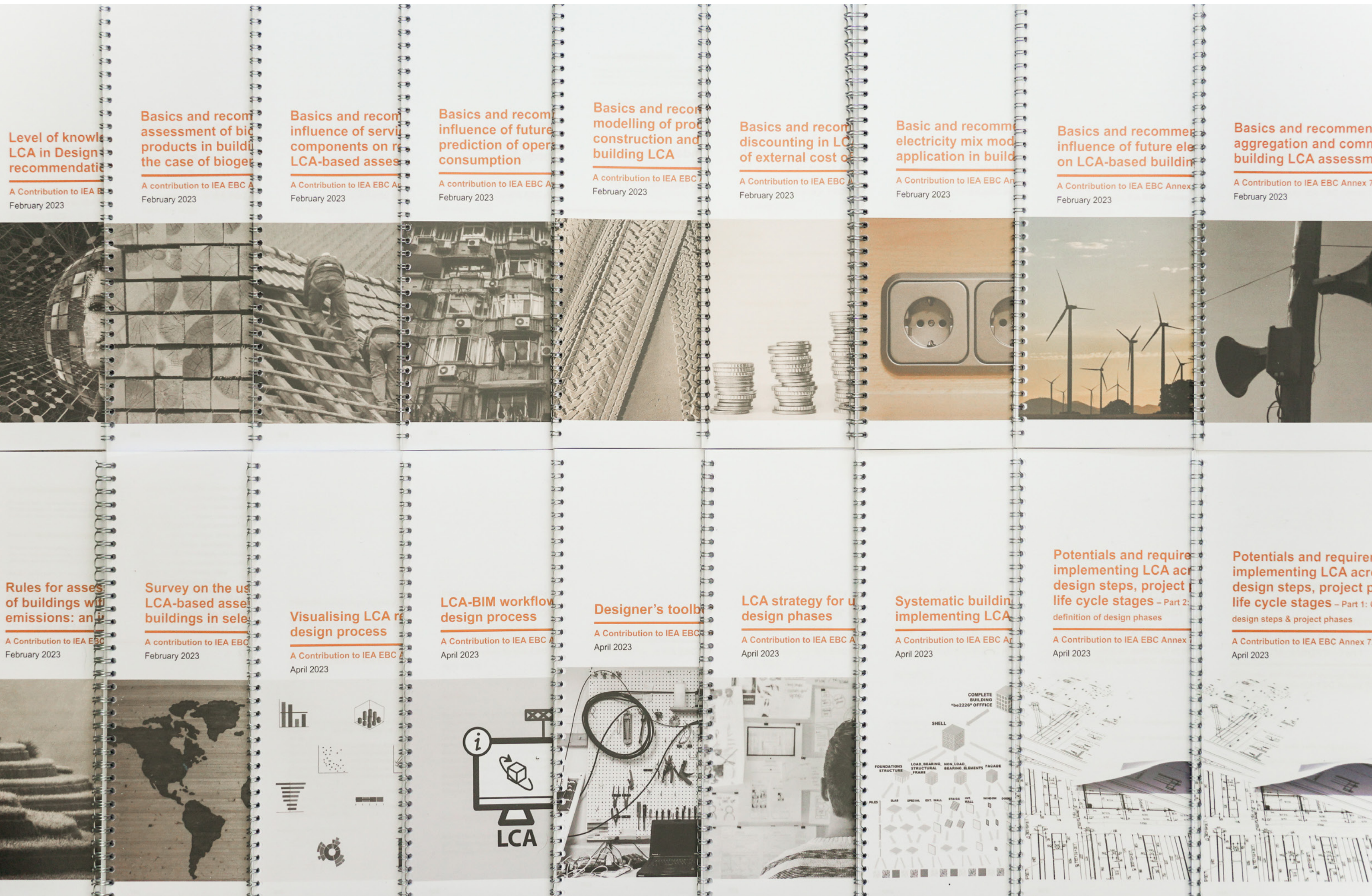
IEA EBC Annex 72

Background information

Assessing life cycle related environmental impacts caused by buildings

May 2023



Imprint:

Published by 2023 Verlag der Technischen Universität Graz, www.tugraz-verlag.at

Editors: Rolf Frischknecht, Thomas Lützkendorf, Alexander Passer, Harpa Birgisdottir, Chang-U Chae, Shivakumar Palaniappan, Maria Balouktsi, Freja Nygaard Rasmussen, Martin Röck, Tajda Obrecht, Endrit Hoxha, Marcella Ruschi Mendes Saade

ISBN: 978-3-85125-953-7
DOI: 10.3217/978-3-85125-953-7
Cover picture: prepared by Sustainable Construction, Institute of Structural Design, Technical University Graz

The official reports from IEA EBC Annex72 are available at following website:
https://annex72.iea-ebc.org/publications

Funding
The work within Annex 72 has been supported by the IEA research cooperation on behalf of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology via the Austrian Research Promotion Agency (FFG, grant #864142), by the Brazilian National Council for Scientific and Technological Development (CNPq, (grants #306048/2018-3 and #313409/2021-8), by the federal and provincial government of Quebec and Canada coordinated by Mitacs Acceleration (project number IT16943), by the Swiss Federal Office of Energy (grant numbers SI/501549-01 and SI/501632-01), by the Czech Ministry of Education, Youth and Sports (project INTEREXCELLENCE No. LTT19022), by the Danish Energy Agency under the Energy Technology Development and Demonstration Programme (grant 64012-0133 and 64020-2119), by the European Commission (Grant agreement ID: 864374, project ATELIER), by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME) in France (grant number 1704C0022), by the Federal Ministry of Education and Research (BMBF) and the Federal Ministry for Economic Affairs and Climate Action (BMWK, the former Federal Ministry for Economic Affairs and Energy (BMWi)) in Germany, coordinated by the project management agency PTJ (project numbers 03SBE116C and 03ET1550A), by the University of Palermo - Department of Engineering, Italy, by the Research Centre for Zero Emission Neighbourhoods in Smart Cities (FME ZEN) funded by the Norwegian Research Council (project no. 257660), by the Junta de Andalucía (contract numbers 2019/TEP-130 and 2021/TEP-130) and the Universidad de Sevilla (contract numbers PP2019-12698 and PP2018-10115) in Spain, by the Swedish Energy Agency (grant number 46881-1), and by national grants and projects from Australia, Belgium, China, Finland, Hungary, India, The Netherlands, New Zealand, Portugal, Slovenia, South Korea, United Kingdom, and the United States of America.

Acknowledgement
The editors thank the authors of the IEA EBC Appendix 72 background reports summarized here and those who contributed in their preparation. Their names are listed on the cover page of each background report. Thanks are also due to all colleagues (from Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Denmark, France, Germany, Hong Kong, Italy, Korea, Netherlands, New Zealand, Norway, Austria, Portugal, Spain, Sweden, Switzerland, United Kingdom, USA, as well as Hungary, India and Slovenia) who supported the preparation of the background reports with their contributions.

IEA EBC Annex 72 Background information

Assessing life cycle related environmental impacts caused by buildings

May 2023

Editors

Rolf Frischknecht
Thomas Lützkendorf
Alexander Passer
Harpa Birgisdottir
Chang-U Chae
Shivakumar Palaniappan
Maria Balouktsi
Freja Nygaard Rasmussen
Martin Röck
Tajda Obrecht
Endrit Hoxha
Marcella Ruschi Mendes Saade

Abstract:
The IEA EBC Annex 72 project continued research already conducted under EBC Annex 56 and 57. It extends the scope of Annex 57, which focused on building-related "grey" components of an LCA, to include the operational impacts of building use. In addition to primary energy demand and greenhouse gas emissions, Annex 72 considered other environmental impacts.

The project addressed, among other things, issues of standardization of methodological principles that arise when applying LCA approaches to buildings. It serves as a platform for the exchange of experience and knowledge within the partner countries and promotes the application of LCA to buildings in countries that have little experience.

The objectives of the IEA EBC Annex 72 were:

- Establish and standardize baselines for assessing life-cycle primary energy demand, greenhouse gas emissions, and environmental impacts of buildings, and develop proposals for the development of national or institutional calculation and assessment rules.
- Development of bases for the development, application and interpretation of environmental benchmarks for different building types
- Derive regionally differentiated guidelines and tools to support design decisions for buildings, such as BIM for architects
- Collection and analysis of case studies to support evaluation of real-world application experiences

The results are available in the final and background reports of IEA EBC Annex 72, including the book “IEA EBC Annex 72 Background Information: Assessing life cycle related environmental impacts caused by buildings” collected here.

Kurzfassung:
Das Projekt IEA EBC Annex 72 führte die bereits im Rahmen der EBC Annex 56 und 57 durchgeführten Forschungsarbeiten fort. Es erweitert den Anwendungsbereich von Annex 57, der sich auf gebäudebezogene „graue“ Anteile einer Ökobilanz konzentrierte, um die betriebsbedingten Auswirkungen der Gebäudenutzung. Zusätzlich zum Primärenergiebedarf und den Treibhausgasemissionen wurden im Annex 72 weitere Umweltwirkungen berücksichtigt.

Das Projekt behandelte u.a. Fragen der Vereinheitlichung methodischer Grundlagen, die sich bei der Anwendung von LCA-Ansätzen auf Gebäude ergeben. Es dient als Plattform für den Erfahrungs- und Wissensaustausch innerhalb der Partnerländer und fördert die Anwendung von Ökobilanzen für Gebäude in Ländern, die noch wenig Erfahrung haben.

Die Ziele des IEA EBC Annex 72 waren:

- Erstellung und Vereinheitlichung von Grundlagen zur Bewertung des lebenszyklusbasierten Primärenergiebedarfs, der Treibhausgasemissionen und der Umweltauswirkungen von Gebäuden sowie Erarbeitung von Vorschlägen für die Erarbeitung nationaler oder institutioneller Berechnungs- und Bewertungsregeln
- Entwicklung von Grundlagen für die Entwicklung, Anwendung und Interpretation von umweltbezogenen Benchmarks für verschiedene Gebäudetypen
- Ableitung von regional differenzierten Leitlinien und Instrumenten zur Unterstützung von Entwurfsentscheidungen bei Gebäuden, wie z. B. BIM für Architekten
- Sammlung und Analyse von Fallstudien zur Unterstützung der Auswertung realer Anwendungserfahrungen

Die Ergebnisse sind in den End- und Hintergrundberichten des IEA EBC Annex 72 verfügbar, darunter im hier vorliegenden Buch „IEA EBC Annex 72 Background Information: Assessing life cycle related environmental impacts caused by buildings“ gesammelt.

Table of content

Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey

A Contribution to IEA EBC Annex 72

February 2023

Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey

A Contribution to IEA EBC Annex 72

February 2023

Authors

Daniel Satola, NTNU, Norway (daniel.satola@ntnu.no)

Maria Balouktsi, KIT, Germany,

Thomas Lützkendorf, KIT, Germany

Aoife Houlihan Wiberg, UU, United Kingdom

Reviewed by:

Bruno Peuportier, MINES ParisTech, France
Rolf Frischknecht, TREEZE, Switzerland

Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Benchmarking and target-setting for the life cycle-based environmental performance of buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

– Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
– Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
– Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
– Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
– Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
– Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
– Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
– Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
– Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
– Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
– Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al. 2023).

It is important to mention that the analysis of net zero definitions in this report is based on a survey among experts which was realized during the first half of 2020. The authors would like to acknowledge the following survey contributors: Seongwon Seo (AU), Damian Trigaux (BE), Claudiane Ouellet-Plamondon (CA), Panu Pasanen (FI), Wei Yang (CN), Harpa Birgisdottir and Freja Rasmussen (DK), Bruno Peuportier (FR), Erik Alsema (NL), Dave Dowdell (NZ), Marianne Kjendseth Wiik (NO), Ricardo Mateus (PT), Antonio García (SP), Tove Malmqvist and Nicolas Francart (SE), Rolf Frischknecht and Livia Ramseier (CH) Jane Anderson (UK), Siva-kumar Palaniappan (IN), Tajda Potrc Obrecht (SI).

Summary

Introduction

Around 40% of global CO_2 emissions can be attributed to the construction, maintenance, and use of buildings. Reducing these greenhouse gas (GHG) emissions is an essential goal in the context of sustainable development (IEA 2019). This is expressed, among other things, in SDG 13: Climate change. Reducing these emissions requires considerable efforts from all those involved in the construction and building sector as actors, decision makers and service providers, including upstream and downstream industries. In order to be able to design and implement appropriate reduction measures, the calculation and assessment of GHG emissions in the life cycle of buildings with the help of indicators, calculation rules, assessment methods and benchmarks is a prerequisite. Particularly benchmarks provide the basis for requirements for carbon performance as part of the environmental performance of buildings. They can be used both in the context of sustainability assessment systems, funding programs, building standards, and policymakers' actions as well as provide the basis for individual design targets.

A new approach is the top-down derivation of benchmarks in an effort to respect planetary boundaries. This involves protecting the natural basis of life by ensuring that future new construction and refurbishment measures lead to buildings with (almost) no negative effects on the climate during their lifecycle which led to the "climate-neutral building" approach in line with numerous are global initiatives.

