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Net zero greenhouse gas emission residential building concepts for warm climates

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Architecture and Design
Department of Architecture and Technology

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Preface

This thesis presents the results of the PhD project conducted during the period from 2018 to 2022 on the topic of net zero greenhouse gas emission residential building concepts located in warm climates. This research was funded by NTNU Energy, a strategic research area at the Norwegian University of Science and Technology (NTNU). The PhD project was carried out at the Department of Architecture and Technology and the Norwegian Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) under the supervision of Professor Arild Gustavsen and the co-supervision of Professor Aoife Houlihan Wiberg from University of Bath, whom I would like to thank for their guidance, openness, and support during the challenging PhD project.

Daniel Satola,

Trondheim, January 2024

Summary

Global warming induced by human activities is increasing at an unprecedented scale. It has already caused multiple observed changes in the climate system, including increases in global average temperature, heatwave frequency and intensity of heavy (more extreme) precipitation events on a global scale. Combating climate change and reducing the environmental impacts of human activities is the most urgent and challenging science and policy issue of the current time. Over 32% of global energy use and nearly 40% of global greenhouse gas emissions (GHG) can be attributed to building construction, maintenance, and service. These emissions may potentially increase three-fold by 2060 due to the rapid population growth and increased access to adequate housing, electricity, and improved facilities for the billions of people in developing economies. The dominant share of these GHG emission-intensive activities will occur in Asia, Africa, and Latin America, all of which have humid subtropical and tropical climates. Consequently, there is an urgent need to address environmental impacts related to the rapid growth of the residential construction sector in these climates. The goal of this thesis is to advance the development of sustainable, low GHG emission design strategies and residential building concepts, particularly those aimed at emerging countries covered by humid subtropical and tropical climates at the policy and design level.

The work presented in this thesis first (Paper I) focuses on improving the transparency and credibility of the net-zero GHG emission building definition and principles, whose implementation in the building design and national building policy is recognised as one of the most promising strategies for decarbonisation of the construction sector globally. The key methodological factors from selected international building standards and schemes were first identified and analysed and then organised and categorised into transparent and easy-to-understand frameworks. The results of the analysis determined that regulation type, system boundaries for both operational and embodied life cycle related GHG emission, approach (static vs dynamic) to the "time" aspect and the possibilities of GHG emission compensation are the most critical issues that should be focused on before creating a country-specific (net) zero GHG emission building framework.

The second research activity (Paper II) investigated the influence of climate conditions, electricity grid mix, and the level of energy efficiency requirements present in the local binding building regulations in Sydney, Atlanta, Shanghai, and New Delhi (all located in humid subtropical climate) firstly on the life cycle GHG emission balance, and secondly on the consequent feasibility of achieving the net-zero GHG emission performance target with a case single-family building powered by grid-connected, on-site PV energy system.

The results indicate that high-level energy-efficiency requirements present in the mandatory building standards in Sydney and Atlanta enable low energy operation and to achieve the net-zero GHG emission performance target with the analysed case building.

Additionally, implementing and enforcing compulsory requirements regarding energy efficiency levels was identified as a key mechanism to achieve a low GHG emission residential construction stock in China and India. In each of investigated locations the energy mix and GHG emission intensity of electricity play a key role in the life cycle GHG emission profile.

On the building design level, a systematic literature review (Paper III) was performed to identify the current state of the life cycle GHG emission profile of residential buildings in humid subtropical and tropical climates, as well as identify effective design strategies to reduce both embodied and operational GHG emissions and existing research gaps. The reported results were harmonised and analysed considering the influence of building location, typology, construction, and energy performance on the life cycle GHG emissions. The results demonstrated that residential buildings with net-zero energy or low-energy performances could reduce the total life cycle GHG emission by 50–80% compared to the most common conventional energy performance of residential buildings, characterised by low energy efficiency. The design strategy connected with the implementation of renewable energy sources in the form of on-site photovoltaic systems was found to provide the highest reduction in total and operational life cycle GHG emissions, whereas the design strategy related to the use of timber-based materials led to the highest reduction in terms of embodied GHG emissions. Some identified research gaps relate to the lack of holistic life cycle assessment and design strategies for decreasing the environmental impact associated with prefabricated housing units and multifamily buildings in humid subtropical and tropical climates. The identified research gaps were covered in this thesis through the case study research based on the extensive use of building performance simulations (BPS) and life cycle assessments (LCA) with the support of global sensitivity analysis and multi-objective optimisation methods.

The case study research (Paper IV) was based on a prefabricated housing unit with a conditioned floor area of 21m^2 produced, located, and tested in Shanghai, China, and evaluated the correlation between energy use, indoor environmental quality, and the economics of various energy efficiency strategies in achieving net-zero energy and cost-effective off-grid operation. The design strategies related to relaxed cooling and heating temperature setpoints outside the building occupancy hours, increased thermal insulation thickness, upgrade to triple layer glazing, and implementation of a hybrid ventilation system were found to provide the most significant energy use savings.

The previous research is further developed in Paper V, which compared different energy efficiency design concepts, including conventional, low-energy, zero-energy, and off-grid design scenarios, and considered the life cycle environmental impacts and the initial investment cost associated with exploring the possible environmental hotspots and trade-offs related to the increased energy efficiency and energy system complexity of the prefabricated housing module.

The initial investment cost associated with the construction of the low-energy (37% higher), zero-energy (99% higher) and off-grid (205% higher) housing module was estimated to be higher than the conventional design scenario.

The life cycle environmental impacts were the lowest for the zero-energy design, with an 86% reduction of GHG emissions compared to the conventional one. The off-grid design presented substantially higher environmental impacts in all investigated categories (by an average of 59%) than the zero-energy design.

Finally, the thesis presents the results of a multifamily building case study (Paper VI) located in three warm climate zones in India. The study illustrates the potential and the added value of using innovative approaches combining building performance simulation, life cycle assessment, and life cycle cost analysis with global sensitivity analysis and multi-objective optimisation. The findings of this research identified the most sensitive design parameters influencing life cycle GHG emissions and thermal comfort level, and the most promising design strategies to reduce the life cycle GHG emissions and cost in multifamily buildings located in humid subtropical and tropical climates. It was found that the apartment floor area, equipment loads, windows-to-floor ratio, mechanical ventilation airflow and cooling set-point temperature were the most influential design parameters for the life cycle GHG emissions in the multifamily building design located in each of the investigated warm climate locations. The design strategies, on the other hand, focused on increasing the space efficiency of the building apartments, minimising the area of windows and the solar heat gain coefficient, implementing the hybrid cooling system with the use of ceiling fans and maximising energy generation from the on-site PV system. Implementation of these design strategies provided the best life cycle performance including GHG emissions and life cycle cost.

The main contribution of this thesis is the holistic and combined analysis based on the life cycle approach of residential buildings in humid subtropical and tropical climates at the policy and building design level, which has revealed critical variables and offers practical recommendations and concepts towards the successfu mitigation of the effects of climate change in the residential construction sector.

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Abbreviations

Abbreviation	Explanation
AP	Acidification Potential
BECCS	Bioenergy with Carbon Capture and Storage
BIM	Building Information Modelling
BPS	Building Performance Simulations
BREEAM	Building Research Establishment Environmental Assessment Method
CED	Cumulative Energy Demand
DACCS	Direct Air Carbon Capture and Storage
DE	Delivered energy
EBC	Energy in Buildings and Communities
ECCRB	Energy Conversation Code for Residential Buildings
EPBD	Energy Performance Building Directive
EU	European Union
FAST	Fourier Amplitude Sensitivity Test
FEP	Freshwater Eutrophication Potential
FFP	Fossil Fuel Potential
FPMF	Fine Particulate Matter Formation
FU	Functional Unit
GBC	Green Building Council
GFA	Gross Floor Area
GHGs	Greenhouse Gases
GWP	Global Warming Potential
HFA	Heated (Conditioned) Floor Area
HOFP	Human health Ozone Formation Potential
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MF	Multi Family
NDC	National Determined Contribution
NET	Negative Emission Technologies
NTNU	Norwegian University of Technology
nZEB	nearly Zero Energy Building
ODP	Ozone Depletion Potential

OECD	Organisation for Economic Co-operation and Development
PE	Primary Energy
PV	Photovoltaic
REC	Renewable Energy Certificate
SA	Sensitivity Analysis
SF	Single Family
VIP	Vacuum Insulation Panels
ZEB	Zero Emission Building
ZEB-O	Zero Emission Building-Operation
ZEB-COM	Zero Emission Building-Construction, Operation and Materials
ZEB-COME	Zero Emission Building-Construction, Operation, Materials and End of Life
ZEB-O-EQ	Zero Emission Building-Operation (excluding plug loads -EQ)
ZEB-OM	Zero Emission Building-Operation and Materials
ZEN	Zero Emission Neighbourhoods

List of Figures

List of Tables

List of scientific publications

This section presents the list of the scientific publications developed and published during the PhD project. The primary journal publications are the core of the PhD project and are presented in detail in the thesis. The secondary publications present the outcomes of the research work conducted during the PhD timeframe; however, despite providing valuable and interesting results, they are not considered as a core of the PhD project.

Primary (P) publications

Paper I. **D. Satola**, M. Balouktsi, T. Lützkendorf, A. Houlihan-Wiberg, A. Gustavsen. (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*, Volume 192.

Paper II. **D. Satola,** A. Houlihan-Wiberg, A. Gustavsen. (2019). Towards zero-emission residential buildings (ZEBs) in a humid subtropical climate. Analysis of emissions from energy use and embodied emissions from materials in referential locations according to obligatory residential energy codes and using generic LCA data sources. *The International Symposium on Heating, Ventilation and Air Conditioning*. Springer, Singapore.

Paper III. **D. Satola**, M. Röck, A. Houlihan-Wiberg, A. Gustavsen. (2021). Life cycle GHG emissions of residential buildings in humid subtropical and tropical climates: Systematic review and analysis, *Buildings*, Volume 11(1).

Paper IV. A.B. Kristiansen, **D. Satola**, K. Lee, B. Zhao, T. Ma, R.Z. Wang, A. Gustavsen, V. Novakovic. (2020). Feasibility study of an off-grid container unit for industrial construction, *Sustainable Cities and Society*, Volume 61.

Paper V. **D. Satola,** A.B. Kristiansen, A. Houlihan-Wiberg, A. Gustavsen, T. Ma, R.Z. Wang. (2020) Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study, *Building and Environment*, Volume 186.

Paper VI. **D. Satola**, A. Houlihan-Wiberg, A. Gustavsen (2022). Global sensitivity analysis and optimisation of design parameters for low GHG emission life cycle of multifamily buildings in India, *Energy and Buildings*, Volume 277.

Secondary (S) publications

Secondary Paper I. **D. Satola**, A. Houlihan-Wiberg, M. Singh, S. Babu, B. James, M. Dixit, R. Sharston, Y. Grynberg, A. Gustavsen. (2022) Comparative review of international approaches to net-zero, climate-neutral buildings. A knowledge-sharing initiative to develop net-zero design strategies for greenhouse gas emissions reduction, *Energy for Sustainable Development*, Volume 71.

Secondary Paper II. **D.Satola**, M. Balouktsi, T. Lützkendorf, A. Houlihan-Wiberg (2022). Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey – A Contribution to IEA EBC Annex 72: Energy in Buildings and Communities Technology Collaboration Programme. Published by *Verlag der Technischen Universitat Graz, Austria.*

Author contributions

Primary publications:

I. The contributions of Daniel Satola were the main elements of research design, data gathering (together with co-authors), modelling and analysis, evaluation of results and conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with co-authors. The co-authors were also central in developing the research questions and research design.

II. The contributions of Daniel Satola were the main elements of research design, data gathering (together with co-authors), modelling and analysis, evaluation of results and conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

III. The contributions of Daniel Satola were the main elements of research design, data gathering, modelling and analysis, evaluation of results and conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with co-authors. The co-authors were also central in developing the research questions and research design.

IV. The contributions of Daniel Satola were developing and validation of the building performance model (BPS), which is a core methodology of the case study. Detailed feedback on the methodology, results, discussion, conclusions in the manuscript were given by Daniel Satola in multiple iterations. The manuscript was written together with all authors.

V. The contributions of Daniel Satola were the main elements of research design, data gathering, modelling and analysis, evaluation of results and conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with co-authors. The co-authors were also central in developing the research questions and research design.

VI. The contributions of Daniel Satola were the main elements of research design, data gathering, modelling and analysis, evaluation of results and conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

Secondary publications:

I. The contributions of Daniel Satola were the main elements of research design, data gathering, modelling and analysis, evaluation of results, conclusions and writing of the article with feedback from the co-authors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

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Part A

Binding article

1. Introduction

1.1 Climate emergency

Certain gases in the atmosphere that block heat from escaping in space include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x) and chlorofluorocarbons (CFCs) (NASA, 2017). These gases are referred to as greenhouse gases (GHGs), and they contribute to the greenhouse effect and global warming. Climate change is mainly caused by human activities. The concentration of GHGs has been rising since the Industrial Revolution, with the most abundant GHG, carbon dioxide (CO_2), being the primary product of fossil fuel combustion (IPCC, 2014). The expansion of GHGs contributes to the global warming trend, with the global average temperature being 1.1 °C above the pre-industrial period and the highest on the record average temperatures for five- and ten-year periods (NASA, 2017). The rise in global temperature is the most evident effect of climate change; other harmful consequences include: i) more severe storms, ii) increased drought and heat waves, iii) warming, rising oceans, iv) loss of species, v) increased health risk and vi) poverty and displacement (IPCC, 2022).

The current global scientific and policy consensus is to reduce the emission of GHGs and related global warming as much as possible. One of the most significant steps toward climate change mitigation is the Paris Agreement, adopted by 196 parties in Paris in December 2015 (UNFCCC, 2015). Its goal is to limit global warming to well below 2 °C and preferably to 1.5 °C above pre-industrial levels. The Paris Agreement requires each party to prepare, communicate, maintain, and update nationally determined contributions (NDCs) to reduce national GHG emissions. Up until now, more than 110 countries responsible for more than 65% of GHG emissions have already committed to achieving a nationwide net-zero GHG emission balance by 2050. A net-zero GHG balance is achieved when the total aggregate GHG emissions over a given period are equal to an equivalent amount of the aggregate GHG removal (Allan, Hawkins, Bellouin, & Collins, 2021). Despite such ambitious political commitments and scientific warnings, there has been no significant reduction in global GHG emissions in the past years. A recent report published by the United Nations Framework Convention on Climate Change (UNEP, 2021) illustrates that the new and updated NDCs are insufficient to achieve the temperature goal set by the Paris Agreement. By 2030, GHG emissions would need to be 30% and 55% lower than in 2021 to put the world on the least-cost pathway to limiting global warming to below 2 °C and 1.5 °C above pre-industrial levels, respectively (UNEP, 2021).

