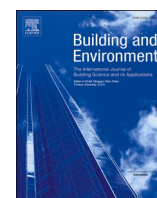


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How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72

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ABSTRACT

The concept of (net) zero greenhouse gas (GHG) emission(s) buildings is gaining wide international attention and is considered to be the main pathway for achieving climate neutrality targets in the built environment. However, there is an increasing plethora of differing terms, definitions, and approaches emerging worldwide. To understand the current progress of the ongoing discussion, this study provides an overview of terms, definitions, and key features from a review of 35 building assessment approaches. The investigation identified that 13 voluntary frameworks from 11 countries are particularly characterised by net zero-carbon/GHG emissions performance targets, which are then subject to a more detailed analysis. The review was organised in the context of the project IEA EBC Annex 72 on “Assessing Life Cycle Related Environmental Impacts Caused by Buildings”, which involves researchers from over 25 countries worldwide.

In the current dynamic political surroundings and ongoing scientific debate, only an initial overview of this topic can be presented. However, providing typologies and fostering transparency would be instrumental in delivering clarity, limiting misunderstanding, and avoiding potential greenwashing. To this end, this article categorises the most critical methodological options—i.e., system boundaries for both operational and embodied GHG emissions, the type of GHG emission factor for electricity use, the approach to the “time” aspect, and the possibilities of GHG emission compensation—into a comprehensive framework for clarifying or setting (net) zero GHG emission building definitions in a more systematic way.

The article concludes that although variations in the existing approaches will continue to exist, certain minimum directions should be considered for the future development of harmonised (net) zero GHG emissions building frameworks. As a minimum, it is recommended to extend the usual scope of the operational energy use balance. At the same time, minimum requirements must also be set for embodied GHG emissions even if they are not considered in the carbon/GHG emissions balance.

1. Introduction

1.1. The role of the construction sector and real estate industry in supporting sustainable development

As part of the way forward for sustainable development, actors in the built environment, including the related upstream and downstream economic sectors, strive to protect their traditional business interests, along with fulfilling their responsibility towards society and the environment. They orient themselves, among other things, towards the internationally recognised sustainable development goals (SDGs) [1–3].

Any specific decision may affect not only the achievement of economic goals but also society and the environment. ISO 26000 [4] on corporate social responsibility (CSR) forms the basis for this. It expressly includes the task of assuming product responsibility. For construction product manufacturers and the actors involved in the design, construction, use, financing, and management of buildings, this means that the characteristics and properties of the use of resources and undesirable impacts on the global and local environment; biodiversity; and the health of construction workers, building users, and neighbours must be documented, assessed, and influenced in a targeted manner, as well as communicated to third parties. These topics together can be summarised

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as the environmental performance of buildings.

Numerous international, regional, and national standards exist to guide the description of the environmental and health-related characteristics and properties of construction products—e.g., ISO 21930 [5] and EN 15804 + A2 [6]—as well as the determination and assessment of the environmental performance of buildings—e.g., ISO 21931–1 [7] and EN 15978 [8]. They contain information on the specification of the respective object of assessment, including the system boundaries, and on the calculation rules. However, they do not include assessment standards in the form of performance levels, benchmarks, or target values. The newly published ISO 21678 [9] provides the basis for the development, description, application, and interpretation of benchmarks, but does not state any specific values. However, these are indispensable for supporting actors in the built environment in their decision-making.

Since climate neutrality and reduced greenhouse gas (GHG) emissions are priorities to be achieved at different scales—such as in countries, sectors, building stocks, cities, or single buildings—a clear definition and specific assessment rules are urgently needed. A balance of GHG emissions, commonly referred to as (net) zero GHG emissions, is interpreted here as a design target, ambition level, benchmark, or budget for buildings. Such an approach, sometimes called carbon performance [10], becomes a crucial aspect of environmental performance assessment and is comparable and compatible with life cycle-related energy performance.

1.2. (Net) zero greenhouse gas (GHG) emissions buildings: the main pathway for achieving climate neutrality in the built environment

The very significant, yet quite general, SDGs must be integrated into the work and responsibility of building-related actors, as well as adapted to the particularities of the specific object under investigation. To both pursue these goals in the area of the built environment and fulfil the commitments made with Conference of the Parties (COP)21, it is necessary to dramatically reduce the greenhouse gas (GHG) emissions associated with the production of construction materials, as well as the construction, use, maintenance, and end of life of buildings.

The aim is to achieve a state in which buildings, during their life cycle, make only a minimal contribution to GHG emissions and thus to global warming. This state is referred to as (nearly) climate neutral [11]. One ambition level is where a (net) zero GHG emissions balance is achieved in the life cycle of buildings and structures, while (net) zero GHG emissions with regard to the operational aspect is a sub-goal that focuses only on balancing the emissions from buildings' operation. From these goals, actual target values for the design and assessment of buildings in relation to their carbon performance can be derived. It should be stressed that carbon performance is one of several aspects of environmental performance. In addition, social and economic performance shall be assessed, and technical and functional requirements must be met.

A new norm is emerging with goals with various synonyms, such as (nearly) carbon-neutral, (net) zero-carbon, climate neutral, and (net) zero emissions buildings, as well as target values such as (net) zero GHG emissions in the operation or life cycle of buildings. For the first time, target values are derived top-down from scientifically recognised necessities (science-based targets [12])—i.e., compliance with the ecosystem's carrying capacity (planetary boundaries [13]) and serve to maintain the natural foundations of life. In the past, target values were mainly developed based on technical and/or economic feasibility or by statistically deriving “best in class” values according to the “less is more” approach [14]. These were different depending on the type of building and use. The top-down approach uses a universal benchmark for the first time—(net) zero GHG emissions for all buildings, regardless of the type of building, use, location, climate, or energy supply system [14]. It becomes clear that the achievement of this universal goal, however, requires the application of specific solutions depending on the climate conditions, type of building, use, and other already-mentioned facts.

So far, however, we have little experience with the development and application of top-down benchmarks. Attempts are currently being made in many countries, organisations, and other institutions to define the term climate neutrality; translate it into measurable target values; and develop calculation and accounting rules, including the definition of system boundaries. This development has so far led to many terms, definitions, calculations, and accounting procedures. The number of different variants is currently still increasing. There is an urgent need to improve transparency; ideally, either a system into which different approaches can be classified or an internationally harmonised approach to the problem should emerge.

1.3. Focus and aim of the research

In the construction sector, there has been an ongoing discussion for decades on the possibilities of describing, assessing, and improving the environmental performance of buildings as part of their overall sustainability performance. This has led to the creation of standards, such as ISO 21931–1 [7]. Only a few of the environmental performance indicators mentioned there have so far been incorporated into the legislation of countries. Therefore, during the past few decades, a building's energy performance has been regulated based on the delivered/final or primary energy use, while legal requirements to reduce GHG emissions are not yet in existence or are just emerging (e.g., in France [15]). For a long time, the protection goal of conserving natural resources (here, fossil fuels) was in the foreground. The development of the discussion led to the increasing recognition of the need to also include embodied energy. Consequently, a significant number of net zero energy approaches occurred in the market, which have already been well covered in the existing body of literature [16–19]. However, discussions about net zero energy targets in operation or life cycle, as part of building policy, are now supplemented by a focus on net zero GHG emissions buildings and GHG emissions as a metric instead of relying on energy demand as a proxy for measuring a building's performance in relation to its impact on global warming.

Therefore, this article focuses mainly on principles related to the concepts of net zero GHG emissions buildings as a contribution to the climate change mitigation process and SDG 13, “Climate action”. The aim of the article and the subsequent analysis is threefold:

- to develop approaches, proposals, and a basis for systematisation and harmonisation to rule out misunderstandings and avoid greenwashing;
- to provide an overview of the key parameters, boundaries, and performance targets mentioned in building assessment approaches in relation to (net) zero GHG emissions buildings in different parts of the world;
- to provide a detailed analysis of the terms, definitions, system boundaries, calculation methodologies, and compensation rules used for GHG emissions balance.