Objectives and contents of the report

The main aim of the present report was to analyse the status of the discussion on "climate-neutral" buildings and to develop proposals for the standardization of terms, definitions, system boundaries and rules for assessment and communication. At a minimum, these recommendations should be viewed as a means for improving transparency and traceability which should also be drawn up to maintain the credibility of the relevant statements.

Although not exhaustive, key international initiatives were identified and analysed that could relate to the topic of "climate-neutral buildings". Key thematic areas which were investigated include (1) terms and definitions, (2) system boundaries for the recording and assessment of GHG emissions, (3) calculation and evaluation rules, (4) balancing and offsetting options when demonstrating "climate neutrality".

Key findings arising from the analysis

Significant differences were found in all the thematic areas examined which makes it difficult to compare the approaches directly, however, the following key points can be deduced:

– **The survey showed that great variations exist in current schemes about (net) zero greenhouse gas emissions buildings (as an alternative term to "climate neutral building") and will probably continue to exist.** These variations raise some important questions on how this concept is evolving. At the minimum, the transparency of the declaration and communication of the system boundaries, calculation, and evaluation rules as part of an assessment process, as well as balancing and offsetting options, must be improved. It is recommended that such information be made publicly accessible.

– **Various terms are used by various countries to describe (net) zero approaches which often leads to confusion.** It is recommended to use the term climate-neutral only colloquially, but to use the term "(net) greenhouse gas-neutral" or "(net) zero GHG-emissions" for approaches in assessment systems, funding programs or legislation. It is also recommended to distinguish between 'absolute' and 'net zero' GHG emissions (as proposed and explained by Lützkendorf and Frischknecht (2020)) and between greenhouse gas neutral (1) in operation, (2) in operation including supply chains (upstream and downstream) and (3) in the life cycle.
– **The survey showed that range of activities included in the operation itself varies;** Some approaches focus on balancing only the regulated building-related energy demand (B6.1), while others also include the non-regulated building-related part (B6.2) and/or user-related energy part (B6.3). The increasing use of renewable energy to the point of the obligation to install systems on the building or on its site makes it necessary to deal methodically with questions relating to BIPV, among other things. It also forces to expand the traditionally considered system boundaries within Module B6. It would be useful to include Modules B6.2 and B6.3 to be able to represent the self-consumed share of the energy generated on-site in a more complete fashion.
– **Most approaches currently follow a net-balance approach with on-site energy generation options, where the embodied impacts of parts of the generated energy exported to third parties and its potentially avoided emissions form also part of the balance (not only the self-used part).** This is indicated in the present report as Type Aa approach. However, when dealing with the effects of exported energy (here potentially avoided emissions from third parties), it is recommended to use solutions that do not involve the risk of double counting. Perhaps such issues will be treated under the ongoing standardization activities recently started for a new standard ISO 14068 about 'Carbon neutrality'.
– **Several approaches allow a variety of balancing and offsetting measures to achieve the net zero status.** However, it should be made sure that the excess use of such measures shall be avoided in order to prevent buildings which are highly energy inefficient from achieving the net-zero carbon/GHG emissions target level. The implementation of energy efficiency measures shall be prioritised with the setting of energy use intensity targets (EUI) for both new and existing buildings. Additionally, it is recommended to ask for the reporting of the results (i.e. achievement of net-zero status) in such a way that both parts of the balance are visible, i.e. the carbon footprint of the building and the amount and kind of offset emissions.

Table of content - K

Abbreviations

Abbreviations	Meaning
AU	Australia
AT	Austria
BE	Belgium
BECSS	Biogenic energy resources with carbon capture and storage
BIPV	Building integrated photovoltaic
BISS	Building integrated solar systems
BR	Brazil
CA	Canada
CED	Cumulated energy demand
CEN	European Committee for Standardization
CH	Switzerland
CN	China
CZ	Czech Republic
DACSS	Direct air capture with carbon separation and storage
DE	Germany
DHW	Domestic hot water
DK	Denmark
EN	European Norm
EPBD	Energy Performance of Buildings Directive
ES	Spain
FI	Finland
FR	France
GHG	Greenhouse gas
HP	Heat pump
HU	Hungary
GWP	Global warming potential
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
IN	India
IT	Italy
ISO	International Organization for Standardization
JP	Japan
KR	South Korea
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
LC	Life cycle
LCIA	Life cycle impact analysis
MJ	Mega joule; 1 kWh = 3.6 MJ

Abbreviations	Meaning
NL	Netherland
NO	Norway
NET	Negative emission technology
NRE	Non-renewable energy (fossil, nuclear, wood from primary forests)
NZ	New Zealand
NZEB	Nearly zero energy building or nearly zero emissions building or net zero emission building (depending on the country)
PE	Primary energy
PL	Poland
PT	Portugal
PV	Photovoltaic (cell or panel)
RES	Renewable energy sources
RSP	Reference Study Period
SE	Sweden
SG	Singapore
SI	Slovenia
SFB	Single family building
SDG	Sustainable development goals
UK	United Kingdom
US	United States of America
UNFCCC	United Nations Framework Convention on Climate Change
ZK	South Africa

Definitions

Potentially avoided emissions: Potentially avoided emissions are the net potential GHG emissions reduction caused by exporting renewable energy produced on-site beyond the building system boundary. This exported renewable energy potentially substitutes demand for fossil fuel derived energy outside the system boundary, e.g. as part of the national/regional grid mix. The determination of potentially avoided emissions requires the definition of a “what if” scenario

Carbon/GHG emission offset: An offset is where a measure of reduction (direct or indirect) or removal of a GHG emission is used to compensate for or neutralise a CO_2 or other GHG emission that occurs elsewhere.

Carbon/GHG emission reduction offset: a measure which reduces emissions in a source outside the value chain of the entity. Emissions can be reduced by e.g. investing in energy efficiency retrofits and renovations of other buildings. A reference scenario is needed to determine the amount of emissions reduced.

Carbon/GHG emission removal offset: measures that removes CO_2 or other GHG emission from the atmosphere.

Negative emission technologies (NETs): NETs refer to all possible options for GHG emissions removal from the atmosphere. The following general categories can be assigned to NETs (EASAC 2018): (1) Afforestation and reforestation; (2) Land management to increase and fix carbon in soils; (3) Bioenergy production with carbon capture and storage (BECCS); (4) Enhanced weathering; (5) Direct capture of CO_2 from ambient air with CO2 storage (DACCS); (6) Ocean fertilisation to increase CO_2.
Note: In some countries like Australia and New Zealand wood landfilling is considered as a partly permanent carbon storage (see: A72 background report by Saade et al. (2023) for more information). However, landfilling wood (and other organic material) does not qualify as NET in the majority of countries as it bears the risk of anaerobic digestion, producing methane and thus potentially be a substantial source of GHG emissions. That is why landfilling organic material is forbidden by law in Europe.

Energy attribute certificate (EAC): A contractual instrument that represents information about the origin of the energy generated. Various energy attribute certificates exist in a variety of markets, e.g., guarantees of origin (GOs) in Europe, renewable energy certificates (RECs) in the United States and international certificates – such as I-RECs. Unbundled EACs (such as GO, REC and I-REC) are the ones that can be purchased separately from the purchase of the generation of electricity (IRENA 2018).

1. Introduction

Since climate neutrality is a target of high priority to be achieved at different scales, such as countries, sectors, building stocks, cities, or single buildings, a clear definition and specific assessment rules are urgently needed. This is not only critical in order to be able to plan and achieve climate neutrality but to also ensure the implementation of international sustainable development goals.

Avoided or balanced GHG emissions, commonly referred to as (net) zero GHG emissions, are interpreted here as a design target, ambition level, benchmark, or a budget for buildings. Such an approach, is also sometimes called carbon performance (Huang et al., 2017) and is a crucial part of an environmental performance assessment.

The aim is to achieve a state in which buildings, during their operation or during their full lifecycle, make only a minimal contribution to GHG emissions and thus to global warming. This state is referred to as (nearly) climate neutral (BMWi, 2010). One ambition level is where a (net) zero GHG emissions balance is achieved for the life cycle of buildings, while (net) zero GHG emissions for the operational part (here B6) is a subgoal that focuses only on balancing emissions from the 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 (expressed as kgCO_2eq.) is one of several aspects of environmental performance. Additional environmental impacts need to be quantified and assessed to avoid burden-shifting between different environmental impacts. Furthermore, social and economic performance shall be assessed, and technical and functional requirements must be met.

A new norm is emerging with goals described by various synonyms, such as: (nearly) carbon-neutral buildings, (net) zero carbon, climate neutral, (net) zero emission, as well as target values such as (net) zero GHG emission in operation or in the full life cycle. For the first time, target values are derived top-down from science based targets (Chandrakumar et al., 2020), i.e. compliance with the ecosystem's carrying capacity (planetary boundaries (Andersen et al., 2020)) and serve to maintain the natural foundations of life. For example, Switzerland began early on to develop standards such as SIA 2040 (SIA, 2011, 2017) which introduced top-down derived benchmarks for buildings (for GHG emissions and non-renewable primary energy). 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 (Lützkendorf & Balouktsi, 2019). They 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 and use, location, climate or energy supply system (Lützkendorf & Balouktsi, 2019).

To date, however, there is 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', to translate it into measurable target values and to develop calculation and accounting rules, including the definition of system boundaries. This development has so far led to a plethora of terms, definitions, calculation 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 should emerge. The new ISO 14068 about carbon neutrality may provide the preconditions for this (currently under an early-stage development).

1.1 Purpose of Report

In the construction and real estate sector, there has been a discussion that has lasted for decades on the possibilities of describing, assessing, and improving the environmental performance of buildings as part of their overall sustainability performance. This led to the creation of standards, such as ISO 21931-1 (ISO, 2010) (updated in 2022). Only a few of the environmental performance indicators mentioned there have so far been incorporated into the legislation of countries. Therefore, during the past decades, a buildings' energy performance has been regulated based on delivered/final or primary energy use (primary energy, non-renewable in most of the cases), while legal requirements to reduce GHG emissions in the life cycle of buildings or their parts have not been in existence or are just emerging (e.g. in France (ECOLOGIQUE, 2020), Sweden (Boverket, 2019), Finland (Kuittinen & Häkkinen, 2020) or New Zealand (Ministry of Business New Zealand, 2020). 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 also to include embodied energy. Consequently, a significant number of net-zero energy approaches occurred in the market, whose approaches are already well covered in the existing body of literature (D'Agostino & Mazzarella, 2019; Marszal et al., 2011; Panagiotidou & Fuller, 2013; Sartori et al., 2012). 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 buildings' performance in relation to its impact on global warming.

Therefore, this report focuses mainly on the principles related to 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 report and the subsequent analysis is threefold:

- to develop a basis for systematisation and harmonisation of building assessment approaches in relation to (net) zero GHG emissions buildings to rule out misunderstandings and avoid greenwashing;
- to provide an overview of the key parameters, boundaries and performance targets mentioned in such approaches in different parts of the world;
- to provide a detailed analysis of the terms, definitions, system boundaries, calculation methodology and offsetting 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 approaches were identified through a survey conducted among Annex 72 participants and selected external stakeholders. The primary target audiences for this report are policymakers, as well as researchers and consultants (incl. architects/designers) interested in the market implementation of (net)zero GHG emissions buildings and/or the development of related standards or certification/assessment systems.

It is important to note that a publication by (Satola et al., 2021) was incorporated into the preparation of this report, in which the interim results of the survey were presented. The results of the survey represent the status in summer 2020. The report presented here takes current developments into account and represents the status in spring 2021, i.e. it additionally includes updated information on new activities and modifications with respect to net net-zero assessment approaches occurring during 2020-21. Finally, it also presents a more detailed overview of the survey responses together with further recommendations.

1.2 Key Features Extracted from the Survey

In the first step of the research, the survey among IEA EBC Annex 72 experts was performed in order to extract the general data related to key features (Table 1.1) occurring in the respective country of the building assessment approach in relation to achieving climate neutrality and/or net zero GHG emission ambition levels. The extracted data from 35 building assessment approaches in 31 countries were crosschecked with the provided references and existing literature.

Table 1.1: Overview of methodological features, extracted from the analysed building assessment approaches (see also Satola et al. 2021)

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, neighbourhood, 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 2.2 (Section 2.2)
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 part
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 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 part
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 for GHG emissions balance/offsetting	
Requirements	Avoidance of double counting
Allowable options for achieving net zero GHG emissions	Net balance options (Allowable renewable energy generation/supply options, allocation of exported energy outside the system boundaries, etc.), offsetting options (i.e. technical reduction and technical removal options outside the system boundaries)
Timing of compensation	What is the time frame for a building to become "GHG emissions net-zero/neutral"?

In the second step, a more detailed review and analysis was performed of the methodology used, particularly in GHG emissions-based building assessment approaches. This meant that the energy metric based approaches were excluded from the second step since those methodologies and approaches were already extensively described in previous research (D'Agostino & Mazzarella, 2019; Marszal et al., 2011; Panagiotidou & Fuller, 2013; Sartori et al., 2012). Consequently, the main analysis in this report focuses on 13 GHG emissions metric-based building assessment approaches in 11 countries on four continents. Specifically, the general data from the first step of the data extraction was complemented by the extraction of detailed data covering features related to the operational and embodied part (including the life cycle modules according to EN 15978) and possibilities of GHG emissions compensation as presented in Table 1.1.

