978, 2011).

The system boundary is from cradle to grave meaning all the stages starting with materials production and ending with demolition of the building and recovery of the building materials. However, the framework also includes two simplified approaches.

For new buildings the quantification of the GWP in the design phase allows the reduction of the embodied emissions in each stage as well as an optimum balance between embodied and operational emissions.

For existing buildings, knowing the already embodied emissions allows for designing renovation packages to counterbalance also the embodied emissions in addition to the operational emissions. However, evaluating the embodied emissions in an existing building could be difficult, even impossible, in the absence of complete and reliable data, which is the case of many existing buildings.

After the life-cycle GWP calculation, scenarios for compensating the residual embodied emissions are elaborated trying to reach out a zero life-cycle emissions.

7 The current state of play

This chapter discusses how the new concept will interact with other building-related concepts and methodologies fostered by the EPBD, the links with other EU policies and finally, the market readiness to deliver zero-carbon buildings.

7.1 Interplay with cost-optimal approach and NZEBs

Over the last years, the European building stock has become more efficient, due to increasing energy performance requirements and constant efforts of the Member States in implementing them. Indeed, according to the EPBD, as of December 2020 all new buildings are NZEB, while in the case of all public buildings the requirement is already in force since December 2018.

A NZEB is broadly defined as a building that "has a very high energy performance with the nearly zero or very low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". The EBPD leaves Member States the freedom to detail their own NZEB definitions, reflecting national, regional or local conditions and including a numerical indicator of primary energy use expressed in kWh/m^2/year (D'Agostino and Mazzarella, 2019). As such, the definition varies greatly across the EU. The most common approach is the energy balance over a year at a single building level including on-site renewables, using as indicator primary energy demand heating, cooling, ventilation, DHW, built-in lighting and auxiliary energy. Some Members States consider in addition the energy used by the appliances and/or central services (Austria, Estonia, Finland, and Lithuania).

Also in the frame of EPBD, Member States are asked to calculate and set cost-optimal levels of minimum energy performance requirements for both new and existing buildings by using the comparative methodology provided by the Commission (European Commission, 2012). Studies show that the cost optimal methodology has been used across Member States to assess and define NZEB levels (Ferrara et al., 2018) (Zangheri et al., 2018). As all new buildings are NZEB and Member States have in force a NZEB definition, the cost-optimal approach remains to be applied in the renovation of the existing building stock. As the EU Green Deal relies on deep energy renovation, where feasible, the cost-optimal approach represents a key tool in the decision making process of renovation and it should reflect the decarbonisation goal.

A comparison between the cost-optimal levels and the NZEB levels suggested that generally Member States have NZEB requirements about 50% lower than the cost-optimal references. At the same time the NZEB requirements are about 70% lower than the national minimum energy performance requirements in 2006 (D'Agostino et al., 2021). It is noticeable that Member States have gradually improved the requirements within the context of at least four legislative steps over the last 15 years (Economidou et al., 2020).

In the framework of the cost-optimal approach, the macroeconomic perspective includes the cost of GHG emissions defined as the monetary value of environmental damage caused by CO_2 emissions related to the energy consumption in a building. The latest assessment of the cost-optimal reports states that almost all Member States have performed the macroeconomic calculation (Zangheri et al, 2020). This means that already by implementing the cost-optimal methodology, Member States investigated, to some extent, the costs associated to the carbon emissions related to the energy use in new and existing buildings undergoing renovation. However, the benchmark perspective, either micro or macroeconomic, is decided at national level, therefore when Member States opted for the financial perspective, the carbon emissions were not covered by the methodology.

In these approaches, the focus is on the primary energy, while for associated carbon emissions no specific threshold values are defined. Only few Member States[1] use carbon emissions indicator in addition to primary energy in the NZEB definition.

As discussed in Chapter 4, in the case of low energy buildings like NZEBs, the embodied energy represents a growing share in the life-cycle of the building as the operational energy is almost zero. Clearly the embodied energy represents a main source of carbon emissions. A common methodology to assess the life-cycle GHG

[1] based on the latest available information: in Ireland the calculated carbon performance coefficient (CPC) of a nearly zero energy dwelling should be no greater than the Maximum Permitted Carbon Performance Coefficient (MPCPC); in Austria, four maximum values for the CO_2 emissions were established for new and existing, residential and non-residential NZEBs; in Romania, threshold values the CO_2 emissions in NZEBs are given depending on the building type and climatic zones and it is planned to reduce the threshold value for CO_2 emissions below 7 kgCO_2/m^2/year.

emissions would raise awareness on the carbon footprint of a building and help identify options for compensation. In addition, clear metrics and numerical benchmark should be defined based on a common methodology both for primary energy and carbon emissions.