To achieve these objectives, data extracted from 35 energy or GHG emissions-based building assessment approaches were used. The primary target audiences for this article are policymakers and building design professionals, as well as researchers and consultants interested in the market implementation of (net) zero GHG emissions buildings and/or the development of standards or sustainability assessment systems.

2. Theoretical basis

2.1. Object of assessment and system boundaries

Essentially, all buildings and building structures should contribute to an (almost) climate-neutral building stock. It is possible that net zero emissions or energy balance can be achieved for single construction works, a group of buildings within a district or a city, or an institutional

or national building stock.

The determination of GHG emissions associated with a building’s life cycle usually includes two parts—an operational part and an embodied part, as shown in Fig. 1. The modular framework is based on the building standard EN 15978:2011 for the sustainability of construction works and maps the environmental information based on the building’s value chain stages (A to D). Some modifications from the modular structure presented in the latter standard is the subdivision of the information module B6 into three parts and the addition of module B8, for the reasons explained in the following section. This is in line with the current discussions on the further development of EN 15978.

In the next version of the EN 15643 standard, there will be an additional module, D2, to cover benefits and loads in relation to exported utilities (e.g., exported energy), and the former recycling potential will be renamed to D1.

2.1.1. System boundaries—operational part

The operational part of a life cycle assessment is based on the calculation of the final energy demand for the operation of the building, typically including heating, cooling, hot water supply, ventilation or air conditioning, auxiliary energy for pumps, and fixed lighting. Using emission factors, information on the final energy demand of a building can be converted into GHG emissions and air pollutants. Using primary energy factors, the determination of the primary non-renewable energy demand is possible. The implementation of an integrated design approach with an extensive use of building performance simulations (BPSs) is necessary for the design of net zero GHG emissions buildings and in the prediction of final energy demand [20]. The accuracy of building-specific energy and carbon performance simulation results depends mainly on the accuracy of the building model; the experience of the user; and the simulation software, which applies different methods in integrated or separated simulation engines [21]. The use of non-validated models and unreliable design assumptions mainly related to occupants’ behaviour may lead to a large performance gap between the simulated and actual energy consumption, as well as the renewable energy production of buildings [22]. Therefore, it is crucial to verify the designed performance of buildings with the measured data from their operation. This is in line with the existing ISO 16745-1-2017 standard [23], which provides methods for the calculation, reporting, and

communication of a set of GHG emissions metrics arising from the measured energy use during the operation of existing buildings.

The type and scope of quantities to be considered when calculating a building’s operational energy demand are regulated in Europe in the legislative framework the Directive Amending the Energy Performance of Buildings and the Energy Efficiency Directives, 2018 [24], which has been translated into national requirements in many countries. This corresponds to module B6 for describing information on selected stages of a life cycle according to the ISO/TC 59/SC 17 and CEN TC 350 standards. However, this does not cover all types of energy demand, and there are gaps—for example, due to a lack of consideration of energy consumption and related GHG emissions for the operation of passengers, freight elevators, and escalators. This can account for 3–8% of the total operational energy consumption [25,26]. On the one hand, energy consumption and GHG emissions are underestimated; on the other hand, there are systematic deviations between the calculation of needs and the measurement of consumption.

It is therefore recommended to extend the primary module B6. In a first step, as suggested by the authors based on [27], a distinction can be made within module B6 as follows:

- B6.1: Building-related operational energy use (final energy), regulated and convertible into primary energy demand, non-renewable and GHG emissions.
- B6.2: Building-related operational energy use (final energy), unregulated (e.g., for elevators) and convertible into primary energy demand, non-renewable and GHG emissions.

In addition, there is another problem in determining operational energy demand—namely, dealing with user-related energy consumption. This is traditionally viewed as a positive contribution to the energy balance in the form of (useable) internal gains, but without considering the occurring resource consumption and GHG emissions. The discussion about the way to deal with the self-use (calculation of the degree of self-use and degree of self-sufficiency) of a building—e.g., as a result of energy generated by building-integrated photovoltaic systems (BIPV)—has complicated the situation. In order to both reduce the systematic difference between the energy demand forecast and consumption measurement and to overcome the contradiction between taking internal

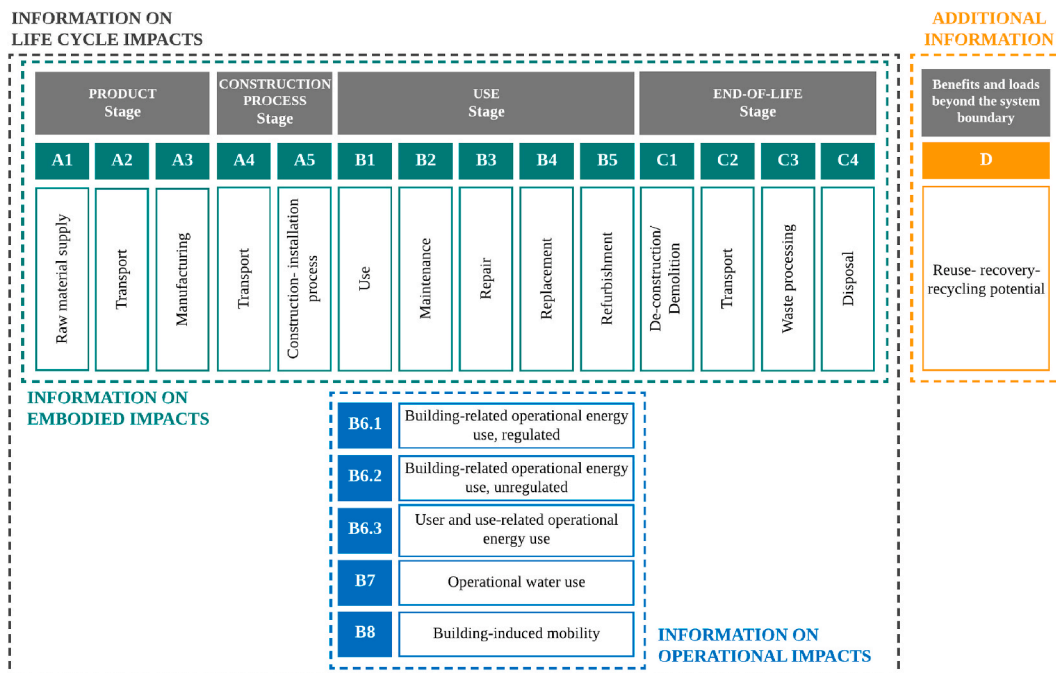


Fig. 1. System boundaries of building life cycle (modified from EN 15978 and Lützkendorf (2019)).

gains into account and not including the related energy, adding a third part to module B6 has been proposed:

- B6.3: Non-regulated user-related energy use (final energy in residential buildings—e.g., household electricity), convertible into primary energy demand, non-renewable and GHG emissions.

The current considerations go beyond the inclusion of the user- and building-related energy consumption. The starting point for this is in countries such as Switzerland, which attempt to incorporate mobility triggered by the location of the building. In Norway, a related module is already included in its standard NS 3720 [28], the so-called “B8 transport in use”, and it is based on “well-to-wheel” emission factors that include infrastructure and the whole life cycle of the vehicle and fuel productions of different modes of transport. The GHG emissions connected with building-induced mobility can be significant. The life cycle assessment performed by Lausset et al., 2019 [29], indicated that operational mobility GHG emissions could contribute up to 15% of the total GHG emissions coming from the life cycle of a (net) zero GHG emissions neighborhood in Bergen city, Norway. The daily distance travelled by inhabitants was found to be one of the critical parameters influencing the mobility GHG emissions. In the coming EN 15643 standard, there will be an additional module B8 for “Users activities” included in the list of information modules describing the model of the life cycle.

In some national assessment approaches, the energy consumption associated with the provision of drinking water and the resulting GHG emissions may also be taken into consideration (B7).

The survey recorded and analysed whether, and to what extent, an expansion of B6 towards the additional consideration of B6.2 and B6.3, the inclusion of B7, and the further consideration of B8 has already been established. It is, therefore, necessary to examine which modules are considered when determining and evaluating the operational part. The results are shown and discussed in Section 4.2.1.