Consequently, there is an urgent need to increase global climate mitigation efforts by i) implementing net-zero emission commitments in the national law, ii) increasing the robustness of the net-zero commitments, and iii) introducing short-term actions that give the confidence that net-zero targets can be achieved (UNEP, 2021).

1.2 Global environmental challenges in the construction sector

Buildings and the related construction industry play a key role in global climate change as they contribute to nearly 40% of the global GHG emissions and 36% of final energy use (United Nations Environment Programme, 2021). Additionally, roughly half of the globally extracted raw materials are consumed in the construction sector, which creates an estimated one-third of the world's overall waste (Huang et al., 2020). Building operations related to energy use, such as heating, cooling, domestic hot water, ventilation, lighting, and equipment use, account for 28% of energy-related GHG emissions (Abergel, Dean, & Dulac, 2017).

In this context, buildings present a significant potential to reduce GHG emissions by implementing energy-efficiency measures that can decrease operational energy use. The IPCC has emphasised the importance of this strategy by stating that «1.5 °C-consistent pathways require building-related GHG emissions to be reduced by 80–90% by 2050, and new construction to be fossil-free and near-zero energy by 2020», and the need for «an increased annual rate of the energy refurbishment of existing buildings to reach 5% target in OECD countries» (de Coninck et al., 2018). Additionally, in the pathways limiting global warming to 1.5 °C, the share of electricity in the energy demand of buildings should be about 55–75% in 2050, thus widely eliminating the GHG emissions from fossil fuel combustion (Allan et al., 2021).

To date, the GHG emission reduction strategies in the global construction sector have mainly focused on reducing operational energy use through improving energy efficiency and increasing the energy coverage from renewable energy sources. This approach has been fundamental in establishing the energy efficiency requirements in binding building policies and developing the zero-energy and nearly zero-energy building concepts (described in detail in section 1.4). However, as recent studies have shown, the success in reducing operational energy demand and related GHG emissions has been accompanied by an increase in embodied GHG emissions in relative and absolute terms (Chastas *et al.*, 2018; Röck *et al.*, 2020). This increase is especially evident for the new advanced and highly energy-efficient buildings powered by a low GHG emission-intensive electricity grid. In such buildings, the average share of the embodied emissions is 45–50% of life cycle GHG emissions and surpasses 90% in extreme cases (Röck et al., 2020). Adding the fact that embodied GHG emissions are responsible for 11% of the total GHG emissions related to the global construction sector, a shift from efficiency in operation towards a full life cycle perspective is required in designing, constructing, using and deconstructing buildings (IEA, 2019; WorldGBC, 2019). Addressing and reducing the initial and upfront embodied GHG emissions from the production of building materials and systems are essential for achieving climate goals and net-zero GHG emissions globally (Allan et al., 2021). The first action toward lowering the life cycle GHG emissions in national building stock has recently been accelerated by building policymakers in France (French Government, 2020), Finland (Kuittinen & Häkkinen, 2020), Sweden (Boverket, 2019) and Denmark (Ministry of the Interior and Housing, 2021), who introduced mandatory limit values of life cycle GHG emissions relating to the construction and operation of new buildings.

However, on policy and scientific levels, most of these climate mitigation efforts in the construction sector have been taking place in developing economies in the Global North. The existing body of literature (Table 1) has mostly analysed buildings in cold and temperate climates. Hence, there is a research gap regarding GHG emissions across the life cycle of buildings located in warm and humid, subtropical, and tropical climate regions. This gap in the literature is significant, considering the geographic extent of these climate regions and the number of people inhabiting them. Considering current and future GHG emissions, humid subtropical and tropical climates are widely recognised as critical regions for mitigating global climate change.

Table 1 Overview of literature review articles analysing buildings' life cycle emissions

Reference	**Number of Cases Analysed**	**Typology (Residential, Office, etc.)**	**Climate Region Focus**	**Life Cycle Stages (Embodied, Operational)**	**Indicator/s**
(Ramesh, Prakash, & Shukla, 2010)	73	Residential and office buildings	Temperate (C), continental (D)	Embodied and operational	Primary energy
(Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014)	38	Residential, office and industrial buildings	Temperate (C), continental (D)	Embodied and operational	Primary energy, GHG emissions
(Säynäjoki et al., 2017)	116	Residential, office and communal buildings	Temperate (C), continental (D)	Embodied	GHG emissions
(Chastas et al., 2018)	95	Residential	Temperate (C),	Embodied and operational	GHG emissions
(Röck et al., 2020)	238	Residential and office buildings	Temperate (C), continental (D)	Embodied and operational	GHG emissions

1.3 Decarbonisation of the residential construction sector in developing economies of humid subtropical and tropical climates—crucial action for combating climate change and its impacts

The humid subtropical and tropical climates are one of the major and most extensive climate types of the Köppen-Geiger classification (Kottek et al., 2006) (Figure 1) and are widely recognised as one of the most GHG emission-intensive regions in the world, with a high share of impact coming from the construction sector, especially residential. At the same time, these climate zones are among the most vulnerable regions of the world with regard to climate change (Asian Development Bank, 2015). The main regions contributing to GHG emissions and global climate change in humid subtropical and tropical can be recognised in the:

i) **South and South-East China,** recognised as China's most populous and economically developed area. GHG emissions from buildings and related construction contribute to nearly 30% of final energy use and 20% of the overall GHG emission in China, representing nearly 6% of the global GHG emissions (Liu, 2016). The residential sub-sector represents roughly 85% of the total building sector's final energy use. The coastal, humid subtropical regions are experiencing the most rapid urbanisation in China and are expected to achieve a 75% urbanisation rate (share of urban population) by 2030 (Liu & Cai, 2018). The major developed mega-cities: Shanghai, Suzhou, Guangzhou and Tangshan, are located in warm, humid subtropical climate zones and are the largest GHG emitters in China with higher per capita GHG emissions than those in European and North American Cities (Liu & Cai, 2018; Wang, Song, He, & Qi, 2015).

ii) **India,** which is the seventh-largest country in land area and recently (April,2023) overtook China to become world's most populous country. India's energy consumption and related GHG emissions have tripled between 1990 and 2018, making it the third largest GHG emitter globally with nearly 7% of the global share (IEA, 2021). Almost 47% of total final energy use and about 22% of GHG emissions are connected to the construction sector, wherein residential construction amounts to 93% of the share (Central Electricity Regulatory Commission, 2019). Most of India is covered by humid subtropical and tropical climate zones.

While the residential building sector's final energy consumption and GHG emissions have considerably increased in China and India since 2000, on a per unit basis (per person or m^2), these countries use significantly less energy and produce less GHG emissions than most developed countries in the Global North (IEA, 2015). This is mainly related to lower living standards and limited access to building services such as thermal conditioning and amenities that are only available to consumers with higher income levels. As living standards in China and India continue to improve, the building energy intensity and related GHG emissions are also expected to increase (IEA, 2021).

At the same time, by 2060, more than half of the new residential buildings are expected to be constructed in African, Asian, and Latin American regions that are covered by humid subtropical and tropical climates (Dean et al., 2016).

Additionally, in these regions, there is an urgent need to address Sustainable Development Goal 11: *Sustainable Cities and Communities,* by providing access to adequate and affordable housing for nearly one billion people living in slums (Missingham, 2020). Even nowadays, there exists a huge gap in access to air conditioning, which is critical for protecting the occupants of a house from the adverse effects of heat exposure that are getting stronger and longer due to global warming. Of the nearly three billion people living in the hottest part of the world (dominantly covered by humid subtropical and tropical climates), most of whom are located in developed economies, only 8% have cooling devices (United Nations Environment Programme (UNEP), 2020). Consequently, with improved access to electricity and enhanced building facilities and services, such as air-conditioning, the extensive growth of construction can double or even triple current GHG emissions by 2060 (Pachauri et al., 2014).

In addition to its crucial contribution to global environmental impacts in the form of global warming potential, the residential construction sector in humid subtropical and tropical climates also strongly contributes to the local environmental effects. Outdoor air pollution from fine particulate matter can be recognised as the most harmful local impact as it contributes to more than four million premature deaths each year. More than half of these deaths occur in India and China and are related to the extensive combustion of coal for energy production (Health Effects, 2017).

Consequently, the transition towards more energy-effective and zero/low GHG emission construction stock, especially with a special focus on the residential sector in warm, humid subtropical and tropical climates, is one of the most challenging and, at the same time, promising strategies for global climate change mitigation and improving the health and living conditions for billions of people.

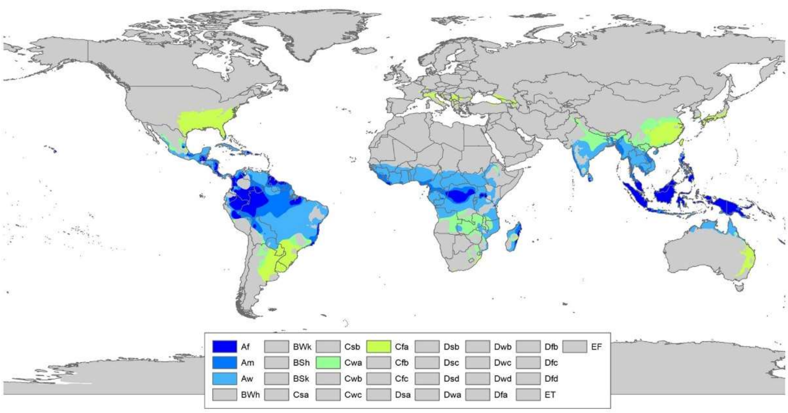


Figure 1 Humid subtropical (Cfa and Cwa) and tropical climates (Af, Am, and Aw), according to the Köppen Geiger classification (Kottek et al., 2006)

1.4 The transition from nearly/zero energy toward net-zero (GHG) emissions building design

Since the 1970s energy crisis, numerous concepts to develop environmentally friendly buildings have been developed within the construction sector, such as green building, eco-house, solar-house, active-house, recycled house, low-energy, and passive houses.

The Energy Performance of Buildings Directive (EPBD), introduced in 2010 by the European Parliament, requires all European Union (EU) member states to ensure that all new buildings constructed from 2021 be nearly zero-energy buildings (nZEB) (European Parliament, 2010). Here, nZEB is defined as a "building *with very high energy performance, and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources on-site or nearby*". The definition of nZEB performance is mainly based on the numerical indicator related to the maximum primary energy use expressed in kWh/m^{2}year. However, the EPBD does not define the concrete threshold or ranges related to primary energy requirements and defines the nZEB target in a nonspecific manner by taking into account multiple criteria, such as the specific country climate locations, energy mix, economic conditions and ambition levels. This is the main reason for the large range in the established nZEB energy performance requirements in EU countries, which vary from 20 kWh/m^{2}year (Belgium Flanders) to 132 kWh/m^{2}year (Estonia) in new residential buildings (D'Agostino *et al.*, 2021). Consequently, some country-specific nZEB definitions do not align with the long-term climate neutrality goals set by the EU.

China has been actively implementing energy efficiency codes and standards for buildings over the past decade. The China Design Standard for energy efficiency in public buildings (GB 50189) debuted in 2005 when China completed its 10th Five-Year Plan. GB 50189-2005 was crucial in regulating energy efficiency in Chinese commercial buildings. The standard was recently updated in 2014 to increase energy savings targets by 30% compared with the 2005 standard (Hong, Li, & Yan, 2015). Based on the climate conditions, which vary significantly from region to region in China, leading to the different thermal characteristics of building energy consumption, the national regulation (Ministry of Housing, 2005) defines five main climate zones according to the mean temperature of the coldest and hottest month: Severe Cold (SC), Cold (C), Hot Summer and Cold Winter (HSCW), Hot Sumer and Warm Winter (HSWW) and Temperate Zone (T). On average, total energy consumption in urban residential buildings in China is around 105 kWh/m^{2}a, with the dominant contribution coming from appliance and lighting use (36%) and cooking (29%). However, the energy use intensity of space heating varies significantly; for the HSCW climate zone, the average value is 16 kWh/m^{2}a, whereas in the SC and S climate zones the average value is close to 90 kWh/m^{2}a. A similar average value (12 kWh/m^{2}a) can be observed in the HSCW climate zone for space cooling, which is about 2 to 3 times higher than in the temperate climate zone (Jiang et al., 2017).

The set of mandatory design standards for energy efficiency of residential buildings are a part of legally binding policy in China and are specified based on the climate zones: JGJ26 (2010) (severe cold and cold zones), JGJ134 (2010) (hot summer and cold winter and temperate zones) and JGJ75(2012) (hot summer and warm winter zone). None of these standards provide specific maximum values of the annual energy demand; however, they provide the minimum performance indicators related to the energy efficiency of the: i) building envelope, ii) HVAC systems and iii) lighting and electrical system.

With rapid urbanisation, the building sector in India is experiencing unprecedented growth. The Energy Conversation Building Code (Ministry of Power, 2017), launched in 2007, was the first-ever initiative by the Government of India to address energy efficiency in the commercial building sector. The building code was revised in 2017 and applied to buildings or complexes with a connected load of 100kW and to additions and major renovations with a floor area larger than 1000m^2. Based on the gained experience from commercial buildings, in 2018, the new standard for residential buildings, Eco-Niwas Samhita 2018 (Bureau of Energy Efficency (BEE), 2018), was published. The standard requirements apply to residential buildings with a floor area larger than 500m^2 and are mainly targeted at setting the minimum building envelope performance benchmarks to limit heat gains (for cooling-dominated climates) and heat loss (for heating-dominated climates). The standard provides different energy efficiency benchmarks following five climate zones in India (hot-dry, warm-humid, composite, temperate, and cold). The hot-dry, warm-humid, and composite climates are cooling-dominated. Compliance with commercial and residential Energy Conversation codes is voluntary at the national level; however, several states and cities have made it mandatory.

The more ambitious concept of zero-energy buildings has already gathered significant attention and market implementation worldwide. According to the definition developed for the U.S. Department of Energy by The National Institute of Building Science, a zero-energy building is an "*energy-efficient building, where on a source energy basis, the annual delivered energy is less than or equal to the on-site renewable exported energy*". The definition of "source energy" is in line with the primary energy indicator (EU) definition, and is calculated from delivered energy and exported energy for each energy category type using source energy conversion factors (US Department of Energy, 2015). In zero-energy building accounting, on-site renewable energy is considered a zero-energy loss resource, and the exported electricity produced on-site displaces electricity that would be required from the grid. The definition of a zero-energy building requires on-site renewable energy to be used to fully offset the actual annual delivered energy. However, in the case of multi-storey buildings with limited renewable energy generation potential or energy-intensive buildings such as hospitals, renewable energy certificates (REC) are allowed as a supplement to balance the energy delivered to the building annually. In that case, the buildings are defined as "Renewable Energy Certificate Zero Energy Buildings" (US Department of Energy, 2015).