To decarbonise the building stock by 2050 a revision of the actual energy performance requirements is needed as they do not automatically lead to carbon-neutral buildings (BPIE, 2021). Considering the efforts and results already achieved by Member States in implementing the cost-optimal methodology and the NZEB definition, GHG emission requirements for buildings could be introduced and gradually improved starting from NZEB definition. This will stimulate Member States to continue upgrading energy efficiency requirements, therefore safeguarding the "energy efficiency first principle".

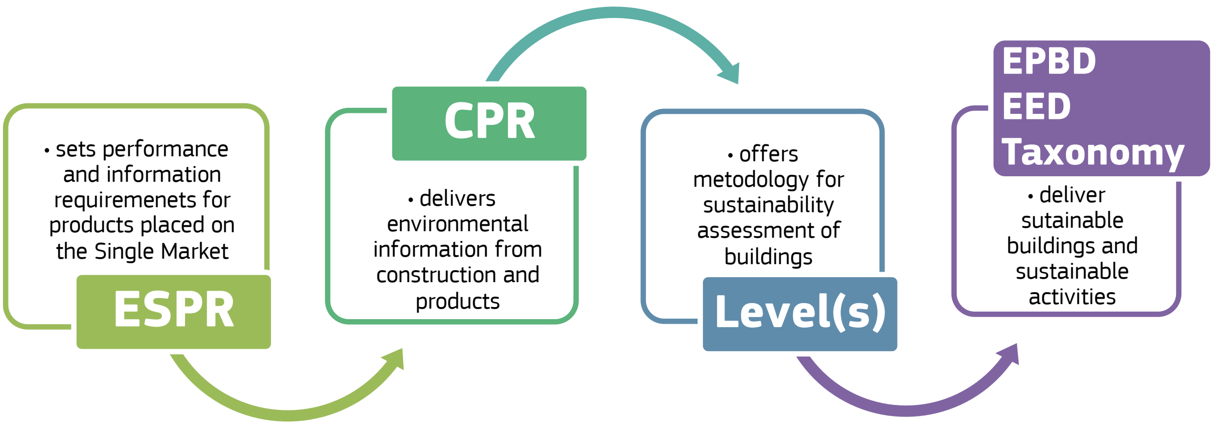
7.2 Interlinkages with other policies

The building sector - being responsible for a significant share of energy consumption and related GHG emission, but also of extracted materials and waste generation - features high among the priorities of the European Green Deal (European Commission, 2019) and of the Circular Economy Action plan (European Commission, 2020b). In an effort to tackle GHG emissions, the Green Deal and the Renovation Wave strategies insist on the enforcement of the energy performance of buildings legislation, and highlights that the principles of circular economy should guide newly constructed and renovated buildings.

The Climate Target Plan 2030 (CTP) (European Commission, 2020c) states that EU buildings by 2030 should reduce their overall GHG emissions by around 60%, their final energy consumption by 14% and energy consumption for heating and cooling by 18% in comparison to 2015. The analysis in the CTP also found that GHG emissions can only be lowered cost-effectively to a level compatible with achieving the goal of -55% by duplicating the floor area renovated every year to improve its energy performance, decarbonising heating and considerably increasing the energy savings achieved through renovations.

The Circular Economy Action plan also mentions the revision of the Construction Product Regulation (European Commission, 2022a), together with other actions such as the application of the Level(s) framework (European Commission, 2021b) to integrate life-cycle assessment in public procurement and the EU sustainable finance framework (European Commission, 2020d), and the possible revision of material recovery targets set in EU legislation for construction and demolition waste.

Figure 8. EU Regulatory framework for sustainable buildings



Legend:
ESPR - Ecodesign for Sustainable Products Regulation
CPR – Construction Products Regulation
Level(s) – European framework for sustainable buildings
EPBD – Energy Performance of Buildings Directive
EED – Energy Efficiency Directive
Taxonomy – EU sustainable finance

Source: modified from (European Commission, 2022b)

Addressing in a comprehensive way lifecycle GHG emissions from the building sector requires coordination among various EU policy instruments. As mentioned before, the EPBD has focused on the operational energy use (and related emissions), leading to new buildings having a very high energy performance. Opportunities exist to drastically reduce GHG emissions from material extraction, manufacturing of construction products, construction and renovation of buildings through greater material efficiency, thus containing the embodied impacts of buildings.