2. Theoretical Basics

2.1 Features Relevant to all Kinds of Benchmarks

Table 2.1 shows a list of generic methodological features against which the different net-zero assessment approaches were checked. These features are not particular to net-zero approaches, and extensive analyses of them have been covered elsewhere (see the last column of Table 2.1), therefore, only the essential information is given here in short explanations. This report later chooses to go more in-depth on the balance/offsetting options, which is a unique characteristic for net-zero approaches.

Table 2.1: Overview of A72 reports where theoretical basics for common benchmark features can be found

Feature	Explanation	Where theoretical basics are provided
Object of assessment	Application scale of standard/scheme (single building, neighbourhood, building stock)	Lützkendorf et al. (2023a), Section 4.5
Metric	Indicator/metric of building performance (primary energy, delivered energy of GHG emissions)	Lützkendorf et al. (2023a), Section 4.4 Lützkendorf et al. (2023b), Section 4.4
Type of regulation	Type of regulation and performance requirements	See Table 2.2
Modules in relation to building operation		
System boundaries	Scope of life cycle modules included in the operational life cycle part	Lützkendorf et al. (2023b), Section 4.1.8
Electricity GHG emissions factor	Principle for environmental impact assessment of electricity use (average, marginal, hybrid)	Lützkendorf et al. (2023b), Section 4.3.25 Peuportier et al. 2023
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 need to be verified during real time operation of certified building	Lützkendorf et al. (2023a), Section 4.8
Modules in relation to production, construction replacement and end of-life		
System boundaries	Scope of life cycle modules included in embodied life cycle part	Lützkendorf et al. (2023b), Section 4.1.8
LCA data source	Reference to calculation standard, recommended LCA database, calculation software if any.	Lützkendorf et al. (2023b)
Approach to ''time'' factor	Approach to ''time factor" in embodied life cycle impact assessment (static vs dynamic modelling)	Lützkendorf et al. (2023b), Section 4.3.1

2.2 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. To systemise the different regulations occurring in building assessment approaches, the authors developed the classification framework (Table 2.2), which presents the options for different regulations and performance requirements related to the operational and embodied parts of the building lifecycle. 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 the 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 limited by mandatory regulatory values in law, while the embodied part is not balanced but is instead limited by informal guide values. Guide values are understood as nonbinding orientation values for partial sizes. For example, SIA 2040 (SIA, 2017) 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.

Table 2.2: Classification framework for system boundaries and performance requirements in building assessment approaches

			Embodied part of the life cycle								
			a	b	c	d	e	f	g	h	i
		TYPE OF ACTION AND REGULATION	Ignored	Calculated	Calculated and limited by informal guide values[1]	Calculated and mandatorily limited by	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 selfuse 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 indirect 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).

2.3 GHG Emissions Balance: Special Feature of Net-zero Approaches

2.3.1 Distinction between absolute zero and net-zero-GHG-emission approaches

To achieve climate-neutral buildings that fulfil the Paris Agreement requires that the GHG emissions caused during their life cycle needs to be (absolute) zero or net-zero (balanced).

A prerequisite for net zero GHG emissions is always the balance of GHG emissions, taking into account defined system boundaries and agreed conventions while with a variant that reaches the 'absolute zero' level, no more GHG emissions occur. For the 'net-zero' level, the first step is to reduce emissions to a technically / economically feasible level. In a second step, a zero (or positive) balance must be achieved with suitable and approved measures.

The question arises as to whether such a target should first be considered for the emissions associated with the operation of a building. The aim is to ensure the continuity of such considerations but also to supplement existing energy balances for the operation of buildings (B6) with a corresponding emissions balance.

Today, zero direct GHG emissions during the operation of buildings and thus absolute zero operational GHG emissions (direct part) are feasible using renewable energy (whether self-produced or not). For the operational GHG-emissions including upstream and downstream chains this is not yet the case. Still, GHG emissions are possibly emitted in the supply chains of systems generating renewable energies and, in addition, in construction material and building element manufacture and end-of-life management (Lützkendorf & Frischknecht, 2020). Thus, absolute zero operational (incl. supply chains) and life-cycle-based GHG-emission buildings are, to date, still difficult to practically achieve. However, there are studies that show in which direction the decarbonisation process in energy supply as well as the construction and real estate sector can be advanced and achieved (Alig et al., 2020).

2.3.2 GHG Emission balance/compensation options

An absolute zero life-cycle-based GHG-emission status is currently not within reach for buildings and leads to the necessary inclusion of measures for GHG emission reductions and ways to balance such emissions in the strategy to achieve a (net) zero target. There are related consequences for the assessment of GHG emissions of buildings. These are discussed in detail in the next below.

GHG Emissions and associated reductions can be assessed for direct operational, both direct and indirect operational (i.e. on-site and supply chain) and for full life-cycle-GHG emissions of buildings. The scope of the analysis and the system boundary needs to be identical for the assessment of the GHG emissions and associated balancing/offsetting options (Lützkendorf & Frischknecht, 2020).

There are three major approaches for balancing/offsetting a building's carbon footprint (Lützkendorf et al. 2023a): (A) a net balance with potentially avoided emissions beyond the system boundary of the building; (B) investing in GHG emission reduction projects either directly or by purchasing certificates; or (C) investing in negative emission technologies that extract CO_2 or CH_4 (the latter only if from biogenic carbon and stored away safely/not reemitted) from the atmosphere either directly or by purchasing certificates.

Options B and C are usually not emission 'reductions' or 'removals' within buildings' value chain, i.e. GHG emissions are not completely avoided, reduced or removed by organizational, structural and technical means applied to the building – therefore these are seen as 'offsets'. When the possibility of offsetting is allowed as part of a net zero approach, the question of the specification of a time period within which the 'arithmetical' compensation must have taken place plays an important role. Usually, one calendar year is specified for this, there are also variants that allow offsetting over longer periods of time or the entire useful life of the building.

It notable that, often, these offsets are realized by the purchase of eligible units that support projects that reduce or remove emissions from the atmosphere. The general framework of measurement and validation of carbon off-set programs, which can be traded on a marketplace was established under the development mechanism (CDM) developed under the Kyoto Protocol. Off-sets certificates/units are considered as an essential tool to improve sustainability and to boost global decarbonisation by financing initiatives related to carbon reduction in developing countries. On the other hand, the compensation by off-set units may lead to the controversy regarding effectivity, and reliability (Gillenwater et al. 2007).

The most important questions in relation to the balance/offsetting options A—C are discussed below:

A) System boundaries for generation, procurement, and assessment of renewable energy

GHG emissions caused by the building construction and operation (or only operation) can be described, according to some suggestions in the literature (Panwar et al., 2011), as being compensated by potentially "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 (D2 in the new EN 15978-1, expected in 2021), in line with European (i.e. EN 15978 (15978, 2011)) and international standards (ISO 16475-1 (ISO, 2017)) (Dodd et al., 2017).

Options with respect to attribution of embodied impacts of on-site energy generation equipment

Options are currently being discussed to either assign the embodied GHG emissions of the renewable energy generation systems to the building or split them proportionally between the building and exported energy according to the self-used and exported energy proportions. Further information on the subject can be found in Lützkendorf et al. (2023b) and Peuportier et al. (2023). Specifically, a clear distinction must be made between four approaches (Table 2.3):

Option 1: Attribute all embodied impacts of energy generation equipment to the building and allow balancing by avoided GHG emissions outside the system boundaries

Option 2: Attribute all embodied impacts of energy generation equipment to the building and show potential effects beyond the system boundary separately in module D (or D2), or

Option 3: Attribute the embodied impacts of energy generation equipment corresponding to the self-consumed part and provide a separate balance for the exported energy (including embodied, operational impacts and potentially occurring benefits and loads outside the system boundary).

Option 4: Attribute the embodied impacts of energy generation equipment corresponding to the self-consumed part and provide the results of a separate balance for the exported energy (including embodied, operational impacts and potentially occurring benefits and loads outside the system boundary) as additional information in module D (D2).

Table 2.3. Overview of the four options with respect to attribution of embodied impacts of on-site energy generation equipment

	Embodied emissions of the renewable energy system are fully allocated to the building	Embodied emissions of the renewable energy system is proportionally allocated to the building (self-use share)
Avoided emissions can be considered in the balance	Option 1	
Avoided emissions are not considered in the balance, but in D2	Option 2	Option 4

Options with respect to allowable types of renewable energy generation

In addition to the handling of the (embodied) energy and/or GHG emissions associated with manufacturing and maintaining the system generating the exported energy, it must also 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 (Marszal et al., 2011) and presented in Figure 2.1.

Option 1 (building-integrated generation) employs the energy generation from the 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 (known as building integrated photovoltaic (BIPV) or building-integrated solar systems (BISS)), are used and directly connected to building energy system.

Option 2 (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 building site but used on-site) is typically less preferable than option 1 and 2, since significant environmental impacts related to transportation of renewable sources (mainly biomass) to the building site may occur (Amponsah et al., 2014). Additionally, some biomass resources which come from unsustainable fields and forests, or dedicated energy crops with a short rotation period, should not be treated as GHG emissions-free sources.

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

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

Purchasing of energy

A special case of "imported" renewable energy (generation fully offsite) is the purchasing of energy (seen as **Option 5 – "Off-site supply"** in Figure 2.1). Despite being widely recognised as a cost-effective and easy to implement strategy for reducing building-related GHG emissions (Lützkendorf & Frischknecht, 2020), the application of this solution may be controversial. Existing research (Pless & Torcellini, 2010; UKGBC, 2021) discusses the fact that buildings that rely on only purchased off-site renewable energy may present a lack of initiative to reduce the building energy demand and related environmental loads. If minimum performance requirements are part of a definition, this is not an issue though. The use of generic primary energy and emission factors for the national mix is commonly appropriate because e.g. in the design phase the occupant is generally not known and neither the electricity provider so that a specific mix cannot be identified, unless the electricity provider is known and verified via long-term contracts (see also Peuportier et al. 2023).

Risk of double-counting

If renewable energy is generated on-site, the excess can be delivered (exported) to third parties after deducting self-consumption. This possibly/eventually reduces the emissions elsewhere compared to an alternative energy generation or procurement scenario. Therefore, from the perspective of the building under study, there are possible effects outside its system boundary. There is currently a debate as to whether these shall be given for information only (e.g. in module D2 following 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 (1 x for the building and 1 x for the purchaser of the exported energy). The risk of double-counting decreases when the building is part of a self-sufficient net zero GHG emission group of buildings or district/neighbourhood (i.e. no exported energy), therefore, part of a larger system which does not export energy.

Similar to on-site generation options, the purchase of renewable energy generated off-site presents the risk of double-counting since it 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, decreasing of GHG emissions factors. The guideline developed by U.S Energy Agency (United States Environmental Protection Agency, 2018) presents the best practices related to making environmental claims from purchased 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 the RECs just after making an official environmental claim. This measure can prevent double counting of environmental benefits in case of selling or transferring the certified green power certificates. Finally, as long as physical production and electricity certificates are purchased from the same (renewable)power plants, the purchase of green electricity is not problematic (see also Peurportier et al. 2023; Lützkendorf et al. 2023b).