So far, the concepts and definitions of sustainable buildings have been focused on zero or nearly zero energy targets in building operations. However, in recent years, the focus has shifted towards the more holistic life cycle approach with GHG emissions as a metric instead of relying on energy demand as a proxy for measuring a building's performance regarding its impact on global warming. A new norm has emerged with goals with various synonyms, such as (nearly) carbon-neutral, (net) zero-carbon, climate neutral, carbon ready, and (net) zero emissions buildings, and target values such as (net) zero GHG emissions in the operation or life cycle of buildings.

In December 2021, the EU proposed moving from the current nearly zero-energy buildings to a zero-emission building target by 2030 to align with a long-term climate neutrality goal. Here, a zero-emission building (ZEB) is defined as a "building with very high energy performance, with a very low amount of energy still required, fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels". While the proposal focuses on reducing operational GHG emissions, the ZEB definition further includes the calculation of life cycle global warming potential (GWP) and its disclosure through the building's energy performance certificate. However, more ambitious goals, including measuring and offsetting the embodied type of GHG emissions, are needed to achieve climate-neutrality targets by 2050 (World Green Building Council, 2019).

The Norwegian Research Centre on Zero Emission Buildings, established in 2009, can be recognised as the frontrunner with respect to the definition, research, and implementation of zero-emission buildings in its national building stock. The main vision of the ZEB Centre is to eliminate the life cycle GHG emissions caused by buildings. Hence, the main objective of the research and development activities has been to develop competitive products and solutions for existing and new buildings that will lead to the market penetration of buildings with zero emissions of GHGs related to their production, operation, and demolition. The work at the ZEB centre resulted in the development and further market implementation of the zero-emission building definition with different performance ambitions. The different ambition levels of ZEB are founded on the life cycle assessment (LCA) boundaries as put forth in EN15978 and defined in the rising ambition levels as below (Fufa et al., 2016):

ZEB–O÷EQ describes a building for which on-site renewable energy production compensates GHG emissions related to the operation of the building - O (ventilation, heating, hot water, lighting), excluding (÷) energy required for equipment and plug loads (EQ),

ZEB–O describes a building where on-site renewable energy production compensates the GHG emissions related to the operation of the building – O, including energy for equipment and plug loads,

ZEB–OM describes a building for which on-site renewable energy production compensates GHG emissions related to the operation (O) of the building, as well as emissions from the production (A1–A3) and replacement (B4) of building materials,

ZEB–COM describes a building for which on-site renewable energy production compensates GHG emissions related to the operation of the building (O), production (A1–A3) and replacement (B4) of building materials and building construction process (A4-A5), and

ZEB–COME describes a building for which on-site renewable energy production compensates GHG emissions related to the entire lifespan of the building (product stage, construction process, use stage and end of life).

The Norwegian framework of zero-emission buildings follows the net-balance approach (type A) based on "potentially avoided' emissions (type Aa) as proposed by the classification developed by Lützkendorf & Frischknecht, (2020). In this approach, the life cycle GHG emissions are balanced by renewable energy that is generated on-site. The surplus of energy can be exported to the local electricity grid, while the related environmental benefits (off-sets) are fully attributed to the building. Approach Aa can be problematic because it bears the real risk of double-counting emission reductions of both the producer (the building) and the user (purchaser of exported energy).

The other proposed approaches for net-zero and zero-emission building are further described by Lützkendorf & Frischknecht, (2020) and include:

Ab: Net-balance approach with allocation, where no potential environmental benefits (off-sets) from exported energy are attributed to the building. In this approach, the zero-emission building ambition cannot be reached with only on-site renewable energy generation and needs to be combined with either approaches B or C.

B: Economic compensation approach based on compensating emissions using purchased CO_2 emissions. The advantage of this approach is cost efficiency and easy implementation.

However, the main disadvantage is that it does not sufficiently contribute to the global net-zero GHG emission target since the building still emits GHG (for which emissions certificates are purchased).

C: Technical reduction approach using technical reduction measures such as i) afforestation, ii) biogenic energy resources with carbon capture and storage (BECCS) or direct air capture with carbon separation and storage (DACCS) to extract CO_2 emissions from the atmosphere. The main advantage of this approach is the direct reduction of the CO_2 concentration in the atmosphere. However, nowadays, technology is only available on a small scale and requires high investment cost.

1.5 Motivation, scope, and research questions

1.5.1 Motivation

The motivation for this PhD thesis comes from the world's most urgent and challenging mission related to combating climate change, which is also a key opportunity to build a better future for the next generations. According to the International Panel on Climate Change (IPCC, 2016), international research collaboration is vital for the successful decarbonisation of regions that are critical to global climate change. Consequently, this thesis focuses on developing the concepts of zero and low GHG emission residential buildings in humid subtropical and tropical climate zones, particularly in emerging countries, which can contribute to the decarbonisation of the construction stock and improving the health and wellbeing of the occupants simultaneously.

1.5.2 Scope and research questions

The general topic of the thesis is the exploration and development of low and zero-emission GHG building concepts and GHG emission reduction strategies, with the main focus on residential buildings located in emerging economies covered by warm and humid climates. The scope of the research follows a life cycle approach investigating both operational and embodied environmental impacts, with the main focus on greenhouse gas emissions and associated GWP.

The research included in the thesis follows two main interconnected directions. The first one is related to the more generic research that focuses on harmonising and fostering the transparency of the existing net-zero GHG emission-building definitions or schemes as the base for developing country-specific or regional frameworks or building policies further. Additionally, it investigates the influence of the energy-efficiency requirements present in mandatory building codes in the selected locations of the humid subtropical climates on the life cycle GHG emission profile and achievement of the net-zero GHG emission performance in a single-family building. The second direction uses a more specific case study research approach for locations in India and China to explore low-emission building concepts and design strategies that can successfully reduce the environmental impacts of residential buildings.

Consequently, taking advantage of established international research networks with China and India, the research scope focuses on two case studies, one of which is related to energy-efficient, container-based residential units, with the possibility of off-grid operation, and the other is related to a low-carbon multifamily building.

The thesis tries to answer the following research questions:

RQ1: How can the transparency and credibility of net-zero GHG emission-building definitions be improved?

RQ2: How do local conditions and binding building policies influence GHG emissions and the achievement of the net-zero GHG emission performance target of residential buildings in humid subtropical climate regions?

RQ3 What is the current state and the existing research gap related to life cycle GHG emissions of residential buildings in tropical and humid subtropical climate regions?

RQ4: How do off-grid container-based housing units perform in the humid subtropical South-East China context in terms of initial investment cost and life cycle impacts, compared to other more conventional design scenarios?

RQ5a What are the most influential design parameters and optimal design solutions for low GHG emissions in a multifamily building design in the warm climate zones of India?

RQ5b What are promising design strategies for GHG emission reduction in residential buildings in tropical and humid subtropical regions?

The answers to these research questions are given using the work developed in six research papers, as presented in Figure 2 below.

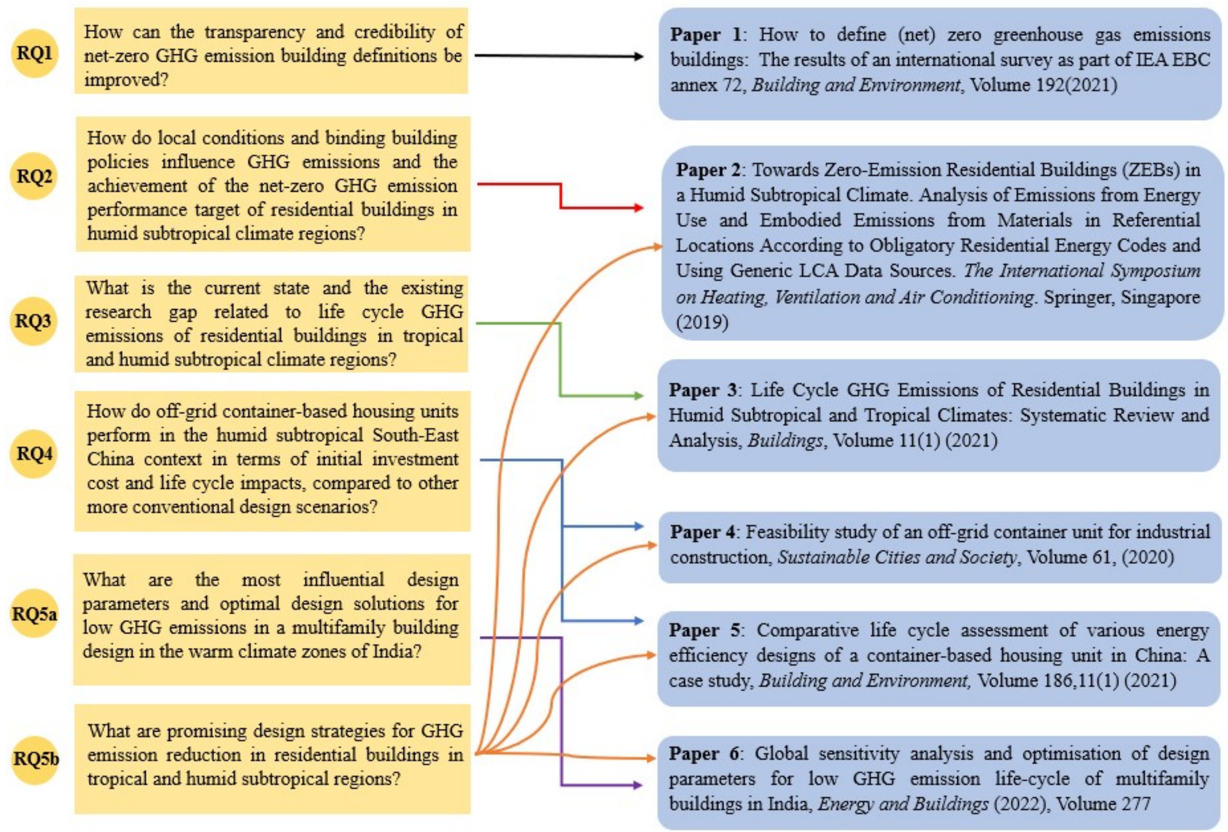


Figure 2 Organisation of the research questions in the thesis and their answers in the research papers contributions

1.6 Structure of the thesis

A binding article (*Norwegian "kappe"*, part A of this thesis) provides an introduction to the topic, summarizes the problems, results, and conclusions presented in the included articles and documents their interrelationship within the thesis.

Consequently, the context and theoretical background of the research in this thesis are presented in Chapter 1. Chapter 2 provides an overview of the methodology used in the research papers included in the thesis. Chapter 3 presents a summary of each of the primary publications. A discussion of the results in relation to the research questions is presented in Chapter 4, together with the presentation of the scientific contribution of this thesis and the outlook in terms of future work and policy recommendations. Chapter 5 draws the conclusions. Section 6 lists the references.

Part B of this thesis contains the scientific papers that provide the basis for the dissertation, either as the published version or as the submitted manuscript.

2. Methodology

2.1 Systematic literature review

A literature review is an essential method and feature of academic work that enables an understanding of the depth of existing work and helps to identify research gaps that can be explored. Depending on the purpose of the literature review, there are many useful methodological approaches, including integrative, semi-systematic and systematic (Snyder, 2019). A systematic literature review can be defined as a research method and process for identifying and evaluating a clearly formulated research question using systematic, explicit and well-documented methods to collect, select and critically appraise relevant research (Moher, Liberati, Tetzlaff, & Altman, 2010). The main aim of a systematic review is to collect and analyse the empirical data that fits the pre-specified inclusion criteria to answer a particular research question or hypothesis. Implementing screening and inclusion measures in the systematic review process minimises bias and provides more reliable findings (Xiao & Watson, 2019). A good systematic literature review should incorporate a meta-analysis, which involves the application of suitable statistical methods to compare and evaluate the quantitative results from multiple literature studies to present the general trends and knowledge on a given topic or a research question (Littell, Corcoran, & Pillai, 2008).

The systematic literature review and meta-analysis methods included in the research activities described in this thesis followed the four-step approach developed and described by Moher et al., (2010) as a part of the PRISMA framework, which is in line with the more recent guidelines for conducting a systematic literature review (Xiao & Watson, 2019). The four phases of a systematic review include (Figure 3):

i) The identification phase, which includes a general searching strategy and uses global databases for literature positions.

ii) The screening phase, which evaluates the identified studies based on the established inclusion and exclusion criteria.

iii) The eligibility phase, which evaluates the already collected and screened studies based on quality assessment and full text of the article.

iv) The inclusion phase, which is the final step and is based on data extraction, analysis, and meta-study findings.

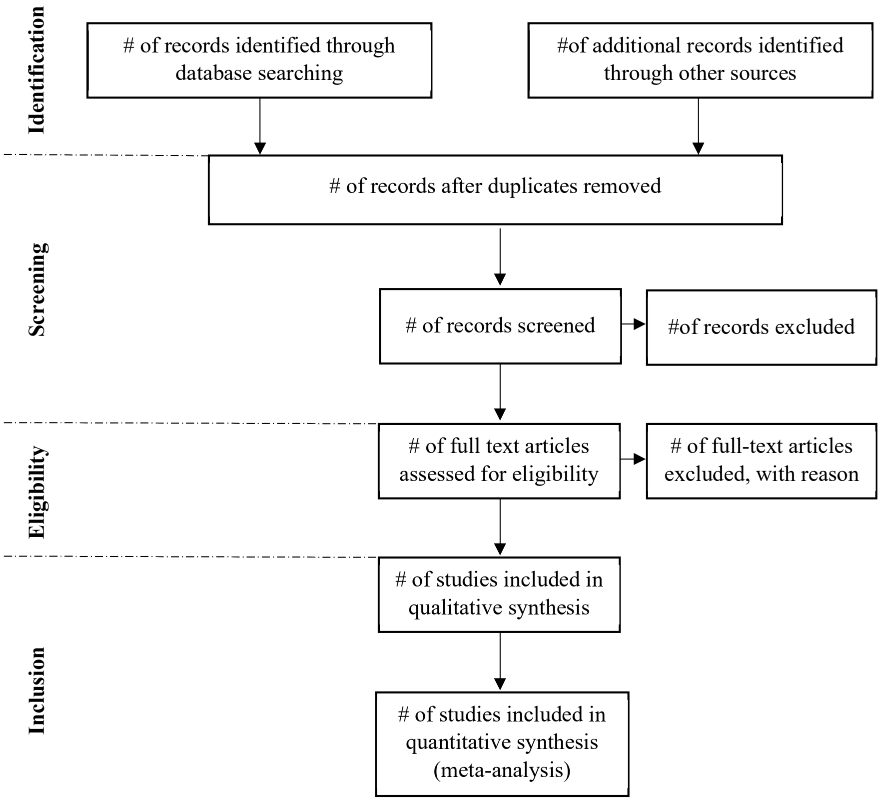


Figure 3 Flow of information through the different phases of a systematic review. Adopted from Moher et al. (2010)

2.2 Life cycle assessment of buildings

Life cycle assessment (LCA) is a tool for quantifying the environmental performance of products considering their complete life cycle, starting from the production of raw materials to the final disposal of the products. Consequently, the LCA applied to the buildings and construction sector is widely recognised as a leading quantitative and scientific basis for research and development activities related to environmentally friendly building designs and the development of concepts, strategies, and roadmaps toward the carbon neutrality of buildings and the related construction sector.