2.1.2. System boundaries: embodied part

Life cycle-based assessment methods, and consequently also net zero definitions, differ in their scope in relation to the life cycle stages covered. It is expected that most methods/definitions cover product-related modules (A1-3, C3-4), due to the availability of such information in national databases and environmental product declarations (EPDs). For the embodied part, it is also important to consider the replacements of building components (B4), since, depending on the replacement rate, this can be considerable and comparable to the construction-related embodied part [30,31]. This becomes even more important in the case of net zero energy/GHG emissions buildings, since the installation of photovoltaic systems (PVs) is a common measure.

It is, therefore, necessary to examine which information modules are included in the determination and evaluation of the embodied parts. The results are shown in Section 4.2.2.1.

2.2. Indicators and metrics of balance

As described in the ISO 15392 standard, both criteria and indicators, as well as action goals, can be derived from the areas of protection and protection goals (issues of concern) of sustainable development. The areas of protection correspond to the “endpoints” of an assessment approach, following the rules of a life cycle assessment (LCA).

The use of energy and the consumption of energy carriers play an essential role in the description, assessment, and targeted influencing of environmental performance. The energy performance is one aspect of the environmental performance. Embodied energy can become a factor in the energy performance if a life cycle-based approach is considered. 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. Still, today the requirements for climate protection are expressed in goals for improving the energy efficiency of buildings.

It is now being discussed whether, and to what extent, indicators for quantifying and assessing energy resource consumption should be supplemented or replaced by indicators representing impacts on the global environment/climate [32]. The study by Parkin et al., 2020 [33], indicates that moving attention from energy metrics to GHG emissions indicators in policymaking and the building design process is crucial for meeting climate goals. The present authors are in favour of pursuing requirements for reducing the use of non-renewable primary energy and requirements for reducing GHG emissions at the same time, since these are equal protection goals—resource conservation on the one hand and climate protection on the other.

Global warming potential with a 100-year time horizon (GWP 100) is now viewed as a leading indicator in the construction sector. It can be expressed as carbon footprint to describe and communicate carbon performance. As a result, in many countries building requirements can usually be found regarding a net zero or positive energy balance in operation or with the inclusion of embodied energy in the complete life cycle. These approaches directly pursue the goal of resource conservation and, indirectly, that of climate protection. For a few years now, however, there has been a development that introduces GHG emissions as the main performance indicator and formulates requirements for climate neutrality in operations and life cycle.

2.3. Principles for an environmental impact assessment of electricity use

Generally, environmental impact evaluation methods for the electricity mix can be divided into two main distinct concepts: average and marginal. The use of the “average electricity” principle presents the statistical average emissions, which are usually given as the gram carbon dioxide equivalent per kWh ($\text{gCO}_2\text{eq/kWh}$) from the entire electricity mix and usually contain several interconnected regional zones. In contrast, 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. Consequently, this principle takes into consideration the local and actual effects of different actions on the power grid.

The difference in GHG emission intensity between “average electricity” and “marginal electricity” tends to be significant [34]. It is highly dependent on the combination of the energy mix, which covers the base electricity load and the source type of marginal (additional) energy. The study conducted by Bettle et al., 2006 [35], indicated that the marginal emission factor for the gas-based energy mix in England and Wales, with marginal electricity generation from coal-fired plants, was up to 50% higher than the average emission factor type. Contrary, in electricity grids characterised by high GHG emissions, where the base-load is substantially met with coal-based electricity generation, and marginal electricity is provided from other, more sustainable sources (gas, nuclear, or renewables), the average emission intensity is higher than the marginal emission intensity [36]. Consequently, the use of the specific approach may underestimate or overestimate the GHG emission reduction measures.

The implementation of average and marginal electricity factors in Norwegian (net) zero-emission building (ZEB) assessment approaches was discussed by Graabak et al., 2014 [37]. In conclusion, the authors recommended using the average electricity factor for the design and deployment of ZEBs, since this type of approach is more robust and suitable for all building types and patterns of use. On the other hand, the use of the marginal conversion factor was stated as necessary for the optimal operation and verification of the net zero GHG emissions performance of specific, existing buildings.

Table 5 In Section 4.2.1 presents how building assessment approaches are addressing this issue.

2.4. Aspect of time—static versus dynamic approach

As a rule, life cycle-based energy performance and energy balance assessments, as well as the assessment of carbon performance and GHG emissions balance, are used for the service life of buildings or for a defined reference study period (RSP). As buildings are usually long-lasting products, the question arises of how to deal with the “time” factor. Thus far, deterministic models with a static approach have been used in the known applications of such balances within the framework of laws, funding programs, and sustainability assessments. Therefore, changes over time have so far been under-addressed. The consideration of the complete life cycle is based on the prevailing conditions at the time of the assessment.

However, how realistic are static models? Over time, there will be changes in climate conditions, user behaviour, and the energy mix (amongst other factors). In addition, technical improvements related to the characteristics of construction products and the conditions/technology of production also need to be taken into consideration. Consequently, a dynamic analysis is needed, which includes future climate data, since this mainly has an impact on the operational part and will lead to a reduction in heating requirements and an increase in cooling requirements [38,39]. Similarly, a dynamic analysis of user behaviour should be included to account for future changes in awareness and changes in occupant behaviour due to the implementation of new technologies [40,41].

Dynamic approaches are now also an object of intense scientific discussion, which usually focuses on how to deal with a changing energy mix or electricity mix [42–44]. While this represents an indispensable question in the future, from the authors’ point of view, when considering climate neutrality in operation, there are further challenges/considerations when considering the life cycle. For example, changes in the energy mix are not just important for the operational aspect, but also have an impact on the embodied energy consumption and GHG emissions. The decreasing GHG emission intensity of energy mixes will lead to conditions where the replacement of construction products will cause less GHG emissions and other impacts related to the global and local environment and/or resource depletion [45]. This is important for the modelling of replacement measures (B4) and refurbishments (B5), because these will take place in the future. Following a dynamic approach for the operational aspect, often the energy and/or GHG emissions balance, while maintaining a static approach for the embodied part, leads to a distortion of reality. IEA EBC Annex 72 is currently working on solving this problem by discussing options for a dynamic approach to construction product-related LCA results. There is also the possibility of introducing additional columns into databases to show a forecast for data in 20–40 years.

When analysing different approaches among building assessment approaches, it is, therefore, necessary to examine whether a static or dynamic approach is being followed, for which sub-aspects a dynamic approach may be permitted, and whether the dynamic approach is only for the operational part or for the embodied part.

Additionally, the GHG emission intensity of the electricity mix can be considered on an annual, seasonal, monthly, daily, or hourly basis. 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 [46]. The use of seasonal GHG emission factors of the electricity mix takes into consideration the variation in the environmental impacts of electricity in the different seasons of the year, which is driven by seasonal changes in the energy production on the supply side (f.ex increased renewable energy generation in the summer) and/or a variation on the demand side (f.ex an increase in heating energy needs in winter) [47]. The implementation of hourly GHG emission electricity factors besides including seasonal variations enables taking into consideration the changes in electricity demand related to human activities (f.ex lower electricity need during the night time).

The extensive development and use of hourly and regionally specific (marginal) GHG emissions factors are 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.

The results of how building assessment approaches are handling this in relation to the aspect of time are presented in Section 4.2.1 for the operational part and in Section 4.2.2.2 for the embodied part.

2.5. Options for compensation

For all variants that follow a net zero GHG emissions approach, the question arises of how a GHG emissions balance can be achieved and what compensation options (technologies or other measures) should be used.

The most important questions are discussed below.

2.5.1. System boundaries for the generation, procurement, and assessment of renewable energy

The GHG emissions caused by the building construction and operation (or only operation) can be according to some suggestions in the literature [46] compensated by “avoided” GHG emissions outside the system boundary through the export of renewable energy. Other authors suggest presenting the benefits of exported energy as additional information—e.g., under module D, in line with European (i.e., EN 15978 [8]) and international standards (ISO 16475–1 [23]) [47]. However, it must first be clarified which type of renewables generation can be attributed to the building and within which system boundaries. There are different options for system boundaries for the generation of renewable energy, as defined by Ref. [16] and presented in Fig. 2.