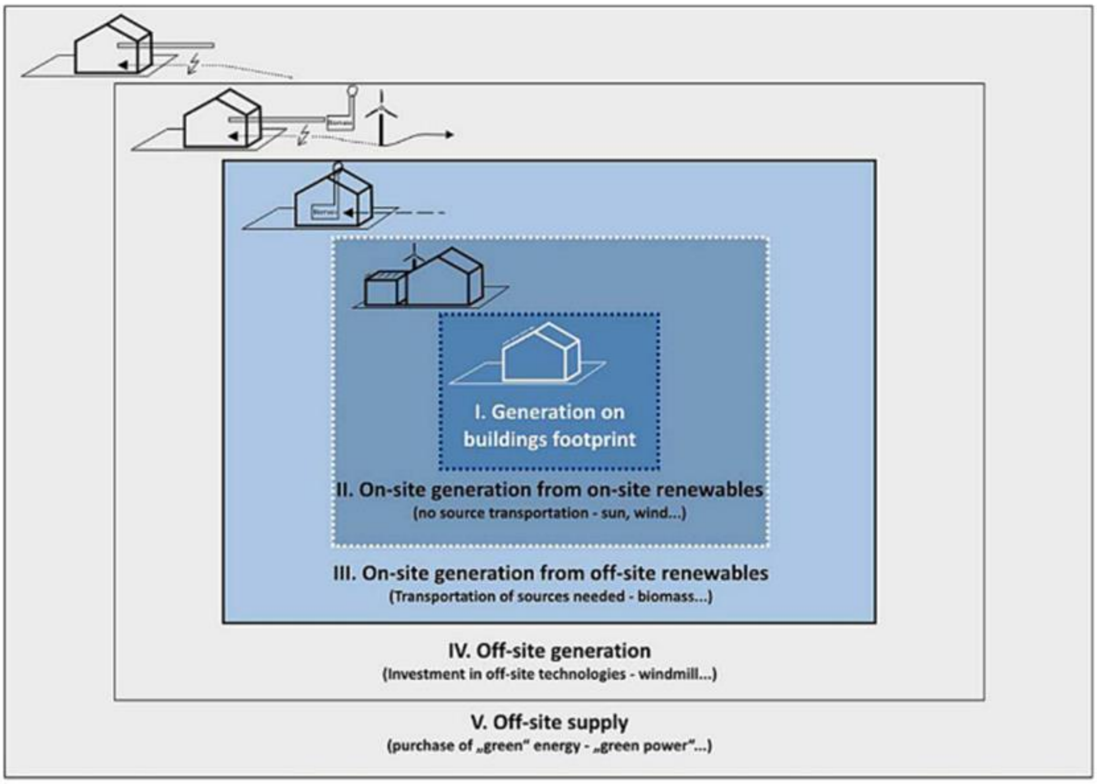


Figure 2.2: Overview of possible renewable supply options by Marszal et al. (2011)

B) GHG emissions reduction compared to a reference scenario through technical measures

There are different types of reduction projects, but not of the same traceability. For example, for some type of projects the emission reduction is directly measurable and therefore real reductions are claimed and shared between the building at issue and the offset project (e.g. CCS equipment in coal power plants). Others are simply leading to potentially avoided emissions elsewhere (investments in renewable energy production plants), and therefore potential (i.e. scenario-based) reductions are claimed and shared between the building at issue and the offset project. Based on this consideration, Approach B is further distinguished between two categories: ‘direct’ (Ba) and ‘indirect’ (Bb). An issue particularly with Approach B is that with an emission reduction outside the building’s boundary (real or scenario-based), CO_2 is still being emitted by the building at issue. Therefore, on a global level, net-zero emissions cannot be reached with reductions only, but they can help to reach a maximum reduction of 50% of GHG emissions: per 1 tonne emission reduction, 1 tonne is still being emitted (by the entity purchasing the certificate or investing on a project). Furthermore, considering that the cheapest reduction potentials are likely located in emerging and developing economies, these countries may face high costs in future when it is their turn to reduce their GHG emissions (Lützkendorf & Frischknecht, 2020). Based on these considerations, the transition from reductions to removals becomes critical because even if the building sector would stop emitting GHG emissions right now, the quantity of emissions in the atmosphere is still vast to stop the warming trajectory

C) Negative GHG emissions through technical measures

Off-setting takes place with negative GHG-emissions achieved via negative emissions technologies (NETs). Not all NETs are the same, therefore this approach can be further distinguished into two categories (Ca and Cb) based on the reversibility of the storage permanence (see Minx et al. (2018) for a more detailed analysis). It is important to note that, currently, most carbon offset projects available to invest in are either a type of emission reduction or a type of carbon removal with reversible permanence. These can provide additional social and environmental co-benefits that advance the UN Sustainable Development Goals as well as contributing to overall emissions reductions and sector decarbonisation (WEF, 2021). This makes them essential also for years to come. However, several organisations acknowledge the need to shift to more high-technology permanent carbon removal offsets, such as bioenergy with carbon capture storage (BECCS), which will require more investment and development in many cases. It is not only possible but also necessary for net zero GHG emission definitions to encourage investment in the research and development of these technologies as part of a carbon offsetting strategy.

2.3.3 Typology of options

Terms such as 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. 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 (2020). Based on the latter authors and all approaches and options laid out in the previous section, a more detailed division is proposed by Lützkendorf et al. (2023a) and shown in Table 2.4.

In order to deliver clarity, limit misunderstanding and avoid potential greenwashing, it is therefore important to state the chosen term in connection with related system boundaries, calculation and balancing rules very clearly and specifically. The same applies to the term “(net) zero emission”, which is used for both CO_2 emissions and GHG emissions. However, there are cases that do not cause CO_2 emissions, but still contribute to GHG emissions through the release of methane and other GHGs.

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, possibly even a positive balance. While for the operational part, there are at least theoretical possibilities of absolutely avoiding any CO_2 emissions, 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. It depends on whether the focus is on direct emissions, or 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. One of the main goals of this report is to create the basis for developing a transparent and systematic approach for a definition of (net) zero GHG emissions buildings which would be instrumental to delivering clarity, limit misunderstanding and avoid potential greenwashing. A clear description of the life cycle modules included combined with the typology presented in Table 2.4 provides a flexible, transparent classification system for different approaches for a chosen emissions balance.

Table 2.4: System of approaches for net-zero and zero-emission building during operation or full life-cycle (Source: Lützkendorf et al. 2023a)

Code	Name	Description	Note
Aa	**Net-balance approach, potentially avoided emissions**	Embodied impacts of exported energy produced on-site, and its potentially avoided emissions, as part of the GHG-emission balance of the building	Risk of double counting, unless emissions equivalent to the amount of avoided emissions booked on the building are booked by the party using the exported energy. Approach Aa is a special case of Approach Bb as the investment is made on the building under assessment.
Ab	**Net-balance approach, allocation**	Embodied impacts of exported energy produced on-site and its potentially avoided emissions as additional information (either as part of module D2 of the building or the balance of exported energy)	Life cycle related net-zero GHG-emission buildings are reachable only with additional technical reduction or removal (offsets)
Ba	**Technical reduction, direct** (emission reduction within the project)	Investment in CO_2/GHG emission reduction projects by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: carbon capture and storage (CCS) equipment in coal power plants, energy retrofit of existing buildings.	The emission reduction is directly measurable. The emission reduction is shared between the building at issue and the project, in which the technical reduction is realised. If claimed by the building, it shall not be claimed by the project.
Bb	**Technical reduction, indirect** (potential emission reduction occurs beyond the project)	Investment in projects, which lead to potential CO_2/GHG emission reductions elsewhere, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: investments in solar or wind power plants.	The emission reduction is determined indirectly using "what-if" scenarios. The potential emission reduction is shared between the building at issue and the project, in which the technical reduction is realised. If claimed by the building, it shall not be claimed by the project.
Ca	**Technical removal** NETs with potentially reversible permanence)	Investment in projects, which remove CO_2 from the atmosphere with potentially reversible performance, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: Biological fixation, achievable with afforestation, improved forest management; the storage of carbon in long-living buildings and wood products; the storage of carbon in the soil; and long-term underground storage of biogenic carbon	This approach allows to reach net zero GHG emissions buildings and contributes at the same time to the global net zero emissions goal. The viability of such measures is still questionable. For example, planting trees does not claim of taking care of them until they are grown up nor about the fate of the mature tree (afforestation may not be efficient in regions where there is a risk of fire).
Cb	**Technical removal** (NETs with stable permanence)	Investment in projects, which remove CO_2 from the atmosphere with stable performance, by contributing to its initial financing and implementation, or purchase of corresponding CO_2/GHG emission certificates. Examples: biogenic energy resources with carbon capture and storage (BECCS) or direct air capture with carbon separation and storage (DACCS)	This approach allows to reach net zero GHG emissions 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.
D	**Absolute zero approach**	Use of construction materials and components with zero GHG emissions	An absolute zero life-cycle-based GHG-emission status is currently not within reach

	(including supply chain emissions), purchase of operational energy and water with zero GHG emissions (including supply chain emissions)	for buildings and leads to the necessary inclusion of some kind of measures for GHG emission reductions and ways to balance such emissions in the strategy to achieve a (net) zero target.

3. Results and Discussion

3.1 General Data

The overview of general data from the first step of data extraction based on 35 building assessment approaches is presented in Table 3.1. Despite the high variation of key factors among the analysed building assessment approaches, general findings are summarized as follow:

1. A single building is the dominant object of assessment in the analysed data set.
2. Primary energy is the most common assessment metric, observed in most of the European countries, where the implementation of nearly zero energy building (nZEB) performance target, is applied in national policy.
3. In most of the 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 NGO's or research organisations.
4. Most of reviewed building assessment approaches are titled as "zero carbon" even though their frameworks not only cover carbon dioxide (CO_2) emissions but also set of other gases, which emissions contribute to the global warming.

Table 3.1: Overview of key methodological parameters from 35 building assessment approaches. Note: the highlighted ones indicate the building assessment approaches focusing on GHG emissions as the metric of balance.

Country name and code	Building assessment approach, reference	Status, launching year	Founder	Scale of application	Metric	Regulation type (acc. to Table 2.2)
Australia (AU)	Climate active, carbon neutral standard for buildings, (Australian Government Initiative, 2019)	Voluntary, 2019	Government	Buildings and neighborhoods	GHG emissions	G5.a
Austria (AT)	OIB-300.6-009/2015, Guideline 6 (EPBD), (Austrian institute of construction engineering (OIB), n.d.)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Belgium (BE)	Energieprestatie en Binnenklimaat (EPBD), (Vlananderen is Energie, 2013)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Brazil (BR)	Zero Energy Standard, (Brazil Green Building Council, 2017)	Voluntary, 2017	Brazil Green Building Council	Buildings	Delivered energy	DE7.a
Canada (CA)	Zero Carbon Building Standard, (Canada Green Building Council, 2020)	Voluntary, 2020	Canada Green Building Council	Buildings	GHG emissions	G5.f
China (CN)	Technical Standard for Nearly Zero Energy Buildings, (Ministry of Housing and Urban-Rural Development (MOHURD), 2019)	Voluntary, 2019	Government	Buildings	Primary energy	PE4.a
Czech Republic (CZ)	Energy Management Act, 78/2013 Coll (EPBD), (Republic, 2013)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a

Denmark (DK)	Danish Building regulations (EPBD), (Danish ministry of Transport Building and Housing, 2018)	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Finland (FI)	Method for whole-life carbon assessment of buildings, (Kuittinen, 2019) and Finish regulatory life cycle carbon limits of buildings	Draft, 2020	Finish Green Building Council	Buildings	GHG emissions	G4.e
France (FR)	France E+C-, (MTES, 2017)	Draft, 2020	Government	Buildings	Primary energy	PE4.a
	France EQUER, (Peuportier, Thiers, & Guiavarch, 2013)	Voluntary, 2017	Research	Buildings	GHG emissions	G5.f
Germany (DE)	Framework for “carbon neutral buildings and sites” (DGNB, 2018)	Voluntary, 2018	German Sustainable Building Council (DGNB)	Buildings	GHG emissions	G5.f
	Energy efficiency for buildings. Methods for achieving a virtually climate-neutral building stock. (Federal Ministry for Economic Affairs and Energy (BMWi), 2015)	Public framework, 2015	Government	Building stock	Primary energy	PE4.a
Hungary (HU)	Decree about Determination of Energy Efficiency of Buildings (EPBD), (“7/2006. (V.24.): Hungarian Government Decree on the energy performance of buildings, 2006 (in Hungarian).,” n.d.)	Mandatory, 2016	Government	Buildings	Primary energy	PE4.a
India (IN)	Net-zero energy rating system (Council, 2018)	Voluntary, 2018	Indian Green Building Council	Buildings	Delivered energy	DE7.a
Italy (IT)	Law 90/2013 and Decree 26/06/2015 (EPBD) (Italian Republic, 2013)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Japan (JP)	Japan’s Strategic Energy Plan, (Japan Ministry of Economy and Industry, 2018; Tanabe & Committee, 2016)	Mandatory, 2014	Government	Buildings	Primary energy	PE4.a
Netherland (NL)	Almost Energy Neutral Building requirements (EPBD), (Rijksdienst voor Ondernemend Nederland, 2019)	Mandatory, 2019	Government	Buildings	Primary energy	PE4.a
New Zealand (NZ)	CarboNZero Building Operations pilot scheme as a part of Zero Carbon Road Map for Aotearoa’s Buildings, (New Zealand Green Building Council, 2019)	Voluntary, 2019	New Zealand Green Building Council	Buildings	GHG emissions	G5.d

Norway (NO)	Zero Emission Building (ZEB) definition ,(Fufa et al., 2016)	Voluntary, 2014	Research	Buildings	GHG emissions	G5.f
	Zero emission neighborhoods in Smart Cities ,(Wiik et al., 2018)	Voluntary, 2019	Research	Neighborhood	GHG emissions	G5.f
Poland (PL)	Buildings and their location – Polish Technical Conditions (EPBD), (Ministry of Construction and Infrastructure, 2018)	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Portugal (PT)	Art. 16 of DL 118/2013 (EPBD) (No, n.d.)	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Slovenia (SI)	Action plan for nZEB until 2020 (Evropskega, 2020)	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Spain (ES)	Net-zero energy buildings, (Montoro, 2016)	Voluntary, 2019	Spanish Green Building Council	Buildings	Delivered energy	DE7.a
South Korea (KR)	The green building promotion act (Kim & Yu, 2018)	Mandatory, 2013	Government	Buildings	Delivered energy	DE7.a
South Africa (ZK)	Net-zero and net positive certification scheme (Green Building Council South Africa, 2019)	Voluntary, 2019	South Africa Green Building Council	Buildings	GHG emissions	G5.a
Sweden (SE)	NollCO2 (Sweden Green Building Council, 2020)	Voluntary, 2020	Sweden Green Building Council	Buildings	GHG emissions	G5.h
	Local Roadmap Malmö ("Local Roadmap Malmo 2030," n.d.)	Draft, 2020	Malmö municipality with industrial partners	Buildings	GHG emissions	G5.f
Switzerland (CH)	Net-zero energy building (MINERGIE-A) (MINERGIE, 2016)	Voluntary, 2012	Minergie Association	Buildings	Primary energy	PE7.d
Singapore (SG)	Green Mark for Super Low Energy Buildings, (Building and construction authority (BCA) of Singapore, 2018)	Voluntary, 2018	Building and construction authority (BCA) of Singapore	Buildings	Delivered energy	DE7.a
United Kingdom (UK)	Net-zero carbon building, (UKGBC, 2019)	Voluntary, 2019	UK Green Building Council	Buildings	GHG emissions	G5.f
USA (US)	Zero energy building, (US Department of Energy, 2015)	Voluntary, 2015	Government	Buildings and neighborhood (campus)	Delivered energy	DE7.a
	LEED zero carbon (USGBC, 2019)	Voluntary, 2016	United States Green Building Council (USGBC)	Buildings	GHG emissions	G5.a
	Zero carbon building (International Living Futures Institute, 2019)	Voluntary, 2019	International Living Future Institute	Buildings	GHG emissions	G5.h

[1] Nearly zero energy building target mandatory for all building types from 2017, except public sector which net-zero energy target is required from 2020

3.2 Type of Regulations and Performance Requirements in 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 2.2, the authors identified the nine following types of regulations, which present the system boundaries and performance requirements presented in building assessment approaches (Table 3.2). 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.