The revised CPR defines environmental obligations for manufacturers including the obligation to declare the GWP, thus enabling the assessment and reporting on the sustainability performance of buildings, using the European framework Level(s). Moreover, the new CPR relies on digitalisation (i.e., Digital Product Passport) to process all information on products ensuring better transparency and allowing data to be stored in Building Logbooks.

In addition, the EU sustainable finance taxonomy sets contribution requirements climate mitigation for each activity, including for the construction of new buildings and renovation of existing buildings. For new buildings larger than 5 000 m^2, the substantial contribution criteria is that the life-cycle GWP resulting from the construction of building have to be calculated for each stage in the life-cycle and disclosed to investors and clients on demand.

Further contribution to limit life-cycle GHG missions from the buildings sector may come from the "Fit for 55" package adopted in July 2021, in particular from the proposal to extend the Emission Trading System (ETS) to buildings and road transport (ETS II). Currently, the ETS covers about 30% of building emissions from heating through the system coverage of district heating and electricity used for heating. The new ETS proposal would contribute to tackling emissions in the building sector by introducing emissions trading as separate self-standing system for all buildings starting from 2025. The initiative will complement the Effort Sharing Regulation (ESR) (European Parliament and Council, 2018b) which establishes an EU-wide GHG reduction target and individual targets for Member States.

The EPBD, the CPR, and the revised ETS may work in synergy in order to tackle GHG emissions produced during various stages of a building life-cycle.

7.3 Market readiness and potential

Building sector decarbonisation can be achieved only by a combination of energy efficiency measures, low carbon construction materials and "clean"/renewable energy sources.

In the design phase of a building two main ways to reduce the embodied emissions are identified: to reduce as much as possible the volume of materials and focus on low carbon structural materials such as recycled steel, green concrete, mass timber, etc. The choice of renewable energy technologies may also have an impact on the embodied carbon of a building that should be considered in the design phase.

More than half of a building's embodied emissions is in its structural elements namely in foundations, beams, columns and walls because of the large volume of materials they used and also because they are based on materials with high carbon emissions such as steel, concrete, aluminium and glass. In fact, construction materials are responsible for approximately 1/5 of the annual global GHG emissions (Keramidas et al., 2021). In particular, concrete is responsible for about 8% of the total global GHG (Lehne and Preston, 2018) This means that a key step towards decarbonisation is a change in the production process of these basic and widely used construction materials.

The use of low carbon concrete in buildings is based on cement industry decarbonisation. Currently, key strategies to reduce the emissions in the cement making process are switching to low carbon fuels derived from waste and new cement formula development reducing the clinker ratio and including the use of raw materials (D'Alessandro et al., 2016) (Bataille et al., 2018). Also, the use of carbon capture, utilisation and storage (CCUS) technologies could contribute in the decarbonisation process (International Energy Agency, 2020a). In addition, the dual role of cement in the global emissions cycle could be considered. Cement has been recognized as a potentially significant carbon sink due to carbon reabsorption of cement based products during carbonation (Pade and Guimaraes, 2007). A recent study found that the magnitude of such carbon sequestration is similar to the active CCUS sequestration, indicating that policies aimed at decarbonising the cement industry should consider the sponge effect of cement (Cao et al., 2020).

Regarding the steel industry, even though steel is one of the most recycled material in use today (80-90% being recycled) the recycled quantities are not enough to fulfil the production needs. The direct carbon intensity in the steel production has been relatively constant in the past recent years (International Energy Agency, 2021b). Low carbon fuels, direct electrification and CCUS technologies are viable paths for carbon emissions reduction in the steel making process. In the sustainable development scenario by IEA (International Energy Agency, 2020b) that anticipates 60% emissions reduction in the steelmaking by 2050, 30% is estimated based on technologies that are only at the prototype stage today, as such, innovation in the following years will be crucial to reduce the carbon intensity of steel production.