Option I (building-integrated generation) employs energy generation from renewable energy sources installed/mounted on the building. In most cases, as part of this option the photovoltaic and solar thermal technologies installed on the building roof or integrated into the building façade (building-integrated photovoltaic (BIPV) or building-integrated solar systems (BISS)) are used and directly connected to the building energy system.

Option II (generation within building site boundaries) addresses renewable energy generation technologies located within building site boundaries, typically from parking lot PV systems, tower-based wind turbines, and ground-mounted PV or solar hot water systems.

Option 3 (generation off the building site but used on-site) is typically less preferable than option 1 and 2, since significant environmental impacts related to the transportation of renewable sources (mainly biomass) to the building site may occur [48]. Additionally, some biomass resources which come from unsustainable fields and forests or

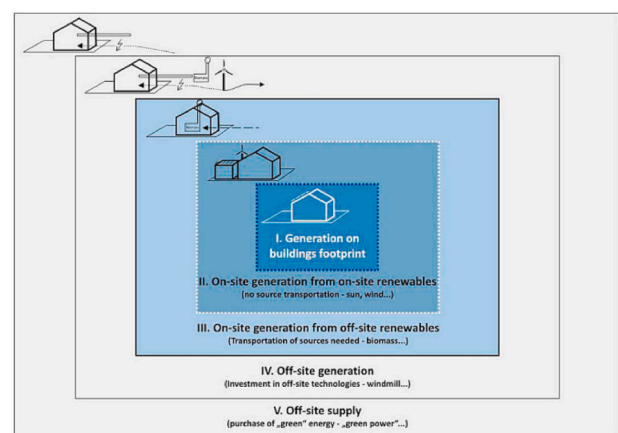


Fig. 2. Overview of the possible renewable supply options by Marszal et al., 2011 [16].

dedicated energy crops with a short rotation period should not be treated as GHG emission-free sources.

Option 4 (generation off-site) uses renewable energy sources available off-site to generate energy through the on-site processes connected to building energy systems.

Options 1 and 2 are of particular importance. After the internal requirements have been met, the surplus of energy produced is exported. The effects of avoided emissions are included in the balance or given as additional information, depending on the convention—see also the discussion below.

A special case of “imported” renewable energy (generation fully offsite) is seen as the purchasing of energy. Despite being widely recognised as a cost-effective and easy-to-implement strategy for reducing building-related GHG emissions [49], the application of this solution may be controversial. Existing research discusses the fact that buildings which rely only on renewable energy purchased off-site may present a lack of initiative to reduce the building energy demand and related environmental loads. In most cases, it is recommended to use average primary energy and emission factors for purchased energy that take into account the situation in the country.

If renewable energy is generated on-site, the excess can be delivered (exported) to third parties after deducting self-consumption. This reduces the emissions elsewhere compared to an alternative energy generation or procurement scenario. From the perspective of the building under study, there are possible effects outside its system boundary. There is currently a lot of debate as to whether these are given for information only (e.g., in module D2 following the latest developments in European standardisation in CEN TC 350) or considered in the balance sheet. Consideration in the balance sheet involves the risk of double-counting (1x for the building and 1x for the purchaser of the exported energy). In this case, in addition to the type of generation of renewable energy and the handling of the (embodied) energy used to manufacture and maintain the system generating the exported energy (fully or partially assigned to the building or/and partially assigned to the exported energy), the result is strongly influenced by which shares can be taken into account in energy consumption (B6.1 or B6.1, B6.2 or B6.3—with/without B8). Similar to on-site generation options, energy generation and purchasing from off-grid sources presents a risk of double-counting, since the operation of these requires a power grid to transfer the generated energy to the building site. The increased number of off-site renewable energy supply options will lead to the decarbonisation of the whole electricity grid and consequently a decrease in the GHG emissions factors. The guidelines developed by the U.S. Energy Agency, 2018 [50], present the best practices related to making environmental claims, such as purchasing green energy in the form of renewable energy certificates (RECs). One of the essential recommendations is connected to avoiding the double-counting of imported clean energy by retiring RECs just after making an official environmental claim. This measure can prevent the double-counting of environmental benefits in the case of selling or transferring certified green power certificates.

2.5.2. Negative GHG emissions through technical measures

Off-setting takes place with negative GHG emissions through technical measures including negative emissions technologies (NET) such as “biological fixation” (e.g., afforestation), biogenic energy resources with carbon capture and storage (BECCS), or direct air capture with carbon separation and storage (DACCS) [51]. This approach allows us to achieve net zero GHG emission buildings and contributes at the same time to the global net zero emissions goal, but the long-term viability of such measures is still questionable.

2.5.3. Purchasing of off-set certificates

The purchase of eligible off-set units supports projects that reduce or remove emissions from the atmosphere and compensate for emissions generated elsewhere. The general framework of the measurement and

validation of carbon off-set programs which can be traded in a marketplace was established under the development mechanism (CDM) developed under the Kyoto Protocol. Off-set certificates/units are considered as an essential tool to improve sustainability and boost global decarbonisation by financing initiatives related to carbon reduction in developing countries. On the other hand, compensation by off-set units may lead to controversy regarding effectivity and reliability [52].

2.5.4. Typology of options

In the literature, a typology for the designation of approaches without GHG emissions (absolute zero) or with a balance of GHG emissions (net zero) is proposed by Lützkendorf and Frischknecht [49]. Specifically, a division is proposed by the latter authors into:

Type A: Net-balance approach, with options A. a (‘potentially avoided’ emissions as part of the balance) and A.b (Avoided emissions as benefit outside the system boundaries and declared as additional information);

Type B: Economic compensation;

Type C: Technical reduction;

Type D: Absolute zero approach.

The options for compensation described in Section 2.5.1 to 2.5.3 above can be assigned to this typology.

3. Materials and methods

3.1. Proposal for a systematic approach

3.1.1. Framework for different options for an energy or emissions balance

Terms such as zero energy, zero carbon, or zero emissions are often used in politics and science, yet it often remains unclear whether such terms refer to an “absolute zero” or a “net zero” in terms of the energy and emissions balance. Absolute zero GHG emissions in operation represents the case of using zero emissions of fuel or electricity (self-produced or not) for covering the buildings’ operational needs, while absolute zero in life cycle additionally requires that the building is made of construction materials with zero-emission supply chains and end-of-life management, as well as that zero-emission fuel and electricity are used in the transport and construction. If all the upstream supply chains are included, an “absolute zero” level is currently practically impossible to achieve. However, studies show in which directions the decarbonisation process in the construction sector can be advanced [45].

In order to deliver clarity, limit misunderstanding, and avoid potential greenwashing, it is therefore important to state the chosen term very clearly and specifically. The same applies to the term “(net) zero emission”, which is used for both CO₂ emissions and GHG emissions. However, there are cases that do not cause CO₂ emissions but still contribute to GHG emissions through the release of methane and other GHGs.

The authors propose a system which clearly distinguishes the contribution of (1) energy balance, (2) CO₂ balance, and (3) GHG emissions balance in the chosen framework (code). It must be declared whether the goal is to avoid, in absolute terms, non-renewable primary energy consumption and emissions, or whether the goal is to achieve a net zero balance or possibly even a positive balance. While, for the operational part, in the areas of both non-renewable primary energy and CO₂ emissions, there are at least theoretical possibilities of absolutely avoiding any impacts, this is currently not possible for the entire scope of GHG emissions and the embodied part. Even though it is theoretically possible to achieve an absolute zero during operation or in the full life cycle, there are strong influences due to the system boundaries. This depends on whether the focus is on the direct use of energy and direct emissions and whether and to what extent upstream processes are included.

Based on the current state of the art, there is initially a need for multiple definitions for a series of specific cases, such as 1.1-A, 1.1-B.1, 2-A, and 2-B.1, as shown in Table 1 below.