Table 3.2: Regulation type recognised in analysed building assessment approach. Note: For frameworks with multiple performance levels, the most ambitious level is here shown.

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
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, BE, CZ, DK, FR1, HU, IT, JP, NL, PL, PT, SI
PE7.d	The operational part of 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 mandatory limited by value introduced in the building assessment approach.	CH
DE7.a	The operational part of energy consumption (delivered energy) of the building is balanced and regulated by maximum limits included in the building assessment approach. The embodied part is ignored.	BR, IN, ES, KR, SG, US1
G4. e	Both the operational and embodied parts of GHG emissions of the building are mandatory, regulated and limited by law.	FI
G5. a	The operational part of GHG emissions of the building is balanced by an individual building assessment approach. The embodied part is ignored.	AU, ZA, US2
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 mandatory and limited by values introduced in the building assessment approach.	NZ
G5. f	Both the operational and embodied parts of GHG emissions of the building are balanced by an individual building assessment approach.	CA, FR2, DE, NO SE1, UK

G5.h	The operational part of 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.	SE2, US3

Definitions based on energy consumption metrics (types: PE3.a, PE4.a, PE7.d and DE7.a) are the most common, occurring in 22 of 35 analysed national building assessment approaches. The requirement in the form of maximum allowable annual primary energy consumption values (Type PE3.a and PE4.a, PE7.d) is present in 15 of 35 building assessment approaches. The net-zero energy performance target based on the metric of delivered energy (Type DE 7.a) is set in 6 of 35 analysed frameworks.

The shift from energy consumption to a GHGs emissions-based metric can be found in 13 building assessment approaches from 11 countries. In Finland, the National Green Building Council follow a government standard (Kuittinen, 2019) 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 Finish Government.

The requirement of 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 USA (LEED zero carbon (USGBC, 2019)) 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% less 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 are 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 the building assessment approaches from Canada, France (EQUER (Peuportier et al., 2013)), Germany, Norway, Sweden, UK and USA (zero-carbon (International Living Futures Institute, 2019)), all of which aim to achieve a net-zero GHGs emissions balance considering the full life cycle scope (Type G5.f and G5.h).

Table 3.3 shows how the existing approaches can be mapped in the overall array of approaches that can exist as earlier presented in Table 2.2. It should be noted that this survey covers activities up to summer 2020. New regulations are emerging in different countries that will introduce benchmarks for embodied energy and/or GHG emissions among others, and such new developments are expected to also influence net zero definitions (see also the A72 background report by Rasmussen et al. 2023). For example, definitions that currently ignore embodied GHG emissions, will probably have to adapt in future if such benchmarks become part of legal requirements.

Noteworthy developments of net zero GHG emission approaches of buildings occurring after the completion of the survey, and not covered in detail here, are:

- **updated versions** of some of the covered schemes, e.g. the Zero Carbon Building Design Standard by Canada (Version 2)[1], or provision of supplementary publications covering more detailed rules for offsets and renewable energy procurement options, e.g. the guidance for Green Star on the use of offsets and renewables[2] or the Renewable Energy Procurement & Carbon Offsetting Guidance for Net Zero Carbon Buildings by UKGBC[3],

[1] See: https://portal.cagbc.org/cagbcdocs/zerocarbon/v2/CaGBC_Zero_Carbon_Building_Standard_v2_Design.pdf
[2] See: https://gbca-web.s3.amazonaws.com/media/documents/climate-positive-buildings-net-zero-ambitions_Z3pcK5R.pdf
[3] See: https://www.ukgbc.org/ukgbc-work/renewable-energy-procurement-carbon-offsetting-guidance-for-net-zero-carbon-buildings/

- **new guidance principles and action plans** by both international organisations, such as the Net-Zero Carbon Buildings Principles by the World Economic Forum (WEF, 2021) and national collaborations of different organisations to reach consensus on definitions to support industry, such as the Net Zero FAQs[4] document in UK.
- **new drafts of laws and standards**, such as the EPBD proposal[5] and the upcoming EN 15978-1 which also deals with the question of how to allocate impacts and benefits associated with exported energy

[4] See: https://www.leti.uk/_files/ugd/252d09_d824a0289c1e40d39cbe62514a285e10.pdf
[5] See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0802

Table 3.3: Classification framework for system boundaries and performance requirements in building assessment approaches. Note: For primary energy (**PE**), delivered energy (**DE**), or GHG emissions (**G**) metric; non-useful combinations are highlighted in grey, while the existing ones acc. to the survey are highlighted in orange (see also Table 3.2).

		Embodied part of the life cycle								
		a	b	c	d	e	f	g	h	i
TYPE OF ACTION AND REGULATION		*Ignored*	*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*	**PE**								
4	*Calculated and mandatorily limited by law*	**PE**				**G**				
5	*Calculated and balanced (individual approach)*	**G**			**G**		**G**		**G**	
6	*Calculated and balanced, incl. limitation by informal guide values*									
7	*Calculated and balanced, incl. mandatory limit values as part of a scheme*	**DE**		**PE**						
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).

3.3 Detailed Methodological Features from GHG Emissions-based Net Zero Approaches

3.3.1 Ambition levels and system boundaries

From the 13 selected building assessment approaches from 11 countries, each of which is characterized by a GHG emission-based metric, five frameworks have been selected from Australia, Germany, Norway, South Africa, and the UK. For each country, the respective standard introduces different levels of building performance target, thus providing some flexibility in the design and construction of net-zero GHG emission buildings.

Table 3.4: Overview of multiple performance levels in analysed GHG emissions-based building assessment approaches

			Regulation type[2]			
Country	**Name of building assessment approach**	**Level of performance[1]:**	**Type G1. f**	**Type G5. a**	**Type G4. e**	**Type G5. f**
Australia	Carbon neutral buildings	Base building operation		X		
		Whole building operation		X		
Germany	Carbon neutral buildings	Climate-neutral by 2050[3]			X	
		Carbon neutral in the ongoing operation		X		
		Carbon neutral through life-cycle				X
Norway	Zero-emission building	ZEB: O-EQ[4], ZEB: O[5]		X		
		ZEB:OM[6], ZEB: COM[7], ZEB: COME[8]				X
South Africa	Net-zero and net positive carbon building	Level 1: Base building emissions		X		
		Level 2: Occupant emissions		X		
United Kingdom	Net Zero Carbon	Net-zero construction	X			
		Net-zero carbon operational energy		X		
		Net-zero carbon – whole lifecycle				X

[1] Name of different, possible performance level allowed in a standard or scheme

[2] Regulation type of performance level based on Table 3.2

[3] This definition is not analysed in the next sections due to lack of information

[4] The building's renewable energy production compensate for greenhouse gas emissions from operation of the building minus the energy use for equipment (plug loads)

[5] The building's renewable energy production compensate for greenhouse gas emissions from operation of the building[6] The building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials

[7] The building's renewable energy production compensate for greenhouse gas emissions from construction, operation and production of building materials.

[8] The building's renewable energy production compensates for greenhouse gas emissions from the entire lifespan of the building. Building materials – construction – operation and demolition/recycling.

The differences between performance levels in Australia and South Africa frameworks are attributed to the scope of operational life cycle boundaries and presented in the following section. The German framework defines three levels of performance, while net zero-emission building standard in Norway provides two different types (ZEB: O-EQ, ZEB:O) which differ in terms of operational life cycle boundaries, as well as an additional three types of increasing performance (ZEB:OM, ZEB: COM, ZEB: COME) with differences in embodied life cycle system boundaries scope. The experiences from the pilot buildings projects in Norway show that reaching the highest level of ambition for ZEB (Type G5.f), which include both operational and embodied emissions is very challenging. For instance, moving the ambition from ZEB:0 (Type G5.A) to ZEB:OM (Type G5.f) in the pilot buildings implies additional implementation of renewable energy sources, which increase initial energy generation in the range between 82%-182% (Hestnes & Eik-Nes, 2017). In the UK Net Zero Carbon Framework Definition for buildings, there is a possibility for achieving two different performance levels, or a combination of those, which take into consideration the whole life-cycle approach.

3.3.2 System boundaries scope and approach to the aspect of ‘’time”: Operational part

Table 3.5 presents the detailed information about system boundaries and approach to a ‘’time” factor in the operational module assessment in the building assessment approaches. In 8 of 13 analysed building assessment approaches, the complete scope of operational energy use modules including B6.1 B6.2 and B6.3 submodules are covered (for more information on how these sub-modules are defined within A72 context see Figure 3.1 and Lützkendorf et al. 2022). The regulated, building-related energy consumption module (B6.1) is a single, scope of operational impact assessment in frameworks from the UK and Finland. The non-regulated use and user-related energy consumption (B6.3) module is not included in the scope of Sweden (Local RoadMap Malmo (“Local Roadmap Malmo 2030,” 2020)) framework, while non-regulated building-related energy consumption module (B6.2) is outside of the scope in the framework from Norway and Canada. It is important to note that all frameworks include only chimney emissions of electricity (e.g. PV electricity with 0 g CO_2-eq/kWh), and therefore ignore the supply chain, however, in some whole life cycle frameworks embodied emissions from PV systems are included in the balance.

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 a “marginal electricity mix” approach, where the different energy production sources are ranked according to merit order. Renewable energy sources (e.g. solar or wind that depend on the weather) that cannot be adjusted to the power demand are the bottom of this ranking, while adjustable technologies with the lowest constraints and the highest cost are at the top of the hierarchy (see Annex A of background report by Peuportier et al. 2023). To do so two methods have been implemented in the tool: (1) the GHG Protocol method (WBCSD & WRI 2007), considering a marginal mix corresponding to the 10% top ranked productions; (2) a more physical 2 steps model, evaluating the mix with and without the studied building, using a model representing the electric system (Roux et al., 2016). The marginal electricity mix can be defined for past years (historical mix) or for a long-term period (future scenario) (Frossard et al., 2020). Both the Canadian “Zero carbon” and Swedish NollCO2 frameworks present the hybrid use of the average and marginal electricity mix factor (Canada Green Building Council, 2020; Sweden Green Building Council, 2020). 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 environmental benefits from locally produced electricity exported to the grid. Both the Swedish and Canadian approach are based on the GHG Protocol method (WBCSD & WRI 2007). Sweden only considers short-term marginal (see Annex A of background report by Peuportier et al. 2023). Arguments behind the application of an “average”, “short-term marginal” or “long-term marginal” electricity mix” are provided in the background report by Peuportier et al. (2023).

Scope of operational impact assessment									
Country	**Building assessment approach and performance level**	**Building types coverage**	**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 buildings operation	All types excluding SF	X	X	X	X		Average	Static
	Carbon neutral: base building operation		X	X					
Canada	Zero carbon building	All types	X		X			Hybrid	Static
Finland	Method for the whole-life carbon assessment of buildings	All types	X					Average	Dynamic, because, during the RSP, energy-based emissions are expected to decrease as a result of the measures under Finland’s National Energy and Climate Strategy.
France	EQUER	All types	X	X	X	X	X	Marginal	Dynamic, considering the hourly variation of emission factors from energy sources
Germany	Carbon Neutral building framework (DGNB)	All types	X	X	X			Average	Dynamic, considering dynamic emission factors for energy services
Norway	Zero-emission building: ZEB: O-EQ level	All types	X					Average	Dynamic, assuming the average value of electricity emission factor that is representative of a 60-year RSP, 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				
New Zealand	A Zero Carbon Road Map for Aotearoa’s Buildings	All types	X	X	X	X		Average	Static
South Africa	Net-zero and net positive carbon building: Level 1 (Base building emissions)	All types	X	X				Average	Static
	Net-zero and net positive carbon building: Level 2 (Occupant emissions)		X	X	X				
Sweden	NollCO2	All types	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	
United Kingdom	Net-zero carbon: operational energy and whole life	All types	X			X		Average	Static
USA	LEED zero carbon	All types	X	X	X	X	X	Average	Static

Zero Carbon Building	X	X	X	X

Table 3.5: System boundaries and approach to the time factor in operational impact assessment. Note SF = single-family houses.