Based on the principle standard for LCA, ISO 14040 (ISO, 2006), the LCA method is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 4). The following sub-section explains these steps and describes the essential methodological features of LCA applied to the case study research and resulting publications in this thesis (Paper II, V and VI).

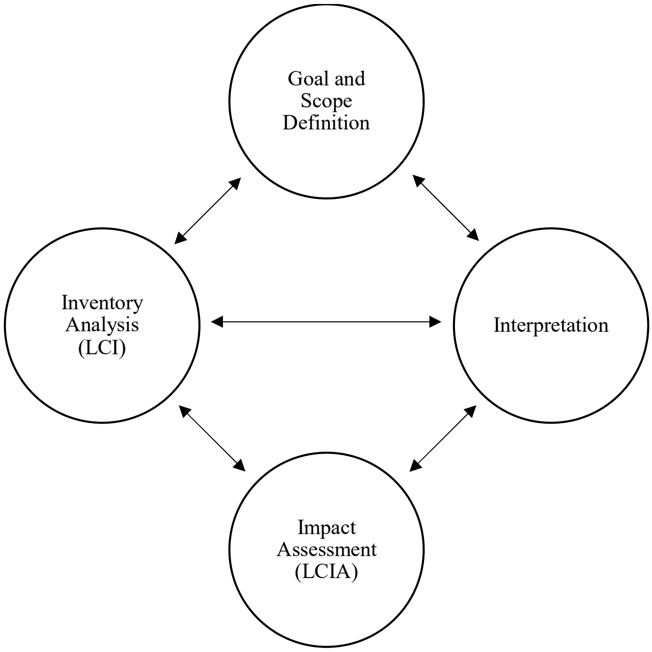


Figure 4 Life cycle assessment framework according to ISO 14040 and ISO 14044

2.2.1 Goal and scope definition

a) Functional unit

The first phase defines the goal and scope, functional unit, system boundaries, and allocation procedures with respect to a particular LCA. The functional unit is a quantified description of the product's function, which serves as the reference basis for all calculations regarding impact assessment. Consequently, a clear definition of the functional unit is important for the final usability of the performed LCA. Using the different functional units in building-based LCA studies makes it difficult to compare results with benchmarks and results of previous studies (Chau, Leung, & Ng, 2015). To enable such comparisons, according to ISO21931-1 and EN15978, a functional unit must include, but not be limited to, the following information: i) building type, ii) pattern of use and iii) required service or design life. The choice of the main functional unit differed in each case study and was based on the specific research questions and objectives (Table 2).

Paper II investigates the life cycle GHG emission profile and the feasibility of achieving zero-emission performance in different locations in the humid subtropical climate based on the performance levels defined in the Norwegian Zero Emission Building Framework. Consequently, the functional unit is in line with the ZEB standard and is defined as a heated floor area of $1m^2$ over the established lifespan of 60 years [$kgCO2eq/m^2year$].

In paper V, the functional unit was defined as the total gross building area over a building life span of 25 years [kgCO2eq]. The rationale for this choice was based on existing research on temporary and social housing in East Asia, which enables a fair comparison of results.

In paper VI, the functional unit of the life cycle GHG emissions is defined as per capita (occupant) over a year [kgCO2eq/capita year]. The selection of this unit over the most used floor-based indicator is recommended when assessing the influence of the different space efficiency design parameters and strategies (de Simone Souza et al., 2021). In addition, the supplementary information presented in each research paper enables the easy transformation of the main functional units into others that are commonly present in the existing literature.

b) System boundary:

A system boundary determines the unit processes taken into account for the object of assessment. Hence, according to the EN15978:2011 standard (CEN, 2011), the system boundaries of the building-oriented LCA include the product stage (Modules A1–A3), the construction stage (A4–A5), the use stage (B1–B7), the end-of-life stage (C1–C4) and module D, which allocates the benefits and loads due to the recycling, recovery or reuse of materials (Figure 5). The selection of the system boundaries in a building LCA can be subject to different scopes and availability, resulting in the lack of comparability between case studies and decreasing the accuracy and validity of results (Chastas et al., 2018b; Rasmussen, Malmqvist, Moncaster, Wiberg, & Birgisdóttir, 2018). However, the environmental impacts from the product (A1-A3) and use stage (B4 and B6) present the highest share of the life cycle impacts (Birgisdóttir, Houlihan-Wiberg, Malmqvist, Moncaster, & Rasmussen, 2016; Röck et al., 2020).

The system boundaries of the LCA included in Paper V cover the complete life cycle scope (A1–D). On the other hand, system boundaries in Paper II and VI are limited to the product stage (A1–A3), replacement (B4) and operational energy use (B6) modules (Table 2), whose related impacts dominate the building life cycle and are the most affected by early design choice.

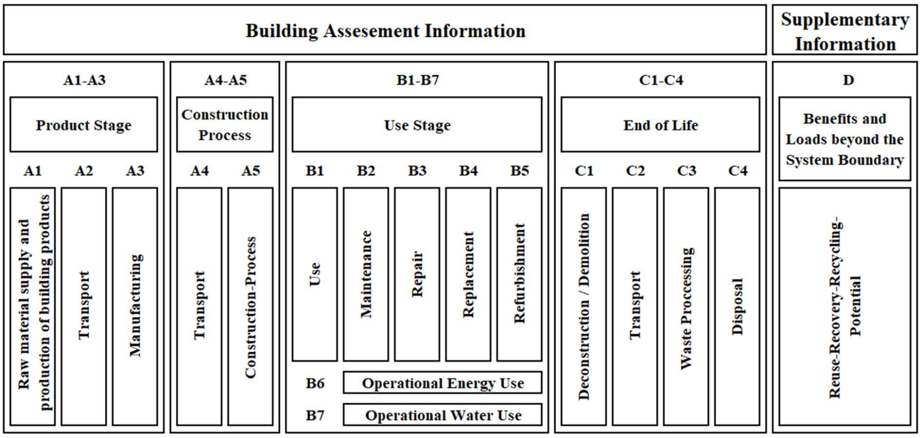


Figure 5 System boundaries according to EN15804/15978 (CEN, 2011)

2.2.2 Inventory analysis and databases

Inventory analysis refers to quantitative data analysis of resources, energy consumption or emissions in the environment through the life cycle stage of a single product, process, or activity resources. For life cycle inventory analysis, it is common to distinguish between attributional and consequential modelling. The attributional approach describes the potential environmental impacts attributed to the product system, on average, for a specified time. Alternatively, the consequential approach aims to identify changes in the system due to the different marginal changes or decisions. The attributional approach is much more widely implemented in the carbon footprinting or LCA of a specific product or building than the consequential approach, which is applied in a more macro-economic context and policy development (Schuller, Baitz, Saint Antonin, & Sabathier, 2020).

Specific inventory product data is usually gathered from many stakeholders and background information. Several generic product databases are available for buildings and related construction sectors, including the most popular ones: Ecoinvent (Wernet et al., 2016) and Gabi Database (Sphera Solutions, 2020), which, to some extent, also cover the regional and country-specific inventory process. The use of a generic LCI database may limit the representativeness and accuracy of LCA, as activities related to the production of construction materials and energy generation vary around the world in terms of quantity of used raw materials, electricity mix, and production efficiency (Zea Escamilla & Habert, 2017). The generic and product specific LCI databases can present significantly different values related to the environmental impact. This difference is generally low for the environmental impacts correlated with fossil fuel consumption, such as global warming potential and primary energy demand. However, the variation can be high, especially for photochemical ozone formation, radioactive waste and abiotic depletion potential indicators (Lasvaux, Habert, Peuportier, & Chevalier, 2015).

The Ecoinvent 3.4 database with adjusted data, considering the local electricity mix, is the primary LCI database used in the life cycle assessments presented in Paper II and V. In the case of Paper VI, the country-specific India Construction Materials Database of Embodied Energy and Global Warming Potential (IFC, 2017) is used, and is supported by the adjusted Ecoinvent 3.6 database (Table 2).

2.2.3 Impact assessment

Life cycle impact assessment (LCIA) is the method for converting inventory data from a life cycle assessment into a set of environmental impacts utilising characterisation factors. Characterisation refers to the calculation of the magnitude of the contribution of each classified input and output to their respective impact categories and the aggregation of these contributions within each category. There are numerous developed and available methods for calculating the impact assessment in an LCA. The most popular methods include CML (Van Oers, 2015), ReCiPe (Huijbregts et al., 2017) and TRACI (Bare, 2011) for the evaluation of several impact categories, or the Cumulative Energy Demand (CED) (Hischier et al., 2010) and IPPC2013 (GWP100) (Stocker, 2014) methods for a single impact category.

The comparative LCA presented in Paper V was based on a combination of the ReCiPe impact assessment method and the single-issue CED method. The main reason for choosing the Recipe Midpoint Hierarchist method is that, unlike most other methods, it allows calculating the environmental impacts of particulate matter formation and water depletion (consumption). Despite being usually excluded in LCA of buildings, assessing these impact categories is crucial for addressing and increasing awareness of local environmental problems in China and other East Asian countries related to respiratory health problems and water scarcity. Additionally, where possible, it uses impact mechanisms that have a global scope and offer the possibility of weighting and aggregating a number of chosen impact categories.

On the other hand, the LCIA presented in Papers II, and VI was based on the single impact category- global warming potential with a 100-year time frame (GWP100), following the IPPC2013 method. The rationale for the choice of this method is based on its simplicity and well-established status in research. In addition, the India Construction Materials Database of Embodied Energy and Global Warming Potential, extensively used in paper VI, is based on the IPPC2013 method. Different impact assessment methods may lead to variation in the life cycle assessment results, especially for the local impact categories such as acidification and eutrophication. On the other hand, the choice of the impact method presents almost no variation for climate change since most of the available methods (including Recipe Midpoint Hierachist) follow the characterization model of the IPCC with a time horizon of 100 years.

2.2.4 Interpretation

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate the information from the previous steps of LCA and life cycle inventory and impact assessment. The outcome of the interpretation phase is a set of conclusions and recommendations for the study (Finkbeiner, Inaba, Tan, Christiansen, & Klüppel, 2006).

2.3 Building performance simulations

Computational building performance modelling and simulation is a multidisciplinary numerical-based method that aims to provide an approximate solution to a realistic model of complexity in the real world (Hensen, 2012). When used appropriately, building performance simulation (BPS) has the potential to reduce the environmental impact of the built environment, to improve indoor quality, as well as to facilitate future innovation and technological progress in construction towards zero-emission goals (Clarke & Hensen, 2015).

In this thesis, dynamic BPS is used extensively to evaluate the building's energy use, renewable energy potential, and indoor environmental quality factors (IEQ). Determining the annual energy use of the investigated case study buildings is the base for calculating environmental impacts related to the operational energy use stage (B6). Various building performance simulation software have been applied for the research activities included in the thesis, including IDA Indoor Climate and Energy (IDA-ICE) (Equa Simulation AB, 2019), TRNSYS (Solar Energy Laboratory, 2018), PVsyst (Mermoud & Wittmer, 2014), and Honeybee and Ladybug tools for Grasshopper environment (Roudsari, Pak, & Smith, 2013).

The relevant software and BPS methods used in the research papers were based on the research questions posed in the thesis and the specific usability and limitations of the available BPS software (Table 2).

Consequently, in Paper II, the use of operational energy by the studied single-family buildings located in different humid subtropical climate zone locations was investigated based on the dynamic, multi-zone performance model created in the IDA-ICE 4.8 software. The software is based on flexible equation-based modelling, using the Modelica-like neutral model format (NMF), and validated according to numerous standards, including ASHRAE 104 (Crawley et al., 2008) and CEN Standard 13791 (Kropf & Zweifel, 2001). Due to the limitations of the IDA-ICE software, the potential of renewable energy generation of the on-site photovoltaic (PV) system was evaluated using the PVsyst software, which is a widely used tool for solar electric production and has a large database of generic and specific PV modules and inverters coupled with performance characteristic. Similarly, the IDA-ICE software was used to create the building model of the housing unit, presented in Paper IV. The simulation model was validated based on energy consumption and indoor temperature measurements and later evaluated on energy use, indoor air quality, and various energy efficiency strategies.

Firstly, the on-site measurements based on the ISO 9869 standard were performed to verify the thermal resistance of the exterior wall of the modular unit based on the two layers of thermal insulation: 50mm of mineral wool and an 8mm layer of Vacuum Insulation Panel (VIP). The performed tests confirmed that the measured thermal performance ($R=3.7m^2K/W$) aligns with the theoretical one based on the declarations of the insulation producers ($R=3.6m^2K/W$).

Secondly, the building performance model was validated by adjusting the generic air/air heat pump model with the specific performance data delivered by the heat pump manufacturer. Additionally, the weather data was based on data from the on-site weather station.

Finally, the performed validation significantly increased the model's reliability. For example, the difference between measured and simulated energy use related to space heating (+5%) and cooling (+2%) was substantially decreased compared to the model without any validation (+13% space heating, +7% cooling).

The validated and tested building performance simulation model from Paper IV was transformed into the TRNYSYS 18.0 software building model in Paper V with new developments, including on-site PV energy systems with energy storage and management system. TRNSYS is a transient system simulation program with a modular structure. It recognises a system description language and allows the user to specify the system's components and how they are connected. The TRNSYS library, unlike other BPS software available in the market, includes elements that are commonly found in thermal and electrical energy systems and component routines to handle the input of weather data or other time-dependent inputs forcing the functions and output of the simulation results.

The core of the parametric framework developed in Paper VI was based on building energy models created in the Ladybug and Honeybee tools, which enabled the evaluation of the annual energy consumption, renewable energy generation and the occupant's thermal comfort levels. Ladybug and Honeybee support detailed daylighting and thermodynamic building performance simulations. Specifically, they create, run and visualise the daylight and radiation simulations using Radiance (Ward, 1994) and energy models with EnergyPlus (Crawley et al., 2001) and OpenStudio (Guglielmetti, Macumber, & Long, 2011). Ladybug and Honeybee tools (Roudsari et al., 2013) accomplish this by linking the Grasshopper/Rhino environments to these engines. Additionally, the flexibility of the parametric Grasshopper environment makes it possible to combine the BPS with other modules, including life cycle analysis, sensitivity analysis (SA) and optimisation algorithms, into one integrated framework (Figure 15) that supports complex design decisions (see 3.6 Paper VI, Methodology for more details).