Table 1

Framework of different options for an energy or emissions balance.

	Energy use (specified by energy carriers) representing use of natural resources [<i>MJ primary energy, non ren.</i>] A	CO ₂ emissions representing impacts to global environment [<i>kg CO₂</i>] B.1	GHG emissions representing impacts on global environment [<i>kg CO₂eq.</i>] B.2
1.1 Operational part of energy consumption and GHG emissions	a) absolute zero b) net zero	a) absolute zero b) net zero	a) absolute zero b) net zero
1.2 Embodied part of energy consumption and GHG emissions	a) absolute zero b) net zero	a) absolute zero b) net zero	a) absolute zero b) net zero
2 Balance, considering full life cycle	a) absolute zero b) net zero	a) absolute zero b) net zero	a) absolute zero b) net zero

One of the main goals of this article is to develop a transparent and systematic approach for a definition of (net) zero GHG emissions buildings, which would be instrumental to delivering clarity, limiting misunderstanding, and avoiding potential greenwashing. The developed framework presented in Table 1 provides a flexible, transparent classification system for different options for a chosen energy and/or emissions balance using a combination of the codes shown in the left column and the top header—e.g., B.2–1.1-b, B.2–1.2-b, or B.2-2-b. The chosen combined code would be representative of a net zero (or, in some cases, absolute) GHG emissions approach either in the operational aspect, embodied aspect, or the full life cycle accordingly. For example, the definition code B2-1.1b would represent an approach based on net zero balance for the operational aspect of GHG emissions.

3.1.2. Framework for different options of regulations and requirements in building assessment approaches

The system boundaries and performance requirements may vary greatly among building assessment approaches. In order to systemise the different regulations occurring in building assessment approaches, the authors developed a classification framework (Table 2) which presents the options for different regulations and performance requirements related to the operational and embodied parts of a building's life cycle. In total, there are 81 possible combinations which may be present in building assessment approaches.

The developed matrix may be useful for mapping and creating a code system for existing regulations. For example, a G.8. c code would represent a “net zero GHG emissions” approach, where the operational part is balanced and mandatorily limited by regulatory values in law, while the embodied part is not balanced but is limited by informal guidance values. Guidance values are understood as non-binding orientation values for partial sizes. For example, SIA 2040 [53] contains such values for the operational and embodied part to support architects in their design process, in addition to the mandatory requirements for reducing GHG emissions in the full life cycle of buildings.

3.2. Systematic review of building assessment approaches—key features

In the first step of the research, a survey of IEA EBC Annex 72 experts was performed in order to extract general data related to key features (Table 3) occurring in the respective country of the building assessment approach. The extracted data from 35 building assessment approaches in 31 countries were cross-checked with the provided references and existing literature.

In the second step, the current study excludes the energy metric-based approaches whose methodology and approach have been extensively described in previous research [16–19]. Consequently, the main analysis focuses on 13 building assessment approaches from 11 countries, which are based on a GHG emissions metric. To provide a detailed review and analysis of the methodology occurring in the GHG emissions-based building assessment approaches, the general data from the first step of the data extraction were complemented by the extraction

of detailed data covering features related to the operational and embodied modules and possibilities of GHG emission compensation, as presented in Table 3 below.

4. Results and discussion

4.1. State of the art

4.1.1. Overview of key methodological features from 35 building assessment approaches

The overview of general data from the first step of data extraction based on 35 building assessment approaches is presented in Table A1 in the Appendix.

Despite the high variation in key factors among the analysed building assessment approaches, the general findings are as follows:

- (1) The system boundaries recognised among analysed data focus mostly on the operational life cycle stage, excluding the embodied life cycle impacts.
- (2) A single building is the dominant object of assessment in the analysed data set.
- (3) Primary energy is the most common assessment metric, observed in most European countries, where the implementation of nearly zero energy building (nZEB) performance target is applied in national policy.
- (4) In most cases, the building standards and schemes based on a GHG emissions metric (zero-carbon, zero-emissions buildings) are voluntary and mostly created and used by NGOs or research organisations.
- (5) Most of the reviewed building assessment approaches are titled “zero carbon”, even though their frameworks not only cover carbon dioxide (CO₂) emissions but also a set of other gases whose emissions contribute to global warming. The use of non-scientific terms can lead to confusion from the point of view of the authors of this contribution.

4.1.2. Type of regulations and performance requirements in the analysed building assessment approaches

Based on an in-depth review of 35 building assessment approaches from 31 countries worldwide and the classification framework proposed in Table 2, the authors identified the nine following types of regulations, which present the system boundaries and performance requirements presented in building assessment approaches (Table 4). The mentioned approaches are not always representative for a situation in a whole country. In most of the cases, proposals and examples by organisations and private institutions are presented and discussed.

Definitions based on energy consumption metric (types: PE3. a, PE4. a, PE7. d and DE7. a) are the most common, occurring in 22 of the 35 analysed national building assessment approaches. The requirement in the form of maximum allowable annual primary energy consumption values (Type PE3. a, PE4. a, PE7. d) is present in 15 of the 35 building assessment approaches. The net zero energy performance target based

Table 2

Classification framework for system boundaries and performance requirements in building assessment approaches.

Note: for primary energy (PE), delivered energy (DE), CO₂ (C), or GHG emissions (G) metric.

		Embodied part of the life cycle								
		a	b	c	d	e	f	g	h	i
	Type of action and regulation	Excluded	Calculated	Calculated and limited by informal guide values ¹	Calculated and mandatorily limited by scheme 2	Calculated and mandatorily limited by law ³	Calculated and balanced (individual approach)	Calculated and balanced, incl. limitation by informal guide values	Calculated and balanced, incl. mandatory limit values as part of a scheme	Calculated and balanced, incl. mandatory limit values as part of a law
Operational part of the life cycle	1	Calculated								
	2	Calculated and limited by informal guide values								
	3	Calculated and mandatorily limited by building assessment approach								
	4	Calculated and mandatorily limited by law								
	5	Calculated and balanced (individual approach)								
	6	Calculated and balanced, incl. limitation by informal guide values								
	7	Calculated and balanced, incl. mandatory limit values as part of a scheme								
	8	Calculated and balanced, incl. mandatory limit values as part of a law								
	9	Calculated and mandatorily limited – only self-use of renewable energy produced at the building is part of the balance ⁴								

¹ i.e., design guidelines which set informal voluntary requirements.² i.e., voluntary building certification schemes, standards, and other building assessment approaches which set mandatory in-direct or direct requirements for achieving certification.³ i.e., national construction codes or standards which set mandatory requirements for building construction and operation.⁴ i.e., the exported energy is seen as additional information (benefits beyond system boundaries).

on the metric of delivered energy (Type DE 7. a) is set in 6 of the 35 analysed frameworks.

The shift from energy consumption to a GHG emissions-based metric can be found in 13 building assessment approaches from 11 countries. In Finland, the National Green Building Council follows a government standard [75] which proposes low-carbon building regulations (Type G4. e) based on the normative life cycle GHG emissions limits for different building types, which are planned to be published by the Finnish government.

The requirement for net zero GHG emissions from the operational life cycle module (type G5. a, G5. d) is implemented in building assessment approaches from four countries: Australia, South Africa, New

Zealand, and the USA (LEED zero carbon [78]). In all these assessments approaches, the GHG emissions from embodied life cycle modules are outside of the assessment scope (Type G5. a), except New Zealand (Type G5. d), where all new buildings need to be constructed with 20% fewer embodied GHG emissions relative to the baseline scenario by 2025.

The significance of including the embodied GHG emissions is highlighted in all these frameworks and is planned to be included in the next revision of the building assessment approaches. The declaration of developing criteria and requirements addressing embodied GHG emissions in the South Africa scheme is made conditional on construction market interests.

The more ambitious performance target requirement can be found in

Table 3
Overview of the methodological features extracted from the analysed building assessment approaches.