Despite the fact that technologies to decarbonise high carbon production processes are available, their costs is the main barrier in a global rollout. Generally, many of the innovative technologies to produce low carbon materials have higher costs than the intensive carbon ones thus making their penetration into the market challenging at a larger scale (Sartor and Bataille, 2019). It is clear that while changes are foreseen in the construction materials sector with the scope to reach carbon neutrality by 2050, it will take decades to decarbonise to a certain extent the production process of the materials.

Partially this problem could be addressed by carbon pricing making the high carbon materials less attractive than the low carbon ones. Indeed, the *High-level commission on carbon prices* acknowledges that carbon pricing is a key policy tool in the strategy to achieve the objectives of the Paris Agreement by discouraging carbon intensive activities (CPLC, 2017). Until recently the EU carbon price was too low to generate important changes. Trigged by the post-pandemic recovery and Russia's war in Ukraine, the EU carbon price almost tripled in 2022 (€98 per tonne of CO_2 in August according to EMBER database[2]). However, without additional policy support even at higher carbon prices, most low-carbon technologies will not be economically viable before 2030 (Cornago, 2022; Sartor, 2021). Intensive policy support from production to end-use is needed for these low-carbon technologies to make an impact in the market towards a successful achievement of the Paris Agreement (Bataille et al., 2018).

[2] https://ember-climate.org/data/data-tools/carbon-price-viewer/

8 Case studies

This chapter presents existing and conceptual examples of residential and non-residential buildings with low or zero emissions, identified in the literature.

8.1 Non-residential buildings

a) Offices

A zero energy office building in Norway is investigated by (Moschetti et al., 2019) in four alternative design solutions to reach zero emissions. The building was designed under the ZEB-Q-EQ Norwegian ambition level meaning that the operational GHG emissions excluding the energy use for equipment (appliances, computers, etc.) should be compensated by renewable energy.

Alternative 1 is the as-built building. Alternative 2 investigates an extensive use of wood for the load bearing system and the envelope. Alternative 3 investigates an extensive use of renewable energy from the PV panels while alternative 4 is a combination between 2 and 3.

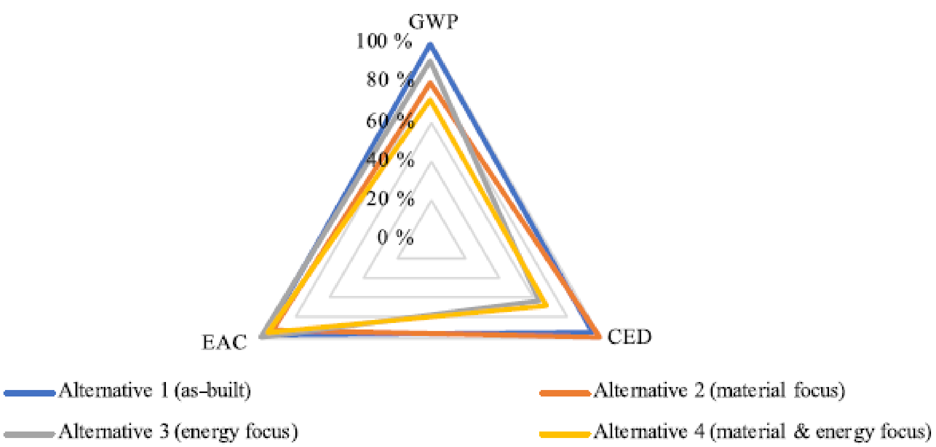
Table 2 shows the total primary energy demand expressed as the Cumulative Energy Demand (CED in kWh/m^2/year, the life-cycle GHG emissions expressed as the Global Warming Potential (GWP) in kgC-eq/m^2/year, and the life-cycle cost defined as the Equivalent Annual Costs (EAC) in EUR/m^2/year for each of the four investigated solutions.

Table 2. Alternatives to achieve zero-emission building from zero-energy building

Description	CED (kWh/m^2/year)	GWP (kgCO$_2$-eq/m^2/year)	EAC (EUR/m^2/year)
Alternative 1	87	9.2	93
Alternative 2	91	7.4	89
Alternative 3	58	8.5	95
Alternative 4	63	6.6	91

Source: (Moschetti et al., 2019)

Figure 9. Normalized values for life-cycle CED, GWP and EAC of the analysed alternative



Source: (Moschetti et al., 2019)

The extensive use of PV panels is the most effective in reducing the energy demand, while the use of extensive wood contributes the most in reducing the carbon emissions. Focusing on both material and energy savings reduces the energy and carbon emissions but still not enough for a zero emissions life-cycle.