2.4 Life cycle cost analysis (LCC)

Life cycle cost analysis (LCC) is a method for measuring and managing the lifetime cost of any project or asset. In the construction sector, the main aim of the life cycle cost analysis is to determine the economic effects of alternative or optimised design of the buildings, quantify these effects, and express them in the cost unit to support the decision-making process.

In recent years many methods for economic evaluation related to LCC have been developed, including a simple payback period (SPF), discounted payback period (DPP), internal rate of return (IRR), net savings (NS) and Present Value (PV) (Schade, 2009). Each method presents advantages and disadvantages when used in the construction sector; however, the PV approach and resulting net present value (NPV) indicator was first recommended and later applied in the ISO 15686-5 standard for the Economic Evaluation of Building Life Cycle Costs (Xie, Cui, & Li, 2022).

The concept of present (PV) value can be defined as the cost or benefit in the future discounted back to the present day using a discount rate (equation 1)

$$PV = \sum_{t=0}^{n} \frac{A_t}{(1+i)^t} \quad (1)$$

where,
A_t – Cash flow at the end of year t

i – Discount rate

Based on the recent development of the Level - EU framework of building sustainability indicators (Dodd, Donatello, Jrc, & Unit, 2021), the complete life cycle cost analysis of the building should encompass all the lifecycle stages (Figure 5), including the cost of construction, operation, maintenance, refurbishment, and disposal. The minimum scope of the life cycle analysis should include at least construction (A1-A3), replacement (B4) and energy use (B6) stages.

The research presented in Paper VI included the life cycle costing analysis as one of the objective functions in the multi-objective optimisation framework. The life cycle cost analysis's functional unit (per capita) and system boundaries (A1-A3, B4 and B6) align with the life cycle GHG emission assessment. The predicted annual increase in the electricity price in India was included in the life cycle cost calculations. Equations (2-4) present the life cycle cost calculation methodology used in paper VI.

The cost of building materials is based on the Analysis of Rates for Delhi (Government of India, 2019). The assumed electricity price of 0.08$/kWh and the increased rate of electricity cost – of 3%/year is based on the Indian central electricity regulatory commission report (Central Electricity Regulatory Commission, 2019). The discount rate – of 6% is based on the average bank rate from the last five years (2017-2022) as presented by the Reserve Bank of India (RBI) (Reserve Bank of India, 2022).

$$LCC_{capita} = \frac{LCC_{embodied} + LCC_{operational}}{n_{occupants}} \text{ [\$/capita]} \quad (2)$$

$$LCC_{embodied} = C_0 + \sum \frac{c_{comp}}{(1+i)^t} \text{ [\$/capita]} \quad (3)$$

$$LCC_{operational} = \sum_{t}^{RSL} \frac{c_{el} * (1+r)^t}{(1+i)^t} \text{ [\$/capita]} \quad (4)$$

where,

LCC_{capita} – life cycle cost per capita [$/capita]

$LCC_{embodied}$ – life cycle cost per capita, including initial material investment costs (A1 – A4)and replacement during service life (B4)

$LCC_{operational}$ – life cycle cost related to energy use (B6) [$/capita]

C_0 − initial investment cost related to building materials [$

C_{comp} − the cost of the replaced component [$]

C_{el} − the cost of electricity [$/kWh]

t − year of analysed building lifetime, $t = (0,50)$

i − discount rate [%]

r − annual increase of electricity price [%]

2.5. Sensitivity analysis

A sensitivity analysis (SA) is a scientific method for determining the variation a system/output has in response to a specific range(s) of input (Simske, 2019). Consequently, SA is an effective tool for studying the robustness of results and their sensitivity to uncertainty factors in LCA and building performance simulations. Additionally, SA can serve as a basis for identifying and choosing the critical design parameters for optimisation frameworks by simplifying the optimisation problem and significantly reducing computation time (Bre, Silva, Ghisi, & Fachinotti, 2016; Li, Wang, & Cheung, 2018). SA methods can be categorised into two main groups: local and global. The local SA assesses model response to only one local parameter, in contrast to a global sensitivity analysis (GSA), which is based on the simultaneous variation of all input factors. The model response is evaluated over the entire range or for each input factor. Consequently, GSA methods provide more accurate information about the effect of varying input factors; however, they require more computational resources. The most commonly used GSA methods include the Morris elementary effect (Morris, 1991), Sobol (Andrea Saltelli et al., 2010) and the Fourier Amplitude Sensitivity Test (Fast) (A Saltelli, Tarantola, & Chan, 1999).

In this thesis, a local SA was performed in Paper V to improve the robustness of the LCA results and investigate the significance of the study assumptions related to climate change effects and end-of-life scenarios to the final life cycle impact results. Here, the possible influence of climate change effects resulting in the change of the space heating, cooling demand, and renewable energy generation from on-site PV systems were included in the building performance simulation model and consequent life cycle model. The climate data, representative of predicted climate conditions in 2020 and 2050, which take into consideration possible climate change effects, were generated by the transformation of the baseline weather file of the building performance model (IWEC2 Shanghai) in the CCWorldWeatherGen software developed by the University of Southampton (Jentsch, James, Bourikas, & Bahaj, 2013). The underlying weather file transformation methodology is based on the IPCC Report AR3 (2001) (Cliamte change, 2001), AR4 (2007) (*Climate change, 2007*) emission scenario A2 (Nakicenovic & Swart, 2000), which assume regionally oriented economic development, continuously increasing population, and global warming gases emissions with 2.0–5.4 °C temperature increase by 2100. The rationale for choosing CCWorldWeatherGen software is the wide accessibility (free tool) and application in the research publications.

In Paper VI, the two-step GSA, based on the Morris elementary effect and the Fourier Amplitude Sensitivity Test (Fast) methods, was used to identify the most influential design parameters for life cycle GHG emissions and thermal comfort level in the multifamily building design.

2.6. Design optimisation

Optimisation can be defined as a set of applied mathematical equations that develop particular methods to find the maximum or minimum values of an objective function by changing the values of the input variables, which are characterised by bounds and constraints (Longo, Montana, & Sanseverino, 2019). Optimisation frameworks can be categorised into two main groups: single objective and multiobjective, depending on the number of objective functions to be solved. The single-objective optimisation aims to find the best solution for a specific objective function, with usually only one optimum value. However, in most cases, the optimisation problem is more complex and based on two or more conflicting optimisation goals. The solutions of multiobjective optimisation are compromise solutions that can be different from the absolute minimum or maximum of each objective function. If no preference is expressed for a specific objective function, the solutions obtained for a multiobjective optimisation will represent a set of equally optimal compromise solutions called the Pareto front (Van Veldhuizen & Lamont, 1998).

In this thesis, the multiobjective optimisation framework based on the HypE genetic algorithms was used in Paper VI to find the optimal combination of multifamily building design solutions concerning three objective functions: i) life cycle GHG emissions, ii) life cycle cost, and iii) initial material investment cost.

2.7 Case study approach

The case study approach is an empirical research method that investigates contemporary phenomena within a real-life context. The method contributes to scientific development by generalising findings on an individual case. Consequently, the case study can be defined as a well-documented and systematic examination of a project's process, decision-making and outcomes to inform future development, policy, theory and research (Francis, 2001). However, the case study research approach has been criticised, commonly in relation to methodological rigour, researcher subjectivity and external validity (Ben Willis, 2014). In the built environment, case studies have usually focused on individual buildings and related construction methods, energy efficiency measures, sustainability strategies and legal cases.

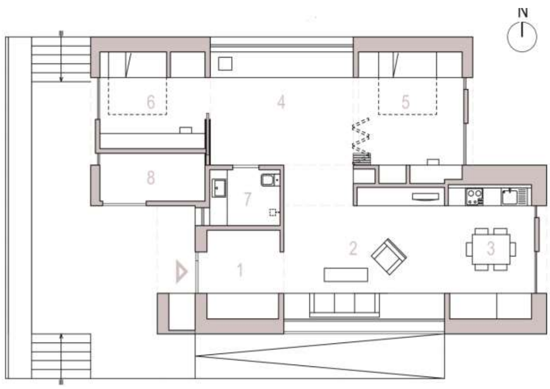
In this thesis, the case study approach has been implemented in Papers II, IV-VI. Paper II evaluated the life cycle GHG emission profile of the case buildings in Sydney, Atlanta, Shanghai, and New Delhi based on a detached single-family building with 102m^2 of conditioned floor area (HFA) and a timber-based structure. This building was constructed and tested as one of the zero-emissions building pilots in the Norwegian ZEB Centre (Figure 6).

The selection criteria for this base building were: the availability of detailed material inventory data (Inman & Houlihan Wiberg, 2016), a validated building performance model for the Norwegian location, and flexibility of changing the building design according to local conditions and energy efficiency requirements in investigated locations.

However, the direct implementation of the building geometry and materiality (timber-based structure) to the humid-subtropical locations may be considered a limitation since it may not be highly representative of the specific local conditions, especially in Shanghai and New Delhi. In these locations, the residential construction sector is dominated by multifamily building types, lower floor areas and reinforced concrete-based structures.

a)

b)



1-Entrance, 2-living room, 3-kitchen, 4-office, 5, 6-bedrooms, 7-bathroom, 8- technical room

Figure 6 Single-family case building (located at NTNU campus, Trondheim, Norway) evaluated in Paper II. a) View from the front, b) floor plan

The case study research in Papers IV and V was based on the prefabricated, affordable, and transportable housing unit with pilot construction located in Shanghai, China (Figure 7–8). The building superstructure is based on a shipping container mainly constructed from weathered (Corten) steel. The residence is on a single level and features a living room/bedroom, office space, and a bathroom (Figure 7). The building is 9 m long, 3 m wide, and 2.9 m high. The total gross floor area is 27 m^2, and the total net floor area is 21 m^2, with an internal volume of 54.6 m^3. The building is designed for two occupants.

This case study was selected based on an ongoing collaboration with the industry partner, who offers single units as a temporary housing solution for the construction workers in Belt-and Road infrastructure projects and for emergency shelters in Asia. Additionally, the flexible potential of the shipping container housing units enables additional modules to be added to transform the temporary housing into a permanent one.

a) b)

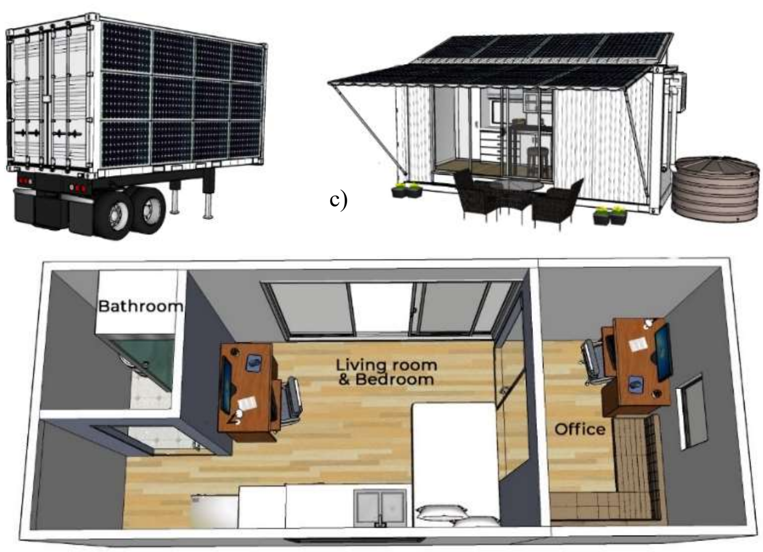


Figure 7 Visualisation of the case study building: a) During transportation, b) The south façade, and c) Bird's eye view

a) b)

Figure 8 The demonstration building at Shanghai Jiao Tong University: a) The south façade and b) Inside the living room

Finally, the case study research in Paper VI was based on a multistorey, multifamily building design in line with minimum energy efficiency requirements and design guidelines presented in the Energy Conversation Code (ECCRB) for Residential Buildings in India (Bureau of Energy Efficency (BEE), 2018). The baseline multifamily building has seven stories and 112 apartments with a heating floor area of 30 m^2 for each (Figure 9–10). Consequently, the total gross area of the building is 4720 m^2. The reference apartment unit area is set to 30m^2, following the referential multi-family building design presented in ECCRB and corresponding to the guidelines related to the minimum floor space being 10m^2/person, which is the average floor space of middle-class Indian homes (Rao & Min, 2018).

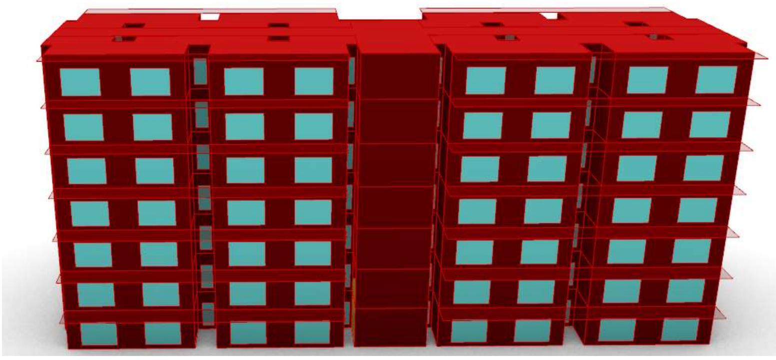


Figure 9 Benchmark, multifamily (7storey) building model (design) in India

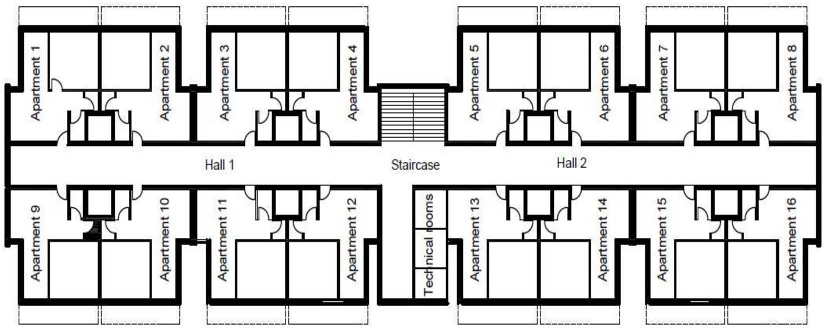


Figure 10 Floor layout of a typical storey in the base multifamily building in India

2.8 Limitations

In contrast to Paper V, where the performed LCA was based on several environmental impact categories, the environmental assessment in the remaining research papers was based only on a single category, the global warming potential (GWP100), which can be considered a limitation in terms of the understanding of the possible environmental impact trade-offs related to different design strategies and solutions. The LCA included in this thesis is based on a process-based methodology, which is sensitive to the truncation error and tends to underestimate the embodied type of GHG emissions compared to input-output and hybrid methods (Crawford, Bontinck, Stephan, Wiedmann, & Yu, 2018; Crawford, Stephan, & Prideaux, 2019). Consequently, calculating the embodied GHG emissions and other environmental impacts in the research papers can be considered as an estimate of the lower bound.