Feature	Description of analysed information
General data (First step of data extraction from 35 building assessment approaches)	
Status and launching year	The legal status of standard/scheme (voluntary, mandatory, framework draft) with launching year.
Founder	The initiator of standard/scheme (government, non-government organisation (NGO) or research organisation).
Object of assessment	Application scale of standard/scheme (single building, neighborhood, building stock)
Metric	Indicator/metric of building performance (primary energy, delivered energy of GHG emissions)
Type of regulation	Type of regulation and performance requirements according to Table 2 (Section 2.5.2)
Detailed data (Second step of data extraction from 13 building assessment approaches)	
Modules in relation to building operation	
System boundaries	Scope of life cycle modules included in the operational life cycle module.
Electricity GHG emissions factor	Principle for environmental-impact assessment of electricity use (average, marginal, hybrid).
Approach to “time” factor	Approach to “time factor” in operational life cycle impact assessment (static vs dynamic modelling).
Verification requirements of building performance	Type of data and performance indicators, which needs to be verified during the real-time operation of certified building.
Modules in relation to production, construction replacement and end-of-life	
System boundaries	Scope of life cycle modules included in embodied life cycle modules.
LCA data source	Reference to calculation standard, recommended LCA database, calculation software.
Approach to “time” factor	Approach to “time factor” in embodied life cycle impact assessment (static vs. dynamic modelling).
Principles/possibilities for GHG emissions balance/compensation	
Renewable energy generation	Possibilities of allowed ways of renewable energy generation/supply. Allocation of exported energy outside the system boundaries.
Other compensation methods	Options for compensation other than renewable energy generation—e.g., biogenic carbon storage, negative carbon technologies, off-set credits/certificates.
Timing of compensation	What is the time frame for a building to become “GHG emissions net zero/neutral”?

the building assessment approaches from Canada, France (EQUER [81]), Germany, Norway, Sweden, the UK, and the USA (zero carbon [87]), all of which aim to achieve a net zero GHGs emissions balance considering the full life cycle scope (type G5. f and G5. h).

4.2. Detailed methodological features from GHG emissions-based building assessment approaches

4.2.1. System boundaries scope and approach to the aspect of “time” in operational life cycle module

Detailed information about the system boundaries and approach to a “time” factor in the operational module assessment in the building assessment approaches analysed in this article is presented in Table 5 below. The details and clarification of the different performance levels occurring in the respective building assessment approach are presented in the Appendix section (Table A2).

Table 4
Regulation type recognised in the analysed building assessment approach.

Regulation type	Description	Country code and building assessment approach reference
PE 3. a	The operational part of energy consumption of the building is regulated by minimum, voluntary requirements (limit values expressed as maximum demand for primary energy, non-renewable) introduced in the building assessment approach. The embodied part is ignored.	CN [54]
PE 4. a	The operational part of energy consumption of the building is regulated by minimum, mandatory requirements (limit values expressed as maximum demand for primary energy, non-renewable) introduced in national law. The embodied part is ignored.	AT [55], BE [56], CZ [57], DK [58] FR [59], HU [60], IT [61], JP [62,63], NL [64], PL [65], PT [66], SI [67]
PE7.d	The operational part of the non-renewable, primary energy consumption of the building is balanced and regulated by maximum limits included in the building assessment approach. Embodied non-renewable, primary energy consumption is mandatorily limited by a value introduced in the building assessment approach.	CH [68]
DE7.a	The operational part of the energy consumption (delivered energy) of the building is balanced and regulated by maximum limits included in the building assessment approach. The embodied part is excluded.	BR [69], IN Ref. [70], ES [71], KR [72], SG [73], US [74]
G4. e	Both the operational and embodied part of GHG emissions of the building are mandatorily regulated and limited by law.	FI [75]
G5. a	The operational part of GHG emissions of the building is balanced by an individual building assessment approach. The embodied part is excluded.	AU [76], ZA [77], US [78]
G5. d	The operational part of GHG emissions of the building is balanced by an individual building assessment approach. The embodied part of the GHG emissions of the building is mandatorily limited by the values introduced in the building assessment approach.	NZ [79]
G5. f	Both the operational and embodied parts of the GHG emissions of the building are balanced by an individual building assessment approach.	CA [80], FR [81], DE [82], NO [83], SE [84], UK [85]
G5.h	The operational part of the GHG emissions of a building is balanced by an individual building assessment approach. The embodied part of the GHG emissions of the building is balanced and limited by maximum values introduced in the building assessment approach.	SE [86], US [87]

Table 5
System boundaries and approach to the time factor in an operational impact assessment.

Scope of operational impact assessment								
Country	Building assessment approach and performance level	B6.1	B6.2	B6.3	B7	B8	Assessment principle on GHG emission factor of the electricity mix	Approach to the aspect of “time”
Australia	Carbon neutral: whole building operation	X	X	X	X		Average	Static
Canada	Carbon neutral: base building operation	X	X				Hybrid	Static
Finland	Zero-carbon building	X		X			Average	Dynamic, because, during the reference study period, energy-based emissions are expected to decrease as a result of the measures under Finland’s National Energy and Climate Strategy.
France	Method for the whole-life carbon assessment of buildings	X					Marginal	Dynamic, considering the hourly variation of emission factors from energy sources
Germany	EQUER	X	X	X	X	X	Average	Dynamic, considering future emission factors from energy sources
	Carbon-neutral building standard (DGNB) Framework	X	X	X			Average	Dynamic, considering future emission factors from energy sources
Norway	Zero-emission building: ZEB: O-EQ level	X					Average	Dynamic, assuming the average value of electricity emission factor that is representative of a 60-year building lifetime, taking into consideration future evolutions in the European electricity generation towards 2050
	Zero-emission building: ZEB:O, ZEB:OM, ZEB:COM and ZEB:COME level	X		X			Average	Static
New Zealand	The Zero Carbon Road Map for Aotearoa’s Buildings	X	X	X	X		Average	Static
South Africa	Net zero and net positive carbon building: Level 1 (Base building emissions)	X	X				Average	Static
	Net zero and net-positive carbon building: level 2 (occupant emissions)	X	X	X			Average	Static
Sweden	NollCO2	X	X	X	X		Hybrid	Dynamic, considering the future evolution of the electricity mix to be carbon-neutral in 2050
	Local Roadmap Malmö	X	X				Average	Static
United Kingdom	Net zero carbon: operational energy and whole life	X					Average	Static
USA	LEED zero carbon	X	X	X	X	X	Average	Static
	Zero-carbon building	X	X	X	X		Average	Static

approaches from the USA (LEED zero carbon [78]) and France (EQUER [81]).

In most of the analysed building assessment approaches, the “average electricity” principle of assessing the GHG emissions from the electricity mix is employed. The EQUER design tool uses the “marginal electricity mix” approach, which can be defined for past years (historical mix) or for a long-term period (future scenario) [88]. In order to identify the short-term marginal mix, the different energy production sources are ranked according to merit order. Renewable energy sources (solar, wind) that cannot be adjusted to the power demand are at the bottom of this ranking, while adjustable technologies with the lowest constraints and the highest cost are at the top of the hierarchy. Both the Canadian “Zero carbon” and Swedish NollCO₂ frameworks present a hybrid use of the average and marginal electricity mix factor [80,86]. The emission factor for the average supply mix is used for estimating the GHG emissions from electricity use in the building. In contrast, the marginal emission factor approach is employed to determine the environmental benefits from locally produced electricity exported to the grid.