The differences in the annual costs (EAC) are insignificant among the alternatives with the investment costs dominating the annual costs in all the alternatives.

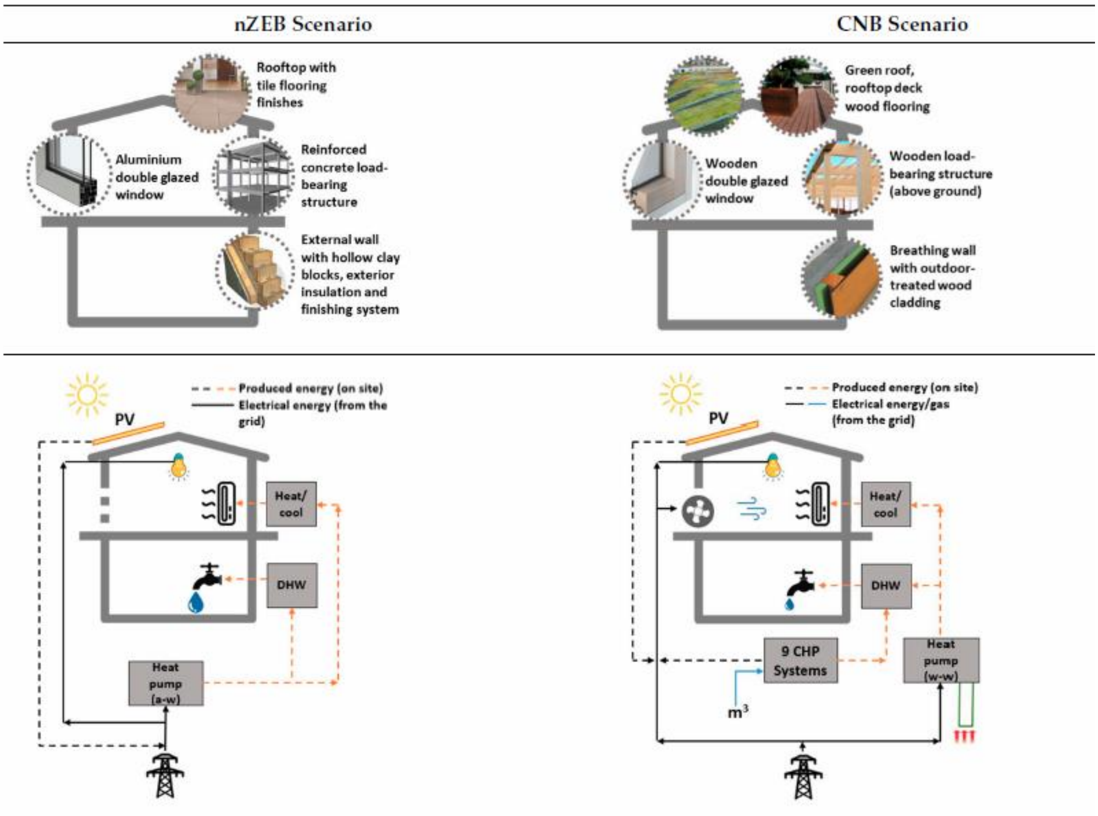
The study demonstrates that a zero emission life-cycle is difficult to achieve even through extensive use of renewable energy, especially in low carbon grids, without focusing on materials' embodied energy and emissions.

b) Hostel

(Causone et al., 2021) investigates the carbon-neutral concept applied to an eight-storey hostel building located in Rome, Italy in comparison with the Italian NZEB definition.

To reach zero carbon emissions, the focus is on low carbon materials (particularly wood), construction technologies and highly efficient technical systems (PV and combined heat and power systems coupled with a geothermal water-to-water heat pump (GWHP).

Figure 10. Materials and technical systems considered in the NZEB and CNB scenarios



Source: (Causone et al., 2021)

The design process lead to a reduction of about 59% in the primary energy demand of the Carbon Neutral Building (CNB) compared with the NZEB, while the life-cycle carbon emissions are reduced by 55%.

The whole life-cycle carbon footprint of the NZEB equals about 11 130 tCO_2-eq, while the carbon footprint of the CNB is approximately 5 016 tCO_2-eq. In both concepts the use phase has the highest environmental impact (responsible of 79% and 69% of the total emissions in CNB and NZEB concept, respectively), followed by the construction and production of materials.