The other limitation of the research in this thesis can be attributed to the case study approach. When analysing case studies, it is important to avoid making general assumptions based on the limited number of studies. These studies should not be viewed as representing the entire construction market. Additionally, the performed case studies are dominantly based in specific locations in China and India, with limited research in other humid subtropical and tropical climate locations. Considering the rapidly growing residential sector in developing economies with humid subtropical and tropical climates, the research included in this thesis is based on new residential construction and excludes refurbishment studies.

The building performance simulation model was validated in the research presented in Paper IV using the available on-site measurements related to local weather, energy use and indoor air quality. In the other research papers, the credibility of the BPS model and results was checked with existing market benchmarks and previous research studies due to the lack of on-site measurements.

Additionally, the results of CCWorldWeatherGen software, used in Paper V to determine the possible climate change effect of weather data, are characterised by significant uncertainty related to the calculation method based on the statistically downscaled weather datasets. This method is based on the transformation of the present data without the possibility of adjusting the data in relation to the historical period. In future work, it is recommended to use the tools based on the dynamic downscaling methods built on high-quality regional climate-based models.

2.9 Summary of the methodology used in primary papers

A summary of the methods used in primary scientific publications is presented in Table 2.

Table 2 Summary of the methodology used in each of the primary scientific papers *(SLR – Systematic literature review, LCA – Life cycle assessment, BPS – Building performance simulation, LCI – life cycle inventory, HFA – Heating floor area, blank cell indicates n/a)*

Scientific publication (paper)	**Methodology** SLR	LCA	BPS	**Functional unit (LCA)**	**System boundaries**	**Main LCI database**	**Impact assessment method and categories**	**BPS software**
I. How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC Annex 72	●[1]							
II. Towards zero-emission residential buildings (ZEBs) in a humid subtropical climate		●	●	HFA of 1 m^2 over the established building lifespan of 60 years [kgCO2eq/m^2year]	A1–A3, B4, B6	Ecoinvent 3.4	IPPC2013, GWP100	IDA ICE 4.8 and PVsyst
III. Life cycle GHG emissions of residential buildings in humid subtropical and tropical climates: Systematic review and analysis	●[1]							
IV. Feasibility study of an off-grid container unit for industrial construction			●[2]					IDA ICE 4.8
V. Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China		●[3]	●	Total gross building area over a building life span of 25 years [kgCO2eq]	A1–A5, B4, B6, C1–C4, D	Ecoinvent 3.5	ReCiPe Midpoint, Hierarchist cultural perspective	TRNSYS 14.0
VI. Global sensitivity analysis and optimisation of design parameters for low GHG emission life cycle of multifamily buildings in India		●[4]	●[4]	Per capita basis (occupant) over the established building lifespan of 50 years [kgCO2eq/occupant year]	A1–A3, B4, B6	India Construction Materials Database of Embodied Energy and Global Warming Potential	IPPC2013, GWP100	Honeybee and Ladybug tools for Grasshopper (Energy+)

[1]Systematic literature review coupled with an expert survey in IEA EBC Annex 72, [2] BPS coupled with on-site experiments, measurements, and validation
[3] LCA coupled with local sensitivity analysis (SA) [4] BPS and LCA coupled with GSA and multiobjective optimisation

3. Results

The main results of the six primary research papers are presented in the following sub-sections. Each publication is presented in terms of motivation, methodology and main results. The detailed results are presented in the complete version of the research publications (Section 7).

3.1 Paper I

How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC Annex 72, published in *Buildings and Environment* (2021).

Authors: **Daniel Satola**, Maria Balouktsi, Thomas Lützkendorf, Aoife Houlihan-Wiberg and Arild Gustavsen

Motivation

The decarbonisation of the construction sector, which is currently responsible for almost 40% of worldwide GHG emissions, is critical for achieving carbon neutrality in the entire economy (Abergel et al., 2017). Consequently, the concept of net-zero climate-neutral buildings is gaining wide international attention and is widely recognised as a key climate mitigation pathway for achieving climate neutrality targets in the built environment (International Energy Agency, 2021). A wide variety of terms, definitions, and approaches related to net-zero buildings have emerged worldwide, leading to confusion and uncertainty, which, combined with the broad scope of interpretation, undermine the transparency and credibility of the net-zero approach. Consequently, this article aimed to provide an overview of the terms, definitions, and key methodological features of the existing building assessment approach and develop typologies and recommendations to foster transparency and clarity in developing country-specific net-zero building frameworks.

Methodology

The research methodology used in this paper was based on a combination of an expert survey, a systematic literature review, and expert knowledge. In the first step of the study, a survey was conducted among experts in IEA EBC Annex 72: Assessing Life Cycle Related Environmental Impact Caused by Buildings (EBC Executive Committee Support Services Unit, 2019) to extract and analyse the general data related to the following key features: i) status and launching year, ii) founder, iii) object of assessment, iv) metric and v) regulation type occurring in the respective country of assessment. The data extracted from 35 building assessment approaches were cross-checked with the provided references and existing literature. In the second step of the study, a detailed analysis of the building assessment approaches based on the GHG emission metric was performed, focusing on the features related to i) operational life cycle stages, ii) embodied life cycle stages and iii) options/possibilities of GHG emission compensation.

Results

The authors developed and proposed the classification framework (Table 3) based on the operational and embodied life cycle regulations to increase transparency and clarity related to the different performance requirements of net-zero building assessment approaches. Eighty-one possible combinations can be present in the building assessment approaches. The developed matrix may be useful for mapping and creating a code system for existing and future net-zero regulations, thus contributing to increased transparency. Forexample, 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.

Based on an in-depth review of 35 building assessment approaches from 31 countries worldwide and the classification framework proposed in Table 3, the authors identified the nine following types of regulations, which present the system boundaries and performance requirements presented in building assessment approaches (Table 4).

Additionally, based on the results, building definitions oriented on energy consumption metrics (primary (PE) or delivered energy (DE) are the most common, occurring in 22 of 35 national building assessments. The shift from energy to GHG emission-based metrics (G) is found in 13 building assessment approaches in 11 countries (Table 4). These standards are mostly voluntary and are created or used by NGOs or research bodies. The results of the review identified that the definition type, scope of system boundaries, approach to the aspect of time (static vs dynamic consideration) and allowed options for GHG emission compensation are key features that should be carefully considered in the development of harmonised net-zero GHG emission building frameworks.

Finally, the authors proposed a set of general recommendations that should be integrated into the development of new net-zero carbon/emission building definitions, including:

i) integration of current, voluntary, and new (net) zero GHG emission building standards into the national and local policy frameworks,
ii) provision of some flexibility in terms of the net-zero target, with the easiest target level being the full assessment and balance of the B6 (operational energy use) impacts, and
iii) prioritisation of GHG emission compensation by on-site renewable energy generation; however, the two sides of the GHG emission balance should always be provided separately.

The further in-depth analysis indicated that the general approach for achieving net-zero GHG emission balance among investigated countries is based on the hierarchical strategies related to:

i) increase the energy efficiency of the building
ii) reduce embodied GHG emissions/ energy
iii) increase renewable energy generation on-site
iv) maximise renewable energy generation off-site
v) offset remaining GHG emissions/energy

These general principles can be widely adopted by developing countries including those in warm climates, which are currently missing the presence of any net-zero frameworks in the market. In the case of locations with an energy grid based on fossil fuels and characterised by high primary energy/GHG emissions, the focus should be on reducing energy needs by implementing energy efficiency measures.

In terms of design strategies, to achieve the net zero-emission ambition in the net-zero frameworks of each analysed country, a common approach is the integration of the passive and active design strategies for operational energy or GHG emission reduction. It can be observed that for analysed developed countries, the design strategies primarily focus the most on the high-tech solutions. In the case of developing countries in warm climates, considering local market conditions, implementing cost-effective design strategies related to the optimised building form and fenestration area, enhancement of the natural ventilation, and ceiling cooling fans should be recommended as a first choice.

Table 3 Classification framework for system boundaries and performance requirements in building assessment approaches

Note: Classification framework can be used for different balance metrics, including primary energy (**PE**), delivered energy (**DE**), CO_2 (**C**), or GHG emissions (**G**).

			The embodied part of the life cycle								
			a	b	c	d	e	f	g	h	i
		Type of action and regulation	Excluded	Calculated	Calculated and limited by informal guide values[1]	Calculated and mandatorily limited by scheme[2]	Calculated and mandatorily limited by law[3]	Calculated and balanced (individual approach)	Calculated and balanced, including limitations by informal guide values	Calculated and balanced, including mandatory limit values as part of a scheme	Calculated and balanced, including mandatory limit values as part of a law
The 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, including limitations by informal guide values									
	7	Calculated and balanced, including mandatory limit values as part of a scheme									
	8	Calculated and balanced, including 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 that set informal voluntary requirements.

[2] i.e., voluntary building certification schemes, standards, and other building assessment approaches that set mandatory in-direct or direct requirements for certification.

[3] i.e., national construction codes or standards that set mandatory building construction and operation requirements.

[4] i.e., the exported energy is considered additional information (benefits beyond system boundaries)

Table 4 Regulation type recognised in analysed building assessment approaches

Notes:
1) For frameworks with multiple performance levels, the most ambitious level is presented
2) The references of country codes and building assessment approaches are presented in detail in Paper Appendix, Table A1

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

3.2 Paper II

Towards Zero-Emission Residential Buildings (ZEBs) in a Humid Subtropical Climate. Analysis Emissions from Energy Use and Embodied Emissions from Materials in Referential Locations According to Obligatory Residential Energy Codes and Using Generic LCA Data Sources, Published in *Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)*

Authors: **Daniel Satola**, Aoife Houlihan-Wiberg and Arild Gustavsen

Motivation

Building energy codes and standards are regulatory instruments that set the minimum requirements for building energy efficiency levels. Together with certification schemes and the use of highly energy-efficient technologies, they are crucial for the transition to a more sustainable construction sector (Abergel et al., 2017). Intensive actions have emerged to lower energy consumption and related GHG emissions in residential buildings during the past decade. However, mitigation strategies have focused mainly on operational energy use, thereby neglecting the embodied environmental impacts related to construction material production, construction and transport processes, maintenance/replacement of construction materials, and end-of-life stages. When moving towards a ZEB performance ambition, the materials' embodied emissions may present a more significant share (contribution) than the GHG emissions related to operational energy consumption (Röck et al., 2022). Consequently, there is an increasing focus on the life cycle-based design of ZEBs and the integration of minimum life cycle performance requirements into the building codes (transition from PE 4.a to G4.e regulation type (Table 3)).

The main aim of this research paper was to investigate how local conditions, including the minimum energy efficiency requirements present in the local building codes, affect the GHG emission profile and the possibility of achieving different levels of the ZEB ambition according to the Norwegian ZEB (Fufa et al., 2016) framework based on the case of single-family buildings located in various humid, subtropical climate locations: Sydney (Australia), Atlanta (USA), Shanghai (China) and New-Delhi (India).

Methodology

The case study building adopted in this study was a detached, single-family house with a timber-framed load-bearing structure (Figure 6). The building consisted of two adjacent cells (12.5x4.1m) with elongated facades facing north and south. The case building was designed for the daily life of three family members. The total heating floor area (HFA) was 105 m^2, and the volume was 315 m^3. The on-site building-integrated PV system was installed on the tilted part of the roof (Figure 6).

The calculation of the annual energy consumption of the case study building in each investigated location was based on the dynamic and multi-zone building performance simulations performed in IDA ICE 4.8 software.

The GHG emission factors of a market-based low voltage electricity mix in a specified location extracted from the Ecoinvent 3.4 database were used to calculate the GHG emissions from operational energy use, as well as avoided GHG emissions from on-site renewable electricity production. The thermal specification of the building envelope (Table 5*),* ventilation system type, efficiency of the air-water heat pump, lighting and equipment energy consumption, and main principles of the occupant behaviour was based on the minimum requirements of the local building codes and if found lacking, on business-as-usual design values.

Table 5 Thermal specification of the residential building fabric in the referential location as per the minimum requirements of the mandatory residential codes

* Business as usual values (lack of local requirements in energy codes).

Building Component	**Materials composition**	**Location/Energy code/Regulation type (Table 3)/U-value [W/m^{2}K]**			
		Sydney	Atlanta	Shanghai	New Delhi
		BASIX	IRC2015	JGJ134	n/a
		D4.a	D4.a	D2.a	n/a
External walls	Timber framed construction, mineral wool insulation, timber cladding	0.20	0.32	1.00	2.20*
Slab on ground	Timber framed construction, mineral wool insulation, parquet timber flooring	0.30	0.27	1.00	3.5*
Roof slope part	Timber framed construction, mineral wool insulation, in-roof PV panels	0.20	0.17	0.80	2.20*
Roof flat part	Timber-framed construction, EPS, insulation, plywood cladding				
Windows	Depending on U [W/m^{2}K]/SHGC [-] values requirements	1/0.25	2/0.25	4/ (0.62*)	5.8*/ (0.82*)
Air tightness n_{50} [1/h]	Vapour and wind barrier	n/a (3*)	3	4	n/a (8*)

Regarding embodied GHG emissions calculations, the functional unit was defined as 1m^2 of heating floor area (HFA) over a building lifespan of 60 years [kgCO_2eq/m^{2}year]. The calculation boundaries were limited to the extraction of raw materials, transport, manufacturing of the products and materials, and their replacement during the building lifespan (A1–A3, B4 (CEN, 2014)). The life cycle inventory data was accessed from SimaPro Analyst version 8.5 using the Ecoinvent 3.4 Rest-of-the-World (RoW) data set (Wernet et al., 2016). The generic data were adjusted using local electricity grid emission factors according to the selected location where the building model was evaluated to attain more accurate and allocated data.