By comparing the approach of the respective standard to the “time” factor in the operational GHG emissions assessment, a significant variance was found. Six building assessment approaches follow the static approach, with a constant emission factor of electricity or district heating used during the entire service life or reference study period, while seven frameworks present a dynamic approach. Here, the dynamic approach proposed in the Swedish frameworks considers the further decarbonisation of the national electricity grid by 2050. A similar approach is proposed in Finland; however, here, the full decarbonisation of the electricity grid is expected to be achieved by 2120. The German example considers a reduction in the electricity emission factor from the actual 589 gCO_{2eq}/kWh to 354 gCO_{2eq}/kWh in 2050. In France, the EQUER method takes into consideration the dynamic approach by including an hourly variation in the emission factors from energy sources, which provides a more accurate assessment of the operational GHG emissions. In contrast to the building assessment approaches, where the decrease in the energy-related emissions with the time is expected, in Norway the ZEB framework uses the electricity emission factor (134 gCO_{2eq}/kWh), which is higher than the actual values used for GHG emissions of hydro-based electricity (15 gCO_{2eq}/kWh) and takes into account the hourly export and import of electricity to/from Nordel and the European grid and also takes into account the future decarbonisation of the grid (Statistic Norway, 2019, Graabak and Feilberg, 2011 [42]). The implementation of dynamic electricity factors, which will take into account grid variations in the GHG emission intensity, is stated as a key priority for the future development of a net zero-carbon framework in the UK [85]. The GHG emission factor of electricity presents a strong influence on the relative contribution of embodied emissions to the total GHG emissions [44]. In the case of a high emission factor, the operational GHG emissions dominate the embodied emissions, while a low emission factor leads to the opposite case. 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.

Most of the reviewed building assessment approaches mandate the verification of the net zero GHG emissions performance of designed buildings using on-site metered data during the first year of building operation. However, the verification of an embodied GHG emissions calculation using the actual bills of construction materials and products, as well as metered energy used for the actual on-site construction process, is not common among the building assessment approaches. The detailed information is presented in Table A3 in the Appendix.

4.2.2. Life cycle embodied modules

4.2.2.1. *System boundary of the embodied life cycle impacts.* By comparing the system boundaries covered in the building assessment

approaches (Table 6), it can be indicated that the product stage (A1-A3), construction (A4-A5), and replacement (B4) modules are the most common impacts included in the life cycle scope of embodied modules. A significant number of the building assessment approaches do not take into consideration the impact coming from the transportation process to and from the site (modules A4 and C2 according to EN15978), construction work (A5), use and repair processes (B1 and B3), demolition work (C1), or the waste management process (C3-C4). The reason for this exclusion may be often related to time-consuming calculations and significant remaining gaps in the availability of data on the GHG emissions of related life-cycle phases [85]. A solution for addressing this issue is presented in the Finnish framework which consists of introducing generic, predefined GHG emissions values which can be used in the cases where specific information is unavailable. The Norwegian (net) zero-emission building framework is the only one which includes different levels of performance requirements based on the embodied, life cycle modules scope. Among the analysed building assessment approaches, module D (benefits and loads outside the system boundaries) is included in all the selected building assessment approaches. Furthermore, in the current draft of Sweden’s approach and the Norwegian definition, the potential benefits from the reuse, recovery, and recycling of building products are only reported as additional information. This way to deal with Modul D is in line with the current CEN TC 350-related European standards.

4.2.2.2. *Main source of LCA data and approach to the aspect of “time”.* Most of the methodological approaches described in the analysed building assessment approaches (Table 5) suggest using the specific environmental product’s declaration (EPD), supplemented by a generic, national LCA database as the main data source for the calculation and reporting of life cycle GHG emissions. The need for a reliable, country-specific LCA database is highlighted in the Finnish and Swedish building assessment approaches, where a generic national LCA database is missing and is currently under development.

A static approach to the “time” factor in embodied GHG emissions assessment during the building lifespan is evident in most of the analysed building assessment approaches (Table 7), except for Sweden (NollCO₂ scheme), where the GHGs emissions from the end-of-life stage (C1-C4) are assumed to be zero, due to the assumption of carbon neutrality when taking into account the life cycle of all activities up to 2050. The only exception from the static approach suggested in the Norwegian approach is the environmental impact caused by the replacement of PV modules. Here, based on the continuous improvement of new technologies and material use, as well as prospective LCA studies, a 50% reduction in the GHG emissions relative to product stage impact (A1-A3) is applied as a rule of thumb [44,83].

4.2.3. Options and principles of GHGs emissions compensation

An overview of the allowed options for GHG emission compensation by the analysed building assessment approaches is presented in Table 8.

The building assessment approaches from Australia, Canada, France, New Zealand, South Africa, the UK, and New Zealand allow balancing the life cycle GHG emissions by “avoided” GHG emissions outside the system boundaries of the buildings life cycle with the generation of renewable energy from both on-site and off-site levels of system boundaries. However, in the case of Australia, the UK, and South Africa, the building assessment approaches suggest prioritising on-site energy generation. By contrast, according to the building assessment approaches from Finland, Germany, Norway, and Sweden, the production of renewable energy must be located on-site, with the additional possibility of using off-site renewables (e.g., biofuels) for the production of energy on-site.

According to the available information in all the approaches used in the selected frameworks, the exported energy-related benefits—namely, avoided GHG emissions outside the system boundaries—become a part

Table 6
System boundaries of embodied impacts in the analysed building assessment approaches.

Life cycle scope of embodied modules																	
Country	Building assessment approach and performance level	A1 Raw material supply	A2 Transport	A3 Manufacturing	A4 Transport	A5 Construction-installation process	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	C1 Deconstruction and demolition	C2 Transport	C3 Waste processing	C4 Disposal	D Reuse-Recovery-Recycling	
Canada	Zero-carbon building	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
Finland	Whole-life carbon assessment of buildings	X	X	X	✓	✓			X	X		✓	✓	✓	✓	✓	
France	EQUER	X	X	X	X	✓				X	X		X	X	✓	X	
Germany	Carbon neutral building standard (DGNB) framework. carbon-neutral building throughout life cycle ambition	X	X	X			✓	X		X				X	X	X	
Norway	Zero-emission building: ZEB:OM ambition	X	X	X				✓		✓							
	ZEB:COM ambition	X	X	X	X	✓		✓		✓							
	ZEB: COME ambition	X	X	X	X	✓		✓		✓		✓	✓	✓	✓	✓ ¹	
Sweden	NollCO2	✓	✓	✓	X	X		✓	✓	✓	✓	✓	✓	✓	✓	✓ ¹	
	Local Roadmap Malmö	✓	✓	✓	X	X	✓	✓	✓	✓	✓	n/c	n/c	n/c	n/c		
United Kingdom	Level I: net zero-carbon construction	✓	✓	✓	✓	✓											
USA	Zero-carbon building	✓	✓	✓	✓											✓	

X: included with details; ✓: included without details; n/c: not clear.

¹ only as additional information.

Table 7
Main LCA data source and approach to the “time” factor in building assessment approaches.

Country	Standard and performance level	Reference to LCA calculation standard, tool or database source	Approach to ‘time’ factor
Canada	Zero-carbon building	No specific recommendations, however the Athena Impact Estimator and Tally LCA tools are mentioned.	Static
Finland	Whole-life carbon assessment of buildings	Reference to the national method of the whole life cycle carbon assessment of buildings and generic LCA database (under development).	Static
France	EQUER	Eco invent database.	Static
Germany	Carbon-neutral building throughout life cycle ambition	ÖKOBAUDAT, GEMIS, and other possible data sources, such as environmental product (EPD) declarations following EN 15804 standard, are referred to.	Static
Norway	Zero-emission building:	Specific (EPD) data from EPD-Norge. When EPDs are not available, generic Life Cycle Inventory (LCI) data from Eco invent are used.	Static, except PV modules, where a 50% reduction in the embodied emissions during the replacement phase is assumed.
Sweden	NollCO2	Generic national database (under development) and EPD declarations.	The method assumes that all life cycle activities 2050 will be carbon neutral; this is why the impact of the end of life module (C1–C4) is considered to be equal to zero. Not clear
United Kingdom	Local Roadmap Malmö Level I: net zero-carbon construction	RICS professional statement “Whole life carbon assessment for the built environment”, 2017.	Static
United States of America	Zero-carbon building	Carbon data should be sourced from EPDs and verified, as outlined in the ISO 14025 standard. Approved LCA tools: Athena Impact Estimator, eTool, One Click LCA, Tally, Environment Agency’s Carbon Calculator.	Static

of the GHG emissions balance and contribute to the net zero-emissions approach, which is in line with the A. a approach [49]. This approach is not in line with the current standards, which require that the environmental benefits and loads coming from exported energy should be included as additional information in module D. Consequently, there is a need to address these methodological issues.