By comparing the approach of the respective standard to the "time" factor in the operational GHGs emissions assessment, the 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. For example, in France, the EQUER method takes into consideration the dynamic approach by including an hourly variation of emission factors from energy sources, which provides a more accurate assessment of operational GHG emissions (mix dependent on use profile of the building under assessment). The rest five approaches follow a dynamic approach in the sense of considering the evolution of mix in the future. For example, the Swedish frameworks consider 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 of the electricity emission factor from actual 589 gCO_2eq/kWh to 354 gCO_2eq/kWh in 2050. In contrast to the building assessment approaches, where the decrease of 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 actual values used for GHG emissions of hydro-dominant electricity (15 gCO_2eq/kWh) (if Norway was seen in isolation) and takes into account hourly export and import of electricity to/from Nordel and the European grid and also takes into account future decarbonisation of the grid (Statistic Norway,2019, Graabak &Feilberg, 2011, Georges et al., 2015).

The implementation of dynamic, electricity factors, which will take account of grid variations in GHG emission intensity is stated as a key priority for the future development of net-zero carbon framework in the UK (UKGBC, 2019). The GHG emission factor of electricity presents a strong influence on the relative contribution of embodied emissions to total GHG emissions (Georges et al., 2015) In case of a high emission factor, the operational GHG emissions dominate the embodied emissions, while low emission factor leads to the opposite case. The emission factors proposed in building assessment approaches, significantly influence the performance of zero-carbon buildings and the choice of optimal design strategies.

3.3.3 System boundaries scope and approach to the aspect of ''time": Embodied part

By comparing the system boundaries covered in the building assessment approaches (Table 3.6), it can be indicated that the product stage (A1-A3) are the impacts included in the life cycle scope of embodied modules of all approaches, while construction (A4-A5) and replacement (B4) modules are the next most common ones (i.e. included in about 80 percent of the approaches). In relation to the remaining life cycle modules, a significant number of building assessment approaches do not take into consideration the impact coming from use and repair process (B1 and B3), and end-of-life process, i.e. demolition work (C1), transport from the site to disposal/waste treatment facility (C2) or 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 GHG emissions of related life-cycle phases (UKGBC, 2019). A solution for addressing this issue is presented in the Finish framework (Kuittinen, 2019) by introducing the generic, predefined GHG emissions values, which can be used in the case of unavailability of specific information. The Norwegian, (net) zero-emission building framework is the only one which includes different levels of performance requirements based on embodied, lifecycle 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 reuse, recovery and recycling of building products are only reported as additional information (but all the rest approaches with D indicated aggregate it to end of life impacts). This way to deal with Module D (as additional information) is in line with current CEN TC 350 related European standards. The new versions of the related European standards recommend the effects of reuse, recovery and recycling to be assigned to module D1 – they therefore provide a new breakdown for module D into module D1 (Net flows from reuse, recycling, energy recovery and other recovery) and D2 (Exported utilities) – i.e. Figure 3.1 is based on EN 15643:2021. Table 3.6 shows only D1.

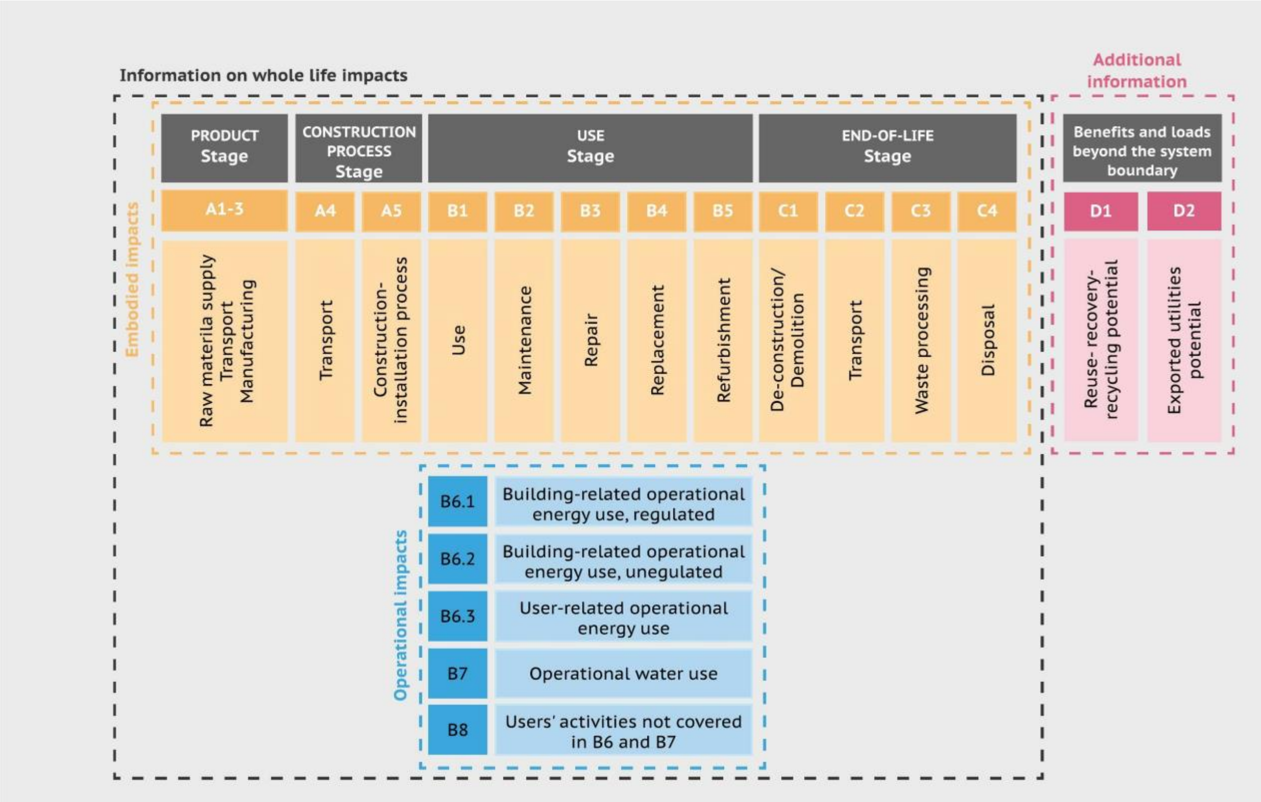


Figure 3.1: Modular approach of building life cycle impacts, distinguishing between the impacts arising from embodied (green dotted line) and operational aspects (blue dotted line). Adapted from EN 15643:2021.

Most of the methodological approaches described in analysed building assessment approaches suggest using the specific environmental product's declaration (EPD), supplemented by generic, national LCA database as the main data source for the calculation and reporting of lifecycle GHG emissions (Table 3.7). The need for reliable, country specific LCA database is highlighted in the Finnish and Swedish building assessment approaches, where a generic national LCA database is currently missing and currently under development.

A static approach to the "time" factor in embodied GHG emissions assessment during the building lifespan is evident in most of analysed building assessment approaches, (Table 3.7) except Sweden (NollCO$_2$ scheme), where GHGs emissions from the end-of-life stage (C1-C4) are assumed to be zero, due to the assumption of carbon neutrality taking into account the lifecycle 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 continues improvement of new technologies and material use, as well as, prospective LCA studies, the 50% reduction of GHGs emissions relative to product stage impact (A1-A3) is applied as a rule of thumb (Fufa et al., 2016; Georges et al., 2015).

Table 3.6: Included modules of embodied impacts in analysed building assessment approaches. Note 1: during the survey there was no D2 in place in standardisation. Module D is here shown in the meaning of new D1. Note 2: Following international and European standards D1 must be provided as additional information.

Country	Building assessment approach and performance level	A1 Raw material supply	A2 Transport	A3 Manufacturing	A4 Transport	A5 Construction-installation	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	Net zero carbon construction	✓	✓	✓	✓	✓										
	Net zero carbon whole life	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
USA	Zero Carbon Building	✓	✓	✓	✓											✓

X – included with details, ✓ - included without details, n/c- not clear, [1]only as additional information

Table 3.7: 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 whole life cycle carbon assessment of buildings and generic LCA database (under development).	Static
France	EQUER	Ecoinvent data base	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.	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 is used.	Static, except PV modules, where a 50% reduction of embodied emissions during 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; that’s why the impact of the end-of-life module (C1-C4) is considered equal to zero
	Local Roadmap Malmö		Not clear
United Kingdom	Net zero carbon construction and whole life	RICS Professional Statement “Whole life carbon assessment for the built environment” 2017, (tools not specified yet, OneClick LCA is expected to be recommended in future)	Static
United States of America	Zero Carbon Building	Carbon data should be sourced from EPDs verified as outlined in ISO 14025 Standard. Approved LCA tools: Athena Impact Estimator, eTool, One Click LCA, Tally, Environment Agency’s Carbon Calculator	Static

3.3.4 Verification of net-zero GHG emissions performance

Most of the reviewed building assessment approaches mandate the verification of net-zero GHG emissions performance of designed buildings using on-site metered data during the first year of building operation. It can be argued that this is insufficient; verifying the energy performance of a building is more complex than just measuring the consumption, which depends on climatic variation (the actual heating bill may be higher than estimated because of a colder year) and on occupants' behaviour (the actual heating bill may be higher because of a high thermostat set point rather than because of a poor building performance). Appropriate protocols (e.g. International Performance Measurement and Verification Protocol) have been defined and tools have been developed (e.g. see (Ligier et al., 2017). However, verification of embodied GHG emissions calculation using actual bills of quantities 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 3.8.

Table 3.8: Overview of verification requirements in analysed GHG emissions-based building assessment approaches

		Verification requirements				
Country	**Building assessment approach and performance level**	**Energy performance by on-site measurements**	**Indoor climate**	**Construction material inventory**	**LCA**	**Other**
Australia	Carbon neutral: whole buildings operation	X	n/c			
	Carbon neutral: base building operation	X	n/c			
Canada	Zero carbon building	X	n/c	X		Airtightness and peak demands
Finland	Method for the whole-life carbon assessment of buildings					
France	EQUER	X				Tool for energy performance verification
Germany	Carbon Neutral building standard (DGNB) Framework	X	X	X		User satisfaction, mobility, economic quality
Norway	Zero-emission building: ZEB: O-EQ level	X	X			
	Zero-emission building: ZEB:O, ZEB: OM, ZEB: COM and ZEB: COME level	X	X	X	X	
New Zealand	Carbon Zero Building Operations pilot scheme as a part of Zero Carbon Road Map for Aotearoa's Buildings	X				
South Africa	Net-zero and net positive carbon building: Level 1 (Base building emissions)	X	X			
	Net-zero and net positive carbon building: Level 2 (Occupant emissions)	X	X			
Sweden	NollCO2	X	X	X	X	Complementary commercial certification
	Local Roadmap Malmö	n/c				
United Kingdom	Net-zero carbon: operational energy and whole life	X				
USA	LEED zero carbon	X	X			

	Zero Carbon Building	X	X	X

3.3.5 Options and principles of GHG emissions balancing and offsetting

The overview of the allowed options for GHG emissions balancing and/or offsetting by analysed building assessment approaches is presented in Table 3.9.

Table 3.9: Options for balancing and/or offsetting allowed in analysed building assessment approaches.

Type of reduction and compensation options following the broad categories of Table 2.4		Potentially "avoided" GHG emissions elsewhere from exported part of renewable energy generation Type A.a					Type A.b	Type B	Type C	
Country	**Name of building assessment approach**	**On building area**	**On-site from on-site renewables**	**On-site from off-site renewables**	**Off-site generation**	**Off-site supply**		**Technical reduction**	**Technical removal**	**Timing of GHG emissions balancing and/or offsetting**
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	A Zero Carbon Road Map for Aotearoa's Buildings	X	X	X	X	X		X[1]	X[2]	Annually
South Africa	Net-zero and net positive carbon buildings	X	X	X	X[3]	X[3]		X[3]		Annually
Sweden	NollCO2	X	X	X	n/c	n/c		X[4]	X	Building lifetime
	Local Roadmap Malmö	X	X	X					X[5]	Building lifetime
United Kingdom	Net-zero carbon	X	X	X	X[3]	X[3]		X[3]		Annually
USA	LEED Zero Carbon	X	X	X	X	X		X		Annually
	Zero Carbon Building	X	X	X	X	X		X[6]	X[7]	Annually

X – Allowed option,
[1] Carbon reduction programs in developing countries
[2] Reforestation, carbon sequestration investments
[3] The on-site renewable generation is prioritised,
[4] Life cycle GHG emissions can be offset by implementing energy efficiency measures in other existing buildings,
[5] Carbon capture and storage,

[6] Renewable energy projects, and landfill gas-to-energy projects, where the methane would otherwise be released to the atmosphere.
[7] Reforestation projects

The building assessment approaches in Australia, Canada, France, New Zealand, South Africa and UK allow balancing the lifecycle GHG emissions by potentially "avoided" GHG emissions outside the system boundaries of the buildings life cycle from the generation of renewable energy from both on-site and off-site levels of system boundaries in line with. However, in the case of Australia, UK and South Africa, the building assessment approaches suggest prioritising the 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 the off-site renewables (e.g. biofuels) for production energy on-site.