To offset part the CNB emissions, the authors proposed the requalification of an adjacent area, including a new green area of 2 400 m^2 with 90 trees with limited need of water and high carbon capture potential. After 30 years, the trees will be able to capture about 300 tCO_2-eq. The remaining emissions may be voluntary offset via the acquisition of carbon sinks or by purchasing renewable energy.

The authors concluded that achieving life-cycle carbon neutrality depends greatly on the building characteristics (such as geometry, destination, and location) and generally in urban environment this might not be achieved at a building level, given the limited spaces for onsite carbon offsetting actions.

8.2 Residential buildings

a) Multi-family house

A typical multi-family building subjected to renovation is investigated by (Panagiotidou et al., 2021) considering several renovation packages that range from cost optimal to net zero operational emissions under four Greek climate zones.

Investigated measures:

- Energy savings: thermal insulation of external walls, roof, floor/basement ceiling, windows replacement and shading installation
- Energy supply: replacement of conventional gas and oil based heating systems with gas absorption HPs and biomass boilers, respectively; new efficient air-to-air and air-to-water HPs for cooling, HP water heating system , HVAC control system, RES (PV panels, HPs and others)

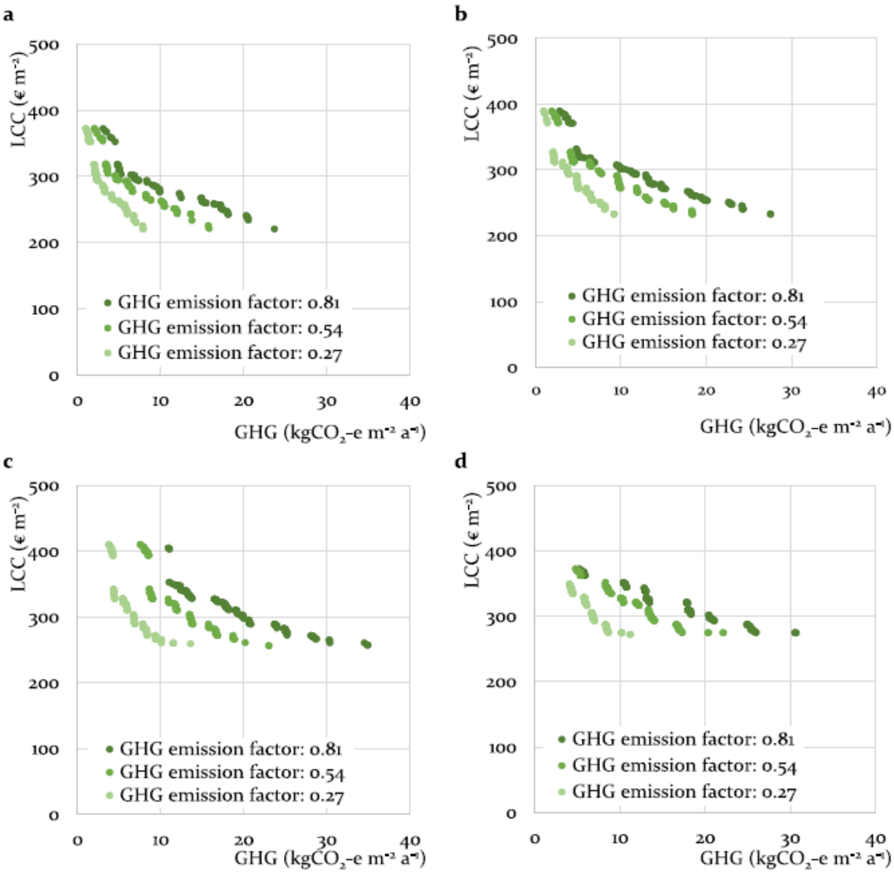
The proposed cost-optimal solutions lead to 60% reduction in the GHG emissions compared to the base case scenario in all climate zones.

For emissions reduction up to 96%, additional measures are needed, such as: triple glazed windows, central biomass boiler in locations without natural gas, gas condensing boiler in location with natural gas and air-to air HPs for cooling or air-to-water HPs for heating and cooling, roof integrated PV and thermal panels and wall integrated PV panels.

However, it was concluded that net zero emissions could not be achieved in any investigated location, mainly due to the limited available rooftop space for RES, as it can be seen in Figure 11.