Results

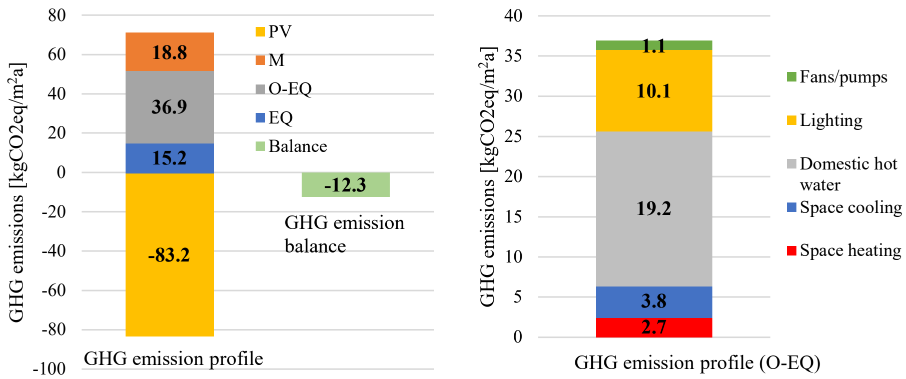
The total calculated embodied GHG emissions from construction material production (A1–A3) and replacement (B4) (M) (Figure 11) vary from 18.9 kgCO_{2EQ}/m^{2}year in Sydney to 14.4 kg CO_{2EQ}/m^{2}year in Shanghai. Compared to Shanghai and New Delhi locations, the higher results seen for Sydney and Atlanta were mainly caused by the requirements for substantial thermal insulation and sealing materials necessary to meet mandatory and more stringent energy building code requirements (Table 5). The insulation and sealing materials accounted for approximately 27% (Sydney) and 25% (Atlanta) of the total embodied emission from materials in these phases (A1–A3, B4). The annual energy use varied from 52 kWh/m^{2}a (i.e., 5 460kWh/a) in Sydney to up to 187 kWh/m^{2}a (i.e., 19 635 kWh/a) in New Delhi. In locations with high thermal performance requirements present in mandatory residential building codes (Sydney and Atlanta), the energy consumption profiles were dominated by the energy use related to the building equipment and domestic hot water production. On the contrary, the energy profile in locations with low (Shanghai) or lacking (New Delhi) energy efficiency requirements was strongly dominated by the energy consumption related to space heating and cooling. Regarding the renewable energy production potential of the on-site integrated PV system, the highest values were observed in New Delhi (88kWh/m^{2}a), while the lowest values were found in Shanghai (60kWh/m^{2}a). The main factor behind this difference was the variation in the local horizontal global irradiations in the analysed locations.

The total GHG emissions related to building operations (O) and the embodied emissions from materials (M) ranged from 69.3 kgCO_{2EQ}/m^{2}a in Atlanta to 338 kgCO_{2EQ}/m^{2}a in New Delhi. In contrast, emission compensation from renewable energy generation (PV) was the highest in New Delhi, at 153.1 kgCO_{2EQ}/m^{2}a, and the lowest in Atlanta, at 52.3 kgCO_{2EQ}/m^{2}a (Figure 11). A zero-emission building ambition (ZEB–OM) was achieved in Sydney, where GHG emissions related to operational energy use and embodied emissions from materials were balanced by on-site renewable production. In Atlanta, zero-emission building ambition (ZEB-O) was accomplished as on-site renewable energy production balanced the GHG emissions related to operational energy use. However, it was impossible to offset embodied GHG emissions from construction materials.

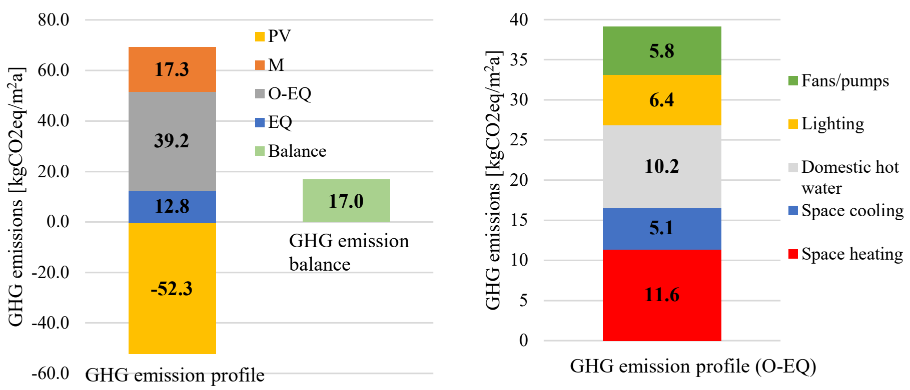
The study's results emphasised that implementing and enforcing mandatory and high-level residential energy efficiency requirements (minimum regulation D4.a type, Table 3 in local building standards is crucial for transitioning towards a low-carbon building stock in China and India.

Graph Abbreviations: M: GHG embodied emissions from building materials production (A1-A3) and replacement during building lifespan, O-EQ: GHG emissions from space heating, cooling, domestic hot water, lighting and appliances (fans/pumps) energy use, EQ: GHG emissions from the plug-loads, PV: off-setting (compensating) GHG emissions from on-site renewable energy generation, Balance: annual GHG emission balance

a) Sydney



b) Atlanta



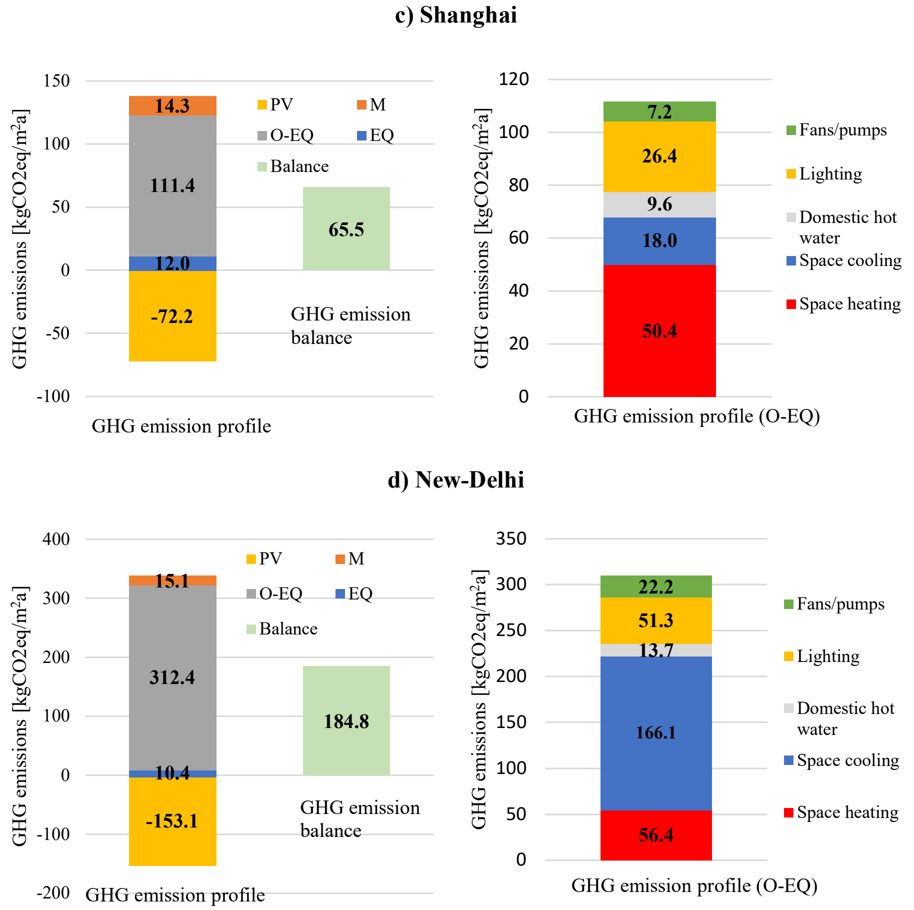


Figure 11 Life cycle GHG emission profiles (left) and operational use (O-EQ) GHG emission profiles (right) of case study residential buildings in a) Sydney, b) Atlanta, c) Shanghai, and d) New Delhi

3.3 Paper III

Life cycle GHG emissions of residential buildings in humid subtropical and tropical climates: Systematic review and analysis, ***published in Buildings (2020)***

Authors: **Daniel Satola,** Martin Röck, Aoife Houlihan-Wiberg and Arild Gustavsen

Motivation

The existing literature mostly focuses on the life cycle performance of buildings in cold and temperate climates (Cabeza et al., 2014; Chastas et al., 2018b; Röck et al., 2020). Hence, a research gap related to the investigation of buildings' environmental life cycle profiles and trends in warm, humid subtropical and tropical climates exists. Considering the geographic extent, the population level and rapid growth of the residential floor area (up to 50% of global growth by 2060) (Abergel et al., 2017) these climates (humid subtropical and tropical) can be defined as key regions contributing to global climate change. Consequently, there is an urgent need to address the environmental impacts related to the rapid growth of buildings in these regions, especially in the residential construction sector, by implementing design strategies that significantly reduce GHG emissions. Firstly, based on the systematic review method, this paper identifies the current state and main research gaps related to the life cycle assessment of residential buildings in tropical and humid subtropical climates. In addition, the paper identifies and analyse the published GHG emission profiles, trends and promising design strategies for life cycle GHG emission reduction. The selected studies assess both embodied and operational GHG emissions, i.e., GHG emissions across the full building life cycle.

Methodology

The analysis presented in this research paper is based on a systematic review of the scientific literature, which follows the step-by-step approach (Booth & Carroll, 2015). In the first step, the keywords were applied to gather potentially valuable publications from public databases based on formulated research questions. An initial sample of 332 articles was screened by title, which resulted in 108 articles remaining. Screening and exclusion by abstract led to the selection of 79 articles presenting 126 case studies for full-paper analysis. The final data sample consisted of 37 articles representing life cycle GHG emission assessments of 75 case studies of residential buildings operating in humid subtropical or tropical climates. The full-paper analysis and data extraction included metadata documentation and methodological and building-oriented features (Table 6). Additionally, the preliminary examination of the assessment methods used in the collected studies showed the need to harmonise life cycle GHG emission results from the different case studies to allow comparisons. Hence, a two-step harmonisation procedure was applied to normalise the reference study period (RSP), ensure compliance with ISO 14040/44 standards (first harmonisation step), and consistency of system boundaries, among other aspects (second harmonisation step).

Consequently, the sample used for the final analysis consisted of 20 articles describing 36 case studies.

Table 6 Overview of methodological and building-related criteria influencing the life cycle

Feature	Description
Methodological Features	
Life cycle calculation method	Description of life cycle calculation methodology: process-based, input-output or hybrid
System boundaries	Processes included in the life cycle assessment (LCA) study
Impact assessment method	Life cycle impact assessment (LCIA) method and category/indicator employed in the study
Operational energy assessment methodology	Method, software, and data source used for assessing operational energy use
Building Related Features	
Location/climate	Location (country, city) of case building and climate type according to Koppen-Geiger classification
Building type/function	Residential building type: single-family (SF) or multifamily (MF)
Gross floor area	The total area of the building measured between the exterior walls
Main structural materials	The primary type of materials used for building construction
Lifespan	The life expectancy of the building
Electricity mixes	The factor applied for evaluating greenhouse gas (GHG) emissions from the local electricity grid (kgCO2eq/kWh)

Results

In the collected 75 case studies (sample data before harmonisation), most of the life cycle GHG emission assessments were performed for buildings in humid subtropical climates, with a limited number of case studies in tropical climates. Based on the harmonised data sample (36 case studies), the highest life cycle GHG emissions were present in China's rapidly developing residential construction sectors, followed by Hong Kong and India.

The results of this study demonstrate that residential buildings with net-zero or low-energy performances have the potential to reduce the total life cycle GHG emissions by 50–80% compared to buildings with the most common conventional energy performances. The share of embodied GHG emissions among total GHG emissions ranged from 16% to 100%, with an average share of 27%. This is similar to previous research that is mostly based on case studies of buildings in cold and temperate climates (Chastas, Theodosiou, & Bikas, 2016). The ratio between embodied and total life cycle GHG emissions were mainly attributable to the choice of material in the building structure, energy performance and electricity emission factor for the grid mix used to calculate emissions from the operation.

The results indicated that the design strategy connected with the implementation of renewable energy sources in the form of photovoltaic systems (S7, in Figure 12) provided the highest reduction of life cycle GHG emissions compared to other recognised mitigation strategies, whereas the design strategy related to maximisation use of timber-based construction materials (S1, in Figure 12) led to the highest reduction of embodied GHG emissions.

Finally, the conclusions emphasised the need for future research on the LCA of GHG emission strategies in the humid subtropical and tropical residential sectors, especially focusing on multifamily buildings in the rapidly developing economies of India and China.

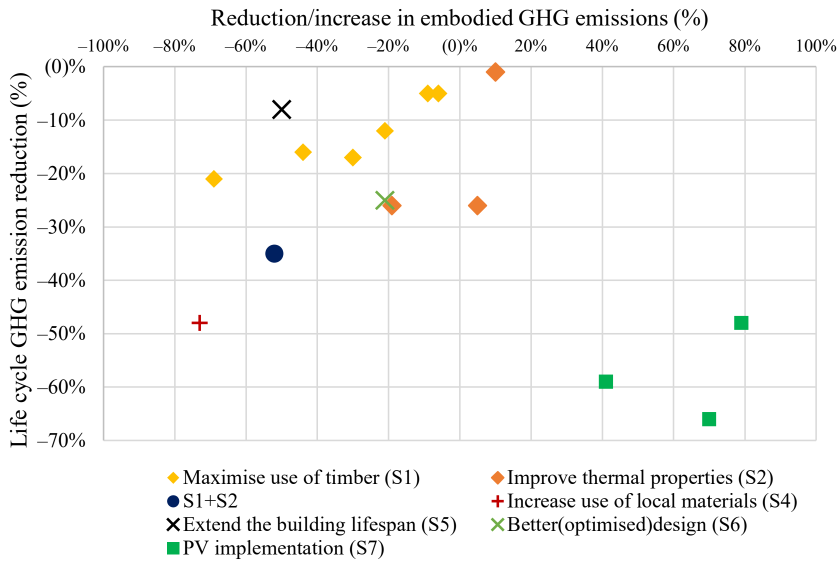


Figure 12 Embodied and life cycle GHG emission reduction potentials of the identified design strategies in the performed systematic literature review

3.4 Paper IV

Feasibility study of an off-grid container unit for industrial construction. *Published in Sustainable Cities and Society (2020).*

Authors: Audun Bull Kristiansen, **Daniel Satola**, Kate Lee, Baiyang Zhao, Ruzhu Wang, Arild Gustavsen and Vojislav Novakovic

Motivation

It is predicted that by 2030, 60% of the world's population will live in cities and this value will increase to 70% by 2050 (World Bank, 2018). With the rapid development of economies in the Global South, especially in China, driven by global infrastructure development projects such as the Belt and Road Initiative (Ascensão et al., 2018), the provision of affordable housing is one of the most crucial societal needs. The development of prefabricated, modular construction systems and building concepts is widely recognised as a promising solution for addressing these global needs as it offers significant advantages over traditional construction methods, including reducing construction time, improving consistency, durability and structural integrity, and lower environmental impacts (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). Being the busiest harbour globally and the production location of more than 90% of shipping containers worldwide, Shanghai is a suitable location for producers of shipping container-based housing units, whose number tripled in the last ten years. This rising number is connected with the strong promotion by and support from the Chinese Government, which mandated that 30% of annual new construction be built in a prefabricated manner by 2025 (Chang et al., 2018).