According to available information in the, all approaches used in the selected frameworks, the exported energy-related benefits, namely avoided GHG-emissions outside the system boundaries become a part of the GHG-emissions balance and contribute to net-zero-emissions approach, which is in line with A.a approach (Lützkendorf & Frischknecht, 2020). This approach is not in line with current standards, which requires that 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 removal offset possibilities (Type C from Table 2.4) mainly include reforestation programs and carbon sequestration investments. In the case of building assessment approaches, which allow offset of GHG emissions through reduction projects, the focus is on either implementing energy efficiency measures in existing, surroundings buildings or the purchase of off-set credits, with the priority given to carbon credits units traded in the national market.

4. Discussion and Recommendations

The previous section showed large differences in all the thematic areas examined in this A72 survey. This complicates the comparison of approaches and statements. General recommendations which should be included in the further development of the country-specific assessment approach or definition of net-carbon/emission buildings are presented below:

- **To ensure transparency in published results**: the respective assessment method of (net) zero GHG emissions must describe the definitions, system boundaries, data bases, rules for calculation, emission balancing, emission offsetting via emission reduction or CO_2 removal, and verification rules in a transparent and comprehensive manner. This information should be public and freely accessible. Since net zero GHG emissions is a benchmark, the above preconditions make its achievement provable. To assist in this direction, a checklist adapted from ISO 21678:2020 to also include 'net zero' benchmarks is shown in Table 4.1. In this sense, this standard should be supplemented in future further developments. Moreover, as far as possible, the suggestions made here for classification in a typology should be adopted.
- **To ensure a wider adoption of the (net) zero GHG emissions target**: the current, voluntary and new (net) zero GHG emissions building assessment approaches should be integrated into national and local policy frameworks (Passer et al., 2020) with the aim to significantly increase the share of (net) zero GHG emissions buildings in the building stock. This action should be supported by voluntary building certification schemes, which should recognise the (net) zero GHG emission concept as the next and more ambitious goal. Focusing on operation is no longer sufficient, comprehensive (i.e. life-cycle-based) (net-) zero-emission building targets are needed by 2025, if 2050 emission targets are to be achieved (Lützkendorf and Frischknecht 2020).
- **To establish minimum levels of ambition and increase the effectiveness in terms of the contribution to the fulfilment of the Paris Agreement:** it is advised that the complete scope of the B6 modules (B6.1, B6.2, and B6.3) impacts is included in a net zero emission building approach at the minimum to be able to represent the self-consumed share of the energy generated on-site in a more complete fashion. Additionally, the building design and construction should follow the minimum requirements for the embodied emissions part based on national benchmarks being developed. At the moment, various net-zero carbon/GHG emissions building definitions show different approaches in terms of the performance target level and the selected scope for the system boundary. The difference in performance levels should be transparently reflected in the naming of the net zero emission buildings.
- **To verify the benchmark fulfilment at post-construction:** for the operational part, the real performance assessment of declared net-zero GHG emissions buildings during use stage should be mandatorily verified during building operation by on-site energy monitoring system. The verification shall be realised on annual basis and not only the first year of operation. Dynamic GHG emission factors of energy sources of the highest resolution possible and available by the specific energy provider should be used. In case of life cycle-based net zero emissions benchmarks, it is also important to verify the material quantities in the embodied emissions calculations in the "as-built" condition. Finally, the GHG emission offsets purchased or invested in shall be verified and compared against the carbon footprint of the building. Up to the point of verification of at least the first years of real operation and the offsetting of real upfront emissions, one can only talk about a 'net zero' in progress than an actual 'net zero' status.
- **To avoid excess use of offsetting measures:** the following prioritisation of measures shall be followed for both new and existing buildings: (1) implementation of operational energy efficiency measures controlled through setting energy use intensity targets (EUI) as well as low embodied carbon measures controlled through benchmarks. These requirements should prevent buildings which are highly energy inefficient and have not performed all the necessary actions to reduce their overall carbon footprint from achieving the net-zero carbon/GHG emissions performance target level by applying above-average offsetting measures; (2) implementation of on-site renewable energy sources; (3) purchase of low

emission off-site renewable energy services and construction products and (4) offsetting measures. Additionally, in the case of net zero solutions, it is suggested to indicate the parts of the balance - in the sense of +10/-10 kg CO_2eq/m²a or +50 /-50 kg CO2 eq/m²a. Therefore, the two sides of the balance should be always provided separately. This is also in line with ISO 16475-1 (2017). Additionally, the type of balancing and offsetting should be clearly stated.

- **To prevent from choosing the low-hanging fruit:** The building assessment approaches should allow for a variety of balancing and offsetting solutions, and not only focus on on-site renewable generation solutions, as this strategy is mainly suitable for new and relatively small buildings. A clear priority 'order' of balance, reduction and removal solutions shall be provided. When on-site renewable generation is not sufficient to cover the operational energy needs of a building, off-site renewable energy generation with additionality and bundled EACs shall be prioritized over other off-site options (if at all allowed). It shall be clearly stated how the potentially avoided emissions by third parties as a result of exported energy shall be handled. Additionality principles shall be clearly stated, as well as a central list of suppliers providing additionality shall be collected and provided. Offsetting shall be limited to the most hard-to-reduce areas, such as Scope 3 emissions, to encourage a focus on emissions reduction. A list of allowable and acceptable offset possibilities in a definition of net zero GHG emission buildings shall be provided. To compensate for residual/unavoidable GHG emissions (after all reduction possibilities on the building itself have been exercised), it is advisable to prioritise carbon removal offsets over reduction offsets over balancing approaches via avoided GHG emissions to the extent possible.
- **To adapt the definition to future changing conditions**: resilience of net zero GHG emissions buildings design should be a key design asset, taking into consideration the future scenarios assuming a constant reduction of GHG emissions intensities of electricity mixes towards (nearly) zero and increased use of intermittent renewable sources of energy, like solar or wind.
- **To enlarge system boundary from building to urban district:** there is a need to move the object of assessment in the form of a single building to broader scope including neighbourhood, city or even national building stock to facilitate GHG emissions 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.

Table 4.1: Checklist for the documentation and communication of benchmarks. Note: Rows A.03 + A.04 cover the functional equivalent description; Row B.05 is only relevant for budget-based benchmarks, while B.06-09 are only relevant for net zero benchmarks (see also Lützkendorf et al. 2022).

PART A	Basic information	Example
A.01	Name of the indicator	*Greenhouse gas (GHG) emissions*
A.02	Level(s) in the benchmark system	*Target value*
A.03	Type of building (function and new, refurbished or in-use)	*Office buildings, New construction*
A.04	More detailed specification if applicable (period and pattern of use)	*Period and pattern of use 5 days/week, 10 hours/day*
A.05	Reference unit	*(kg CO_2eq./m^2) x year* *m^2 based on Gross Internal Floor Area* *'year' based on the number of years defined in the reference study period (RSP)*
A.06	Region/Climate zone of validity	*Germany/ Climate zone III*
A.07	Period of validity	*From 2020 to 2025*
PART B	**System boundaries and methods**	**Example**
B.01	Explanation of methods and data bases	*Following the calculation rules of standard XX* *Data base: Ökobaudat 2017a for construction products, energy services and transport services*
B.02	Building elements/ parts covered (i.e. building model completeness)	*All building elements and services*
B.03.a	Life cycle stages covered (i.e. life cycle model completeness based on the modular structure in EN 15978:2021)	*A1-C4*
B.03.b	Parts of operational energy use covered in detail (B6.1, B6.2 & B6.3)	*B6.1 (heating, cooling, ventilation, hot water supply, lighting)*
B.04.a	Assumptions, defaults, and choices for A4-5 (if covered)	*Average transport distance of 100 km*
B.04.b	Assumptions, defaults, and choices for B1 (if covered)	*e.g. F-gases ignored or included or there are specific rules for selection of products in place*
B.04.c	Assumptions, defaults, and choices for B2-3 (if covered)	*based on date for single processes based on maintenance plan or default values*
B.04.d	Assumptions, defaults, and choices for B4-5 (if covered)	*Reference study period 50 years* *25 years assumed service life for windows, PV panels, etc.* *No technological progress considered (e.g. in relation to future production efficiency of products, etc.)*
B.04.e	Assumptions, defaults, and choices for B6.1	*Average, national annual supply electricity mix (static)*
B.04.f	Assumptions, defaults, and choices for B6.2-3 (if covered)	*Average, national annual supply electricity mix (static)*
B.04.g	Assumptions, defaults, and choices for B7 (if covered)	*average or specific data for LCA for water supply and wastewater treatment*
B.04.h	Assumptions, defaults, and choices for B8 (if covered)	*scenarios for mobility of users*

B.04.i	Assumptions, defaults, and choices for C1-2 (if covered)	*based on process related data or default values*
B.04.j	Assumptions, defaults, and choices for C3-4 (if covered)	*Taking into account current average situation*
B.04.k	Assumptions, defaults, and choices for D1 (if reported)	*Same as above*
B.04.l	Other assumptions and choices (e.g. biogenic carbon, discounting of future emissions, etc.)	*-1/+1 for biogenic carbon,* *No physical discounting*
B.05	Assumptions and choices only relevant for top-down budget-based target values	*Global budget chosen* *Effort-sharing principle chosen to derive the country budget* *Effort-sharing principle chosen to derive the sector budget*
B.06	Allowable types of balancing and/or offsetting (as per Table 5.2 in Lützkendorf et al. 2022) for the different life cycle stages and modules incl. the hierarchy	*Type Aa for B6.1-3* *Type C for A1-5, B4 and C*
B.07	Timing of balancing and/or offsetting for the different life cycle stages and modules	*A1-5, C1-4: Offsetting at practical completion based on actual bill of materials and product-specific emission factors for A1-5 (for C1-4 modelled data are used)* *B1-5: Annually in use offsetting* *Upstream impacts (Scope 3) of B6.1-3, B7: Annually in use offsetting*
B.08	Side requirements for allowable renewable energy procurement options incl. the hierarchy	*Only physical or corporate PPAs in the case of off-site RE generation – if this requirement is fulfilled provider-specific emission factors can be used*[6]
PART C	**Source and type of information**	**Example**
C.01	Source of data if bottom-up (incl. sample size and age)	*Calculated data based on design stage analyses (modelled building variants)* *100 buildings* *Data from 2016-2018*
C.02	Statistical values chosen for the representation of the benchmark (if bottom-up)	*95th Percentile as a target value*
C.03	Source of target if top-down (standard/ political goal/ global goal or budget)	*Not applicable*

[6] If green electricity is connected to the grid, one should think of using the residual mix.

5. Conclusions

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. The 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 operation where the total amount of operational energy used by the building is covered mainly by renewable energy generation typically on an 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, meeting climate Paris Agreement Goals, there is a need for accelerating decarbonisation in the area of action “buildings” by developing and implementing the net-zero GHG emissions buildings (operation or life cycle-related) approach which introduces GHG emissions as one of the primary performance indicators and formulates requirements for climate neutrality in the whole lifecycle.

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

Particularly, the results of the survey 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 offsetting are the most important issues, which should be carefully considered before developing and defining a harmonised (net) zero GHG emissions building framework.

Most likely, variations found in the existing schemes in ways of thinking about a common theme - (net) zero greenhouse gas emissions buildings – will continue to exist. These variations raise some important questions on how this concept is evolving. At the minimum, a typology of system boundaries and other dimensions, as presented in this report, can foster transparency and, consequently, the credibility of current approaches.

6. References

EN 15978 (2011). Sustainability of construction works–Assessment of environmental performance of buildings–Calculation method. *Brussels, Belgium: European Committee for Standardization*.

7/2006. (V.24.): Hungarian Government Decree on the energy performance of buildings, 2006 (in Hungarian). (n.d.).

Alig, M., Frischknecht, R., Krebs, L., Ramseier, L., & Commissioners, P. (2020). *LCA of climate friendly construction materials*. https://doi.org/10.13140/RG.2.2.27488.51209

Amponsah, N. Y., Troldborg, M., Kington, B., Aalders, I., & Hough, R. L. (2014). Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. *Renewable and Sustainable Energy Reviews*, *39*, 461–475. https://doi.org/https://doi.org/10.1016/j.rser.2014.07.087

Andersen, C. E., Ohms, P., Rasmussen, F. N., Birgisdóttir, H., Birkved, M., Hauschild, M., & Ryberg, M. (2020). Assessment of absolute environmental sustainability in the built environment. *Building and Environment*, *171*, 106633.

Australian Government Initiative. (2019). Climate Active Carbon Neutral Standard for Buildings, Commonwealth of Australia 2019. Retrieved from https://publications.industry.gov.au

Austrian institute of construction engineering (OIB). (n.d.). OIB Guideline 6: Energy saving and heat insulation, 2015.

BMWi (2010). Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. *Bundesministerium Für Wirtschaft Und Technologie (BMWi), Bundesministerium Für Umwelt, Naturschutz Und Reaktorsicherheit (BMU), Berlin*.