If the future decarbonisation of the electricity grid is considered simultaneously with the installation of efficient electricity driven system, the annual GHG emissions approach zero balance in 2040.

Figure 11. Scenario analysis for a range of GHG emissions factors
a. Heraklion (A), b. Athens (B), c. Thessaloniki (C), and d. Florina (D)



Source: (Panagiotidou et al., 2021)

b) Single family house

- Oslo, Norway

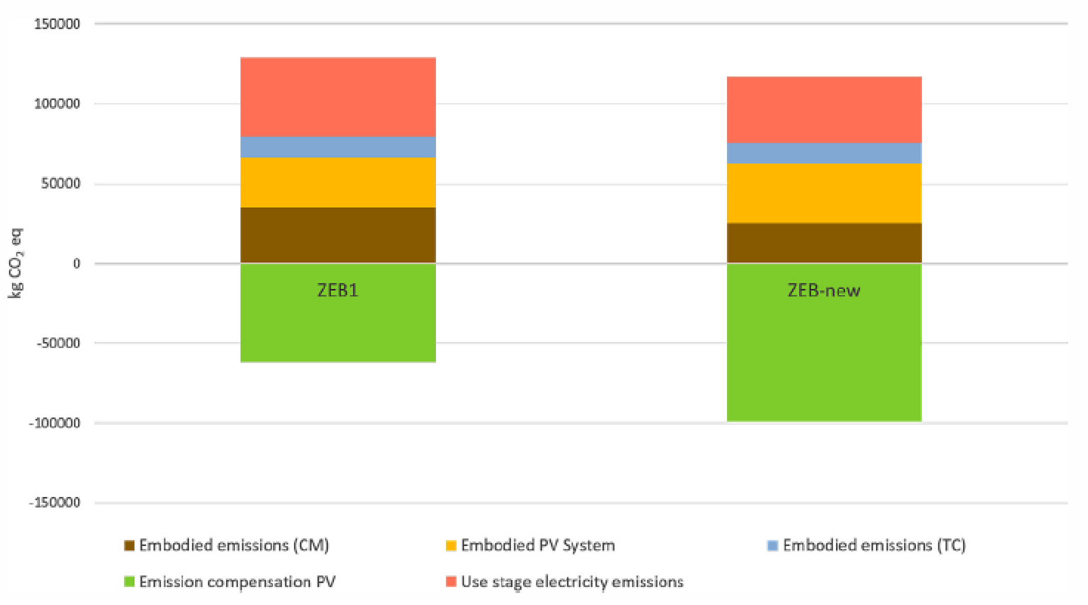
(Kristjansdottir et al., 2018) investigated several zero carbon alternatives and proposed a new model of ZEB for a representative Norwegian single family house located in Oslo to comply with the ZEB-OM definition: the building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials (by Norwegian Research Centre on Zero Emission Buildings). Concretely, the product stage emissions considered are from construction materials (CM), technical components (TC) and the PV system.

The new ZEB model is designed with a strip foundation of low carbon concrete, a timber structure with glass wool thermal insulation and a PV area of 78 m^2 (19 m^2 larger than the ZEB1-default ZEB design). Two heating system alternatives were analysed: (1) an air-to-water heat pump with solar thermal panels and (2) a ground source heat pump.

The life-cycle assessment showed that the embodied emissions account for 60% of the whole life-cycle emissions (in the ZEB-OM scenario).

Compared with the default ZEB design (ZEB1), the new model is significantly closer to achieve ZEB-OM status mostly due to increased PV production, which offsets the operational emissions and about 60% of the embodied emissions (Figure 12), while the ZEB1 was able to balance out all operational emissions and only 5% of embodied emissions. Shows the emissions balance for both ZEB1 and new ZEB

Figure 12. Emission loads and credits for ZEB1 and the new ZEB model



Source: (Kristjansdottir et al., 2018)

The authors concluded that the ZEB compliance highly depends on the choice of the conversion factor for grid electricity as well as on the embodied emissions boundaries, service lifetime and emissions data sources. Further studies are needed to increase the performance of the new building concept.

- Melbourne, Australia

An older study by (Crawford, 2010) evaluated the life-cycle GHG emissions and the sizing of a PV system to offset these emissions in typical new detached house located in Melbourne.