The potential of reusing steel shipping containers and transforming them into modular housing units has been considered in previous research (Dara, Hachem-Vermette, & Assefa, 2019; Tavares, Lacerda, & Freire, 2019; Tumminia et al., 2018). However, it has been found that there is limited research on zero-emission building (ZEB) concepts made from shipping containers as a starting point, especially regarding design-optimisation and real demonstration projects toward self-sufficient and off-grid operation, which is receiving increased attention in remote locations (Kristiansen, Ma, & Wang, 2019a). Moreover, Shanghai is located in the climate zone defined as "hot summer and cold winter" (humid subtropical according to Koppen classification) and characterised by a higher number of heating degree days - 897 (HDD15°C) than cooling degree days- 647 (CDD24°C). Based on last fact, one of the main focuses of this article is to study passive design strategies related to improving the thermal performance of buildings, including using Vacuum Insulation Panels.

Consequently, this article aimed to close the research gap by evaluating design solutions and strategies for improved energy efficiency in Shanghai's prototype shipping container building. The goal is to work towards a ZEB for off-grid operation (i.e., energy self-sufficiency).

Methodology

Existing performance studies of container buildings reveal gaps concerning the quality of construction, thermal comfort and airtightness (Elrayies, 2017). In this study, the heat transfer resistance of a container wall was improved by installing Vacuum Insulation Panels (VIP), verified through measurements with heat flow meters. Furthermore, building validation and performance simulation in the IDA ICE 4.8 software (Equa Simulation AB, 2019) investigated energy use, indoor air quality and energy conservation strategies for different ventilation scenarios and temperature setpoint schedules in Shanghai. The experiments and building performance simulations described in this article were based on a single housing unit prototype with a gross HFA of 21m^2 predicted for two adult persons (Figure 7-8). The main planned market application of the single units was temporary worker's housing in the Belt-Road initiative, emergency shelters and as the housing solution for economically weaker section (EWS) slums replacement in Asia. Additionally, based on the modular approach, housing solutions can be scaled up by adding additional modules to improve the living standard and provide valuable access to electricity, heating, and cooling in the rural areas of China and Asia.

Results

A full-scale experiment showed that the thermal resistance of a container building envelope increased from 1.1 m^{2}K/W to 3.7 m^{2}K/W by applying 8 mm VIP insulation. Consequently, the average energy use after VIP installation was reduced by about 40% based on the on-site measurements. The energy model was validated mainly by comparing simulation results to measurements and by validating the energy model using the local weather data and specific air-to-air heat pump performance data provided by the producer. The mean bias error of simulated indoor temperature compared to a measured one was 0.13 °C and 0.08 °C for the heating and cooling period, respectively. The measured energy consumption was 5% and 2% higher than the simulation results in heating and cooling mode, which shows the accuracy of the developed building performance simulation model. Simulations based on the validated energy model indicated that a natural ventilation system could provide almost as good indoor air quality as mechanical ventilation with heat recovery for the described case study, with only 7% higher annual energy consumption for heating, cooling, and ventilation (Table 7). Interestingly, hybrid ventilation had the lowest energy requirements, but for a single container building in a subtropical climate, the 11% difference compared to natural ventilation is not large enough to justify the investment based on a Net Present Value evaluation of the annual energy-saving. Upgrading from double to triple-glazing windows or reducing the window area was the most economical way of improving the energy performance of the case study building. Additionally, the strategy related to providing a wider range of heating and cooling setpoints outside the occupancy time and lowering the heating and cooling setpoint at night led to an over 40% reduction in heating energy requirements without a significant decrease in the thermal comfort level.

Finally, based on the recommendations and strategies developed for improving the energy efficiency of on-grid shipping-container housing modules, the paper emphasised the need for future research on the simulating and testing performance of the off-grid design, including LCA, which is missing in the literature.

Table 7 The electric energy needs, and peak power compared to the base case for alternative ventilation strategies

	Ventilation scenario			
	Base case Exhaust fan 68 m^3/h	**Natural ventilation (NV)**	**Mechanical ventilation with heat recovery (MV)**	**Hybrid ventilation (HV)**
Electric energy requirement				
Heating (H) [kWh]	440	516 (+17%)	332 (-25%)	319 (-28%)
Heating (H) [kWh/m^2a]	21.2	24.0	15.4	14.8
Cooling (C) [kWh]	693	694 (+0%)	638 (-8%)	645 (-7%)
Cooling (C) [kWh/m^2a]	33.0	32.6	29.7	30
Fan (F) [kWh]	41.7	0 (-100%)	159.8 (+283%)	112.2 (+169%)
Total (H+C+F) [kWh]	1175	1210 (+3%)	1130 (-4%)	1076 (-8%)
Peak power				
Heating [kW]	1.1	1.07 (-3%)	1.07 (-3%)	1.07 (-3%)
Cooling [kW]	1.06	1.06	1.06	1.06

3.5 Paper V

Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study. ***Published in Building and Environment (2020)***

Authors: **Daniel Satola**, Audun Bull Kristiansen, Aoife Houlihan-Wiberg, Arild Gustavsen, Tao Ma and Ruzhu Wang

Motivation

A review by Kristiansen, Ma, & Wang, (2019) demonstrated how prefabricated PV-powered homes based on a steel-container structure can provide affordable and decent housing solutions in China and surrounding countries. An LCA approach is crucial for identifying and assessing environmental trade-offs between operational and embodied emissions, such as PV panels and energy storage. However, the existing literature shows a gap in the LCA of modular buildings in China, particularly for low-energy, net-zero energy, and off-grid designs, which are receiving increasing market interest nowadays. To fill this gap and increase the available number of studies on modular buildings in China, this research explored the environmental impacts related to the life cycle of various building designs of transportable modular housing units. This design is based on the findings from Paper IV (Kristiansen et al., 2020).

Methodology

The main aim of this study was to identify, quantify and assess the environmental impacts and trade-offs that emerge from the development of a baseline building design (Scenario 1) for low-energy (Scenario 2), net-zero energy (Scenario 3), and off-grid energy (Scenario 4) designs. Consequently, the methodology is based on LCA with the extensive use of BPS. The functional unit of this study, which enables comparisons across the design scenarios and existing literature studies, was the "total gross building area over a building life span of 25 years". The LCA follows the cradle-to-grave system boundaries (Figure 13), and the impact assessment was based on the ReCiPe midpoint methodology with a hierarchic cultural perspective (Huijbregts et al., 2017). Due to the lack of a transparent national life cycle inventory database in China, Ecoinvent 3.6 was used as the main database in the current study, with adjusted data based on a local electricity grid in Shanghai. The building performance simulation models were based on the author's previous research (Paper IV) (Kristiansen et al., 2020) and created using the TRYNSYS software. To increase the robustness of life cycle impact results and investigate the significance of the study assumptions, a sensitivity analysis (SA) was performed, taking into consideration: a) building location, b) possible climate change effects, and c) end-of-life scenario.

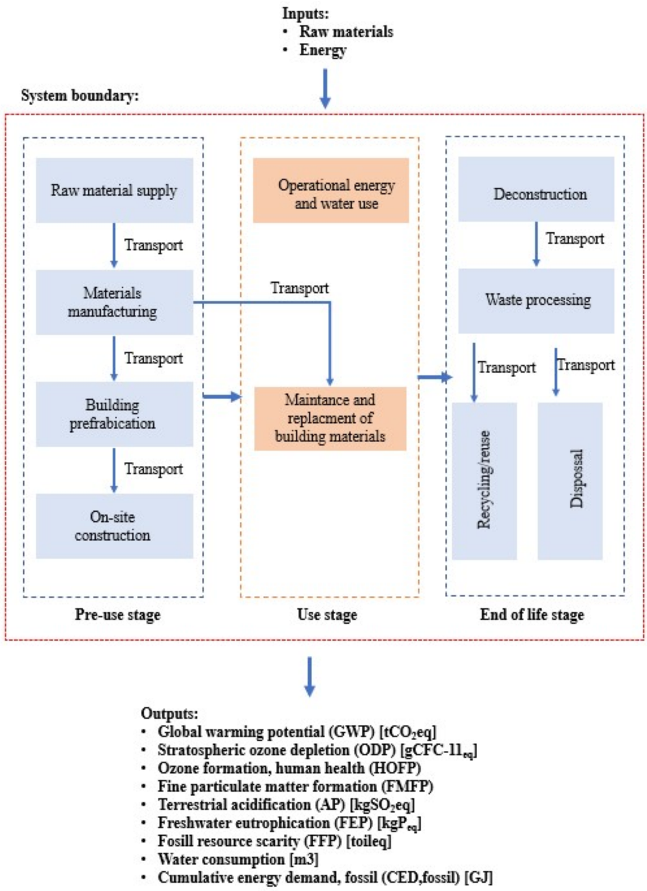


Figure 13 System boundaries and environmental impact outputs of performed comparative life cycle assessment

Results

The LCA results indicated that the life cycle impacts in all environmental categories in the baseline design scenario (Scenario 1) and the low-energy design scenario (Scenario 2) were strongly dominated by the use phase (86% and 80% on average, respectively). These impacts were mainly attributed to the electricity consumption derived from the hard coal-based electricity grid. The implementation of energy and water reduction measures in Scenario 2 led, on average, to a 25% reduction of total life cycle impacts, with the highest reduction observed in the GWP (28%) and water use (30%) impact categories. Improving the thermal properties of the building envelope by adding additional insulation materials can significantly contribute to the reduction of life cycle impacts.

In contrast to the first two design scenarios, the life cycle impacts of the net-zero energy and off-grid design scenarios were dominated in most categories by the pre-use phase. The net-zero energy design scenario presented the lowest life cycle impacts in all categories except the water consumption category, with an 81% lower GWP impact than the baseline scenario. This study shows that a net-zero energy building design with on-site renewable energy sources can offer great life cycle impact reduction potential, especially in highly carbonised electricity production locations.

On average, the off-grid design scenario (Scenario 4) presented 53% higher life cycle impacts than the grid-connected net-zero energy design scenario (Scenario 3). The highest increase (88%) was observed in the freshwater eutrophication potential (FEP). The ambition of going off the conventional electricity grid led to a higher power requirement for the PV system and a need for energy storage, which together were responsible for more than 60% of the impact in the pre-use phase.

Due to the prefabricated technology of the building module production and the short distance between the factory and the building site or landfill (less than 50 km), the construction and end-of-life phases had a marginal contribution to the total impacts. However, the sensitivity analysis (SA) indicated that if the building module is transported to East-Asian cities such as Guangzhou (China), Hanoi (Vietnam), and Kolkata (India), the life cycle impact related to transportation can become significantly larger.

The SA results indicated that implementing a circular approach to building products, with the reuse of the building structure in the form of a weathering steel container, can significantly increase the potential life cycle environmental benefits (Figure 14). The highest environmental benefits, from 4.8% (for water consumption) to 29.6% (for FEP) that came from the reuse of the building superstructure, can be observed in Scenario 3 (net-zero energy), which is characterised by the lowest life cycle impacts. The decrease of the metal recovery rate from the baseline of 90% to 25% led, on average, to a 1.3–7.2% increase in the total life cycle impacts (Figure 14).

Additionally, SA shows that the projected climate change effects had a minor influence on the life cycle impact.

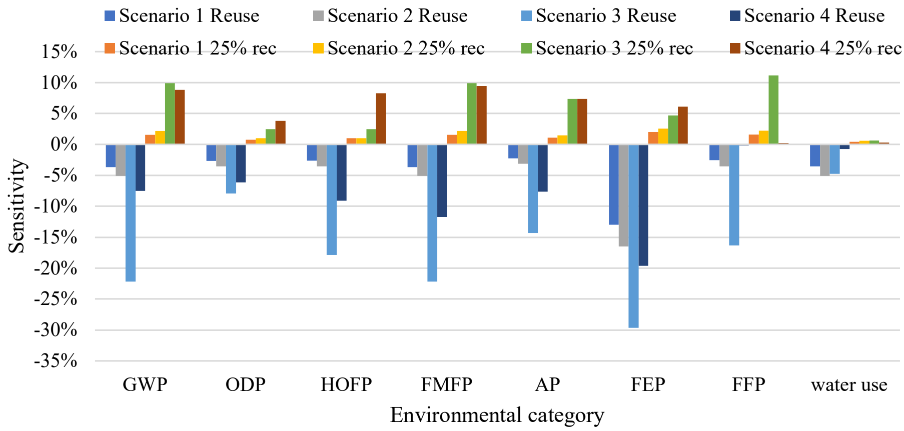


Figure 14 Sensitivity analysis of end-of-life scenarios on total LCA impacts relative to baseline assumptions

3.6 Paper VI

Global sensitivity analysis and optimisation of design parameters for low GHG emission life cycle of multifamily buildings in India. Published *in Energy and Buildings (2022).*

Authors: **Daniel Satola,** Aoife Houlihan-Wiberg and Arild Gustavsen

Motivation

Based on future projections, the development of the residential building sector and the rapid growth of the economy and standard of living in India may increase energy consumption and related GHG emissions by more than four times in the next 20 years (Central Electricity Authority, 2017). Because most areas in India are located in cooling-dominated climates, the increased use of air-conditioning systems to achieve thermal comfort in buildings is widely recognised as the major contributor to GHG emissions nationwide (Ali, 2018). Consequently, there is an increased need to develop low GHG emissions and affordable residential building concepts with extensive use of energy efficiency measures that can be successfully implemented in the construction market.

When analysing existing literature, a research gap related to the lack of global sensitivity studies based on the residential building typology in India seems to exist. Further, objectives in existing studies are based mainly on energy indicators, and therefore neglect the building's life cycle impact and indoor environmental quality. This research paper tried to fill this gap by exploring the influence of the design parameters and optimal design solutions and strategies for low GHG emission design of multifamily residential buildings located in warm Indian climate zones.

Methodology

The base case study model was developed using the benchmark design (Figure 9, Table 8*)* of a multifamily building, which follows the minimum energy efficiency requirements presented in the Energy Conversation Code (ECCRB) for Residential Buildings developed by the Indian Government (Bureau of Energy Efficency (BEE), 2018). The building model was created using the Rhinoceros 3D software along with the Grasshopper plugin, which enabled a parametric design model (Figure 15, (1)) based on the 30 main parameters grouped into seven categories (Table 8). In this study, the performance of the multifamily building design was evaluated for three cities in India located in different cooling-dominant climate zones: Bhubaneswar (hot and humid), New Delhi (composite), and Jodhpur (hot and dry).

The annual energy consumption, renewable energy generation, and occupant thermal comfort levels were evaluated using the building energy models created with the Ladybug and Honeybee tools (Roudsari et al., 2013), based on the parametric geometry models. The parametric multifamily design model was integrated by a Python scripting language, first with the calculated inventory quantities of building materials and then with the background data related to the construction material's embodied GHG emissions and cost (Figure 15, (2)). The primary source of the material's embodied GHG emissions was the Indian Construction Materials Database of Embodied Energy and Global Warming Potential (IFC, 2017).

Evaluation of investment and replacement material cost was based on the government database, Analysis of Rates for Delhi (Government of India, 2019).

Identification of the