Boverket. (2019). *Regulation on climate declarations for buildings proposal for a roadmap and limit values*.

Brazil Green Building Council. (2017). Zero energy standard.

Building and construction authority (BCA) of Singapore. (2018). Green Mark for Super Low and Zero Energy Buildings.

Canada Green Building Council. (2020). *Zero Carbon Building Standard*. Retrieved from http://www.un.org/en/events/ozoneday/background.shtml.

Chandrakumar, C., McLaren, S. J., Dowdell, D., & Jaques, R. (2020). A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house. *Building and Environment*, *169*, 106560.

Council, I. G. B. (2018). IGBC green new buildings rating system—Version 3.0. *India, April*.

D'Agostino, D., & Mazzarella, L. (2019). What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering*, *21*, 200–212.

Danish ministry of Transport Building and Housing. (2018). Building regulations 2018.

DGNB. (2018). Framework for "carbon-neutral buildings and sites."

Dodd, N., Cordella, M., Traverso, M., & Donatello, S. (2017). Level (s)—A common EU framework of core sustainability indicators for office and residential buildings. *JRC Science for Policy Report, European Commission*.

ECOLOGIQUE (2020). RE2020 Reglementation environnementale. Eco-construire pour le confort de tous. Retrieved from https://www.ecologie.gouv.fr/sites/default/files/DP_RE2020.pdf

Evropskega, E. U. (2020). Akcijski načrt za skoraj nič-energijske stavbe za obdobje do leta 2020 (AN sNES) 1 Slovenija, *2020*(April 2015).

Federal Ministry for Economic Affairs and Energy (BMWi). (2015). Energy Efficiency Strategy for Buildings. https://doi.org/10.1109/ICCAS.2007.4406985

Frossard, M., Schalbart, P., & Peuportier, B. (2020). Dynamic and consequential LCA aspects in multi-objective optimisation for NZEB design. *IOP Conference Series: Earth and Environmental Science*, *588*, 32031. https://doi.org/10.1088/1755-1315/588/3/032031

Fufa, S. M., Schlanbusch, R. D., Sørnes, K., Fufa, S. M., Schlanbusch, R. D., Sørnes, K., & Inman, M. (2016). *A Norwegian ZEB Definition Guideline* (ZEB Projec). SINTEF Academic Press.

Georges, L., Haase, M., Houlihan Wiberg, A., Kristjansdottir, T., & Risholt, B. (2015). Life cycle emissions analysis of two nZEB concepts. *Building Research & Information*, *43*(1), 82–93. https://doi.org/10.1080/09613218.2015.955755

Gillenwater, M., Broekhoff, D., Trexler, M., Hyman, J., & Fowler, R. (2007). Policing the voluntary carbon market. *Nature Climate Change*, *1*(711), 85–87. https://doi.org/10.1038/climate.2007.58

Green Building Council South Africa. (2019). NET ZERO / NET POSITIVE CERTIFICATION SCHEME Technical Manual.

Hestnes, A. G., & Eik-Nes, N. L. (2017). *Zero emission buildings*. Fagbokforlaget Bergen.

Huang, B., Xing, K., & Pullen, S. (2017). Energy and carbon performance evaluation for buildings and urban precincts: review and a new modelling concept. *Journal of Cleaner Production*, *163*, 24–35. https://doi.org/10.1016/j.jclepro.2015.12.008

International Living Futures Institute. (2019). Embodied Carbon Guidance: resource for calculating embodied carbon. *International Living Futures Institute*, 0–13. Retrieved from http://www.carbonleadershipforum.org/embodied-carbon-network/

International Renewable Energy Agency (IRENA). (2018). *Corporate Sourcing of Renewables: Market and Industry Trends – REmade Index 2018*. https://www.irena.org/publications/2018/May/Corporate-Sourcing-of-Renewable-Energy

ISO. (2017). ISO 16745-1: Sustainability in buildings and civil engineering works—Carbon metric of an existing building during use stage—Part 1: Calculation, reporting and communication. International Organization for Standardization (ISO).

ISO. (2010). 21931-1: 2010, Sustainability in building construction. Framework for methods of assessment of the environmental performance of construction works. Part 1: Buildings. *International Organization for Standardization, Geneva*.

Italian Republic. (2013). Law 3 August 2013 no. 90 "Conversione in legge, con modificazioni, del decreto-legge 4 giugno 2013, n. 63, recante disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazi.

Japan Ministry of Economy and Industry. (2018). Strategic Energy Plan.

Kim, Y., & Yu, K.-H. (2018). Study on Policy Marking of Passive Level Insulation Standards for Non-Residential Buildings in South Korea. *Sustainability*, *10*, 2554. https://doi.org/10.3390/su10072554

Kuittinen, M. (2019). *Method for the whole life carbon assessment of buildings*. Retrieved from http://urn.fi/URN:ISBN:978-952-361-029-3

Kuittinen, M., & Häkkinen, T. (2020). Reduced carbon footprints of buildings: new Finnish standards and assessments. *Buildings and Cities*, *1*(1), 182–197. https://doi.org/10.5334/bc.30

Ligier, S., Robillart, M., Schalbart, P., & Peuportier, B. (2017). Energy performance contracting methodology based upon simulation and measurement. In *Building Simulation 2017*.

Local Roadmap Malmo 2030. (n.d.). Retrieved from http://lfm30.se

Lützkendorf, & Balouktsi. (2019). Principles for the development and use of benchmarks for life-cycle related environmental impacts of buildings. In *Life Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision. Proceedings of the Sixth International Symposium on Life-Cycle Civil Engineering (IALCCE 2018), 28-31 October 2018, Ghent, Belgium* (pp. 783–790). CRC Press, Boca Raton.

Lützkendorf, T., & Frischknecht, R. (2020). (Net-) zero-emission buildings : a typology of terms and definitions. *Buildings and Cities*, *1*, 662–675.

Lützkendorf, T., Balouktsi, M., Frischknecht, R., Peuportier, B., Rasmussen, F., Satola, D., Houlihan Wiberg, A., Birgissdottir, H., Dowdell, D., Lupisek, A., Malmquist, T., Obrecht, T., & Trigaux, D. (2023a). *Benchmarking and target-setting for the life cycle-based environmental performance of buildings.* IEA EBC Annex 72 Report. (treeze Ltd.) ISBN: 978-3-9525709-4-4; DOI: 10.5281/zenodo.7468752

Lützkendorf, T., Balouktsi, M., Frischknecht, R., Peuportier, B., Birgisdottir, H., Bohne, R.-A., Cellura, M., Cusenza, M. A., Francart, N., García, A., Gomes, V., et al. (2023b). *Context-specific assessment methods for life cycle-related environmental impacts caused by buildings*. ISBN: 978-3-9525709-0-6; DOI: 10.5281/zenodo.7468316

Marianne Kjendseth Wiik, Selamawit Mamo Fufa, John Krogstie, Dirk Ahlers, Annemie Wyckmans, Patrick Driscoll, H. B. and A. G. (2018). *Zero Emission Neighbourhoodsin Smart Cities : Definition , Key Performance Indicators and Assessment Criteria : Version 1.0*.

Marszal, A. J., Heiselberg, P., Bourrelle, J. S., Musall, E., Voss, K., Sartori, I., & Napolitano, A. (2011). Zero Energy Building - A review of definitions and calculation methodologies. *Energy and Buildings*, *43*(4), 971–979. https://doi.org/10.1016/j.enbuild.2010.12.022

MINERGIE, I. (2016). The MINERGIE®-Standard for Buildings. *Ver. Minergie Bern Switz*.

Ministry of Business New Zealand. (2020). Whole-of-Life Embodied Carbon Emissions Reduction Framework Building for climate change programme Ministry of Business, Innovation and Employment (MBIE) Hīkina Whakatutuki-Lifting to make successful WHOLE-OF-LIFE EMBODIED CARBON EMISSIONS REDUCTION FRAMEW, (August). Retrieved from www.mbie.govt.nz

Ministry of Construction and Infrastructure. (2018). Buildings and their location – Polish Technical Conditions.

Ministry of Housing and Urban-Rural Development (MOHURD). (2019). Technical Standard for Nearly Zero Energy Buildings.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., … del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 63001. https://doi.org/10.1088/1748-9326/aabf9b

Montoro, L. G. (2016). Objetivo 2020: de la eficiencia energética a los edificios de consumo de energía casi nulo. *Revista CESCO de Derecho de Consumo*, (19), 263–271.

MTES. (2017). Référentiel « Energie-Carbone » pour les bâtiments neufs - Méthode d'évaluation de la performance énergétique et environnementale des bâtiments neufs, 74. Retrieved from http://www.batiment-energiecarbone.fr/IMG/pdf/referentiel-energie-carbone-methode-evaluation-2017-07-01.pdf

New Zealand Green Building Council. (2019). A zero carbon road map for Aotearoa's buildings.

No, D. L. (n.d.). 118/2013 of August 20, 2013. Energy Certification System Regulations. Portugal.

Panagiotidou, M., & Fuller, R. J. (2013). Progress in ZEBs—A review of definitions, policies and construction activity. *Energy Policy*, *62*, 196–206.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

Passer, A., Lützkendorf, T., Habert, G., Kromp-Kolb, H., Monsberger, M., Eder, M., & Truger, B. (2020). Sustainable built environment: transition towards a net zero carbon built environment. *The International Journal of Life Cycle Assessment*.

Peuportier, B., Thiers, S., & Guiavarch, A. (2013). Eco-design of buildings using thermal simulation and life cycle assessment. *Journal of Cleaner Production*, *39*, 73–78. https://doi.org/10.1016/j.jclepro.2012.08.041

Peuportier, B., Frischknecht, R., Szalay, Z., Birgisdottir, H., Bohne, R.-A., Lasvaux, S., Padey, P., Francart, N., Malmqvist, T., Lützkendorf, T., Balouktsi, M., & Delem, L. (2023). *Basics and Recommendations on 107/110 Electricity Mix Models and their Application in Buildings LCA - A Contribution to IEA EBC Annex 72*. [Forthcoming]

Pless, S., & Torcellini, P. (2010). *Net-zero energy buildings: A classification system based on renewable energy supply options*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Rasmussen, F. N., Trigaux, D., Balouktsi, M., Lützkendorf, T., Peuportier, B., Malmqvist, T., & Dowdell, D. (2023). *Documentation and analysis of existing LCA benchmarks for buildings in selected countries: A contribution to IEA EBC Annex 72*. [Forthcoming]

Republic, M. of T. and I. od C. (2013). Decree 78/2013 Coll. Building energy performance standard.

Rijksdienst voor Ondernemend Nederland. (2019). BENG voorbeeldconcepten woningbouw.

Roux, C., Schalbart, P., Assoumou, E., & Peuportier, B. (2016). Integrating climate change and energy mix scenarios in LCA of buildings and districts. *Applied Energy*, *184*, 619–629. https://doi.org/10.1016/j.apenergy.2016.10.043

Saade, M. R. M., Hoxha, E., Passer, A., Frischnecht, R., Lützkendorf, T., & Balouktsi, M. (2023). *Basics and Recommendations on Assessment of Biomass-based Products in Building LCAs: the Case of Biogenic Carbon - A Contribution to IEA EBC Annex 72*. [Forthcoming]

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

Satola, D., Balouktsi, M., Lützkendorf, T., Wiberg, A. H., & Gustavsen, A. (2021). How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC annex 72. *Building and Environment*, *192*, 107619. https://doi.org/10.1016/j.buildenv.2021.107619

SIA. (2011). SIA Energy Efficiency Path, SIA Technical Specification 2040, Zürich, Switzerland.

SIA. (2017). SIA (2017) SIA Energy Efficiency Path, SIA Technical Specification 2040, Zürich, Switzerland.

Sweden Green Building Council. (2020). NollCO2 Nettonoll Klimatpaverkan.

Tanabe, S., & Committee, R. (2016). *Definition of Zero Energy Building in Japan*.

UKGBC. (2019). Net Zero Carbon Buildings: A Framework Definition. *Advancing Net Zero*, (April).

UKGBC. (2021). Renewable Energy Procurement & Carbon Offsetting Guidance for net zero carbon buildings, (March). Retrieved from https://www.ukgbc.org/wp-content/uploads/2021/03/Renewable-Energy-Procurement-Carbon-Offsetting-Guidance-for-Net-Zero-Carbon-Buildings.pdf

United States Environmental Protection Agency. (2018). Guide to purchasing green power. Retrieved from http://www.epa.gov/greenpower/documents/purchasing_guide_for_web.pdf

US Department of Energy. (2015). A Common Definition for Zero Energy Buildings, (September), 22. Retrieved from https://www.energy.gov/eere/buildings/downloads/common-definition-zero-energy-buildings

USGBC. (2019). LEED Zero Program Guide, (May), 12.

Vlananderen is Energie. (2013). EPB-eisentabellen per aanvraagjaar.

World Economic Forum (WEF). (2021). *Green Building Principles: The Action Plan for Net-Zero Carbon Buildings. Insight Report*. https://www3.weforum.org/docs/WEF_Green_Building_Principles_2021.pdf