The initial embodied, operational, maintenance and refurbishment and demolition and disposal energy related emissions sum up in a life-cycle emissions figure of 603 tCO_2-eq over the predicted 50-year life of the house.

A PV systems of 14.9 kW resulted to be able offset the life-cycle emissions of the building as well as the emissions associated with the manufacture and maintenance of the PV system itself, over a period of 50 years.

9 Conclusions

Building sector play a key role in fighting climate change but current efforts and trends are not enough to achieve carbon neutrality by 2050. Against this background, the revision of the Energy Performance of Buildings Directive brings stricter paths to reduce the greenhouse gas emissions (GHG) of buildings, by putting forward a definition for Zero-Emission Buildings (ZEBs).

So far, the focus has been on the operational energy use of buildings, controlling the regulated building-related energy use of heating, cooling, ventilation, hot water, lighting and auxiliary energy. Heating and hot water alone account for about 80% of the final energy use in the EU's households while cooling, although represents a smaller share, shows an increasing trend linked to climate change. In this context it makes sense to concentrate efforts on reducing these categories in the first place.

Aiming at zero emissions, it is relevant to acknowledge the contribution of other building-related energy uses, currently not under regulation, such as energy consumed by lift, escalators, safety and security systems and by any other technical system needed for the proper functionality of the building. Going further, the user-related energy use (e.g. IT equipment, appliances) and the energy use for the provision of water, both known as non-building-related energy use, could also be included in the boundaries of the operational energy use.

The reduction of the operational energy use triggers reduction in the operational carbon emissions. As operational emissions are being reduced in low energy/carbon buildings, the importance of the embodied emissions rises dominating the life-cycle emissions. It is estimated that the upfront carbon emissions (released before the use of the building) will represent about 50% in the life-cycle emissions of a new building in the next decades. Therefore, the embodied emissions will become more prominent or even dominant in the life-cycle carbon emissions balance.

Within the above framework, the study depicted how a ZEB should consider both operational energy/emissions and embodied energy/emissions. The efforts already made within the European Union to reduce the operational energy and consequently, the operational emissions through nearly-zero energy buildings could be a starting point in shaping the ZEB definition. In line with the "energy efficiency first principle", measures to reduce energy needs are crucial to prevent energy generation that can be avoided with cost-effective energy efficiency measures. Practically, this could involve strengthening the requirements for energy efficiency through mandatory numerical benchmarks for operational energy use.

In addition, the study emphasised that the definition should clearly point out the role of renewable energy. In absolute zero operational emission buildings, renewable energy is used to cover all operational energy need without using any fossil fuel sourced energy. In the case of net zero operational emissions, the renewable energy covers to a certain limit the energy need and offsets the emissions generated by fossil fuel energy use when renewable is not available, offering more flexibility. Regarding the location of renewable energy production, the definition should prioritise available options. Generally, on-site and nearby renewable energy production are preferred, although purchasing off-site renewable energy should remain an option where on-site production is limited.

Moving on to zero life-cycle emissions, the assessment of the embodied GHG emissions should become mandatory as well. For new buildings, it will be crucial to lower as much as possible the initial embodied emissions by prioritising low carbon materials, also considering that these emissions might not be displaced with more decarbonised electricity grids. Carbon reduction should always come before carbon offset. Of course, this is further conditioned by the market readiness. For existing buildings, the calculation and disclosure of the global warming potential will raise awareness on the embodied emissions and guide decision-makers on carbon offset options.

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List of abbreviations and definitions

BIPV	Building Integrated Photovoltaics
BPIE	Building Performance Institute Europe
CCUS	Carbon Capture, Utilisation and Storage
CED	Cumulative Energy Demand
CNB	Carbon Neutral Building
CPR	Construction Product Regulation Member State
DHW	Domestic Hot Water
EAC	Equivalent Annual Costs
EE	Energy Efficiency
EE1st	Energy Efficiency First principle
EPBD	Energy Performance of Buildings Directive
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gases
GWHP	Groundwater Heat Pump
GWP	Global Warming Potential
HP	Heat Pump
HVAC	Heating, Ventilation and Air-conditioning
MFH	Multi-family House
MS	Member State
NZEB	Nearly-Zero Energy Building
PEF	Primary Energy Factor
PV	Photovoltaics
RES	Renewable Energy Source
SFH	Single Family House
ZEB	Zero-Emission Building

List of figures

List of tables

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