Recognised compensation possibilities by the implementation of carbon-negative technologies (Type C from Lützkendorf and Frischknecht, 2020 [49]) mainly include reforestation programs, carbon sequestration investments, or implementing energy efficiency measures in existing surrounding buildings.

In the case of building assessment approaches which allow the compensation of GHG emissions through the use of renewable energy certificates or off-set credits (Type B), priority is given to carbon credits units traded in the national market.

5. Conclusions and recommendations

During the past few years, the attention given to reducing operational energy demand and resulting environmental impacts in the construction sector has increased significantly. In many countries, national governments have established mandatory policy frameworks, introducing nearly zero-energy buildings in operation as their main building stock ambition. Government incentives are often supported by voluntary certification schemes, which are meant to push building ambitions to reach a (net) zero-energy building level in terms of operation, where the total amount of operational energy used by the building is compensated mainly by renewable energy generation on a typically annual basis.

However, in order to achieve carbon neutrality in the construction and real estate sector by 2050 or earlier and, at the same time, meet the climate Paris Agreement Goals, there is a need for accelerating sector decarbonisation by developing and implementing the net zero GHG emissions buildings (operation or life cycle-related) approach, which introduces GHG emissions as a primary performance indicator and formulates requirements for climate neutrality throughout the whole life cycle.

Based on the current review of 35 building assessment approaches, the present authors identified 13 voluntary frameworks from 11 countries, characterised by net zero-carbon/GHG emissions performance targets. There is a significant variance in the methodological principles and approaches between these frameworks. In order to rule out misunderstandings and greenwashing, the key methodological factors from

the building assessment approaches were identified, explained, and analysed. One of the proposals suggested by the authors is to extend the scope of the operational energy module (B6) and develop a systematic approach which defines the performance target of the building on the basis of a different energy or emissions system balance.

The results of the review identified that the definition type, scope of system boundaries, choice of an average vs. marginal emission factor for the electricity mix, approach to the aspect of “time”, and options for compensation are the most important issues and should be carefully considered before developing and defining a harmonised (net) zero-GHG emissions building framework.

General recommendations which should be included in the further development of the country-specific assessment approach or the definition of net zero-carbon/emissions buildings are presented below:

- The current, voluntary, and new (net) zero-GHG emissions building assessment approaches should be integrated into national and local policy frameworks with the aim to significantly increase the share of (net) zero-GHG emissions buildings in the building stock. This action needs to be supported by voluntary building certification schemes, which should recognise the (net) zero-GHG concept as the next and more ambitious goal.
- To overcome the limitations in the design and construction of specific types of new buildings or retrofitting of existing buildings, the net zero-carbon/GHG emissions building definitions should provide some flexibility in terms of the performance target level based on the selected system boundary scope. However, here the authors propose that at the lowest performance target level, the complete scope of the B6 module (B6.1, B6.2, and B6.3) impacts should be included and balanced. Additionally, the building design and construction should follow the minimum requirements for the embodied emissions aspect based on the national benchmarks being developed.
- The performance of net zero GHG emissions buildings for the operational aspect during the use stage should be mandatorily verified during building operation by an on-site energy monitoring system combined with the use of dynamic hourly GHG emission factors for energy sources. The use of “marginal electricity” emission factors for specific building site location conditions is recommended.
- The implementation of energy efficiency measures should be prioritised, with the setting of energy use intensity targets (EUI) for both new and existing buildings. These requirements should prevent

Table 8
Options for compensation allowed in the analysed building assessment approaches.

Type of compensation following Lützkendorf and Frischknecht, 2020 [49]		“Avoided” GHG emissions from renewable energy generation Type A.a					Type A.b	Type B	Type C	
Country	Building assessment approach	On building area	On-site from on-site renewables	On-site from off-site renewables	Off-site generation	Off-site supply		Renewable energy certificates/off-set credits	Implementation of negative carbon technologies	Timing of GHG emissions compensation
Australia	Carbon neutral	X	X	X	X ²	X ²		X		Annually
Canada	Zero-carbon building	X	X	X	X	X		X		Annually
Finland	Whole-life carbon assessment of buildings	X	X	X						Annually
France	EQUER	X	X	X	X	X				Building lifetime
Germany	Carbon-neutral building standard (DGNB) framework	X	X	X						Annually
Norway	Net zero-emission building	X	X	X						Building lifetime
New Zealand	The Zero-Carbon Road Map for Aotearoa’s Buildings	X	X	X	X	X		X	X ^a	Annually
South Africa	Net zero and net positive carbon buildings	X	X	X	X ^b	X ^b		X ^b		Annually
Sweden	NollCO2	X	X	X	n/c	n/c		X	X ^c	Building lifetime
	Local Roadmap Malmö	X	X	X					X ^d	Building lifetime
United Kingdom	Net zero carbon	X	X	X	X ^b	X ^b		X ^b		Annually
USA	LEED zero carbon	X	X	X	X	X		X		Annually
	Zero-carbon building	X	X	X	X	X		X	X ^e	Annually

X: Allowed option.

^a Reforestation, carbon reduction programs in developing countries, carbon sequestration investments.

^b On-site renewable generation is prioritised.

^c Life cycle GHG emissions can be compensated by implementing energy efficiency measures in other existing buildings.

^d Carbon capture and storage.

^e Renewable energy projects, reforestation projects, and landfill gas-to-energy projects where the methane would otherwise be released to the atmosphere.

buildings which are highly energy-inefficient from achieving the net zero-carbon/GHG emissions performance target level.

- The energy flexibility of net zero-GHG emissions building designs should be a key design asset and take into consideration further scenarios, assuming a constant reduction in the GHG emission intensities of electricity mixes towards (nearly) zero, and the more extensive use of intermittent energy sources such as solar or wind.
- Building assessment approaches should allow for a variety of compensation solutions and not only focus on on-site renewable generation solutions, as this strategy is mainly suitable for new and relatively small buildings. However, due to its higher efficiency and credibility, off-setting by on-site renewable generation should instead be prioritised. To ensure transparency in published results, standards and schemes should prescribe that the two sides of the balance are always provided separately. This is also in line with ISO 16475-1 (2017), which advises that, in the case of on-site energy production, the amount of exported energy is reported as additional information.
- There is a need to move the object of assessment in the form of a single building to a broader scope, including neighbourhoods, cities, or even national building stocks to facilitate GHG emission reductions at a larger scale. This is important, since it allows neighbourhoods/cities/nations to make exceptions for specific building cases which cannot achieve a net zero GHG emission level in a technically feasible manner if other buildings can compensate.

It is evident that variations are found in the existing schemes in the ways of thinking about a common theme—(net) zero greenhouse gas-emission buildings—and will continue to exist. These variations raise some important questions about how this concept is evolving. A typology of system boundaries and other dimensions, as presented in this paper, can foster transparency and, consequently, confirm the credibility of current approaches.

Outlook

The presented research results are part of ongoing research activities in the IEA EBC Annex 72: Assessing Life Cycle-Related Environmental Impacts Caused by Buildings. A final series of guidelines and reports summarising research outputs will be published in 2022.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.buildenv.2021.107619>.

Explanation of the authors' contributions

This article was created in close cooperation between the authors who, besides A. Gustavsen, also cooperate in the IEA EBC Annex 72. T. Lützkendorf and M. Balouktsi coordinated subtask 1 (ST1) of this project. As part of the work of ST1, an expert survey was prepared, carried out, and evaluated. The authors involved in IEA EBC Annex 72 jointly developed the concept for the survey and the questionnaire. The methodical part of this contribution was worked on by T. Lützkendorf and M. Balouktsi, with support from D. Satola. The actual analysis and discussion of the results were carried out by D. Satola. A. Houlihan Wiberg and A. Gustavsen supported the analysis and the development of conclusions. The recommendations for action were developed jointly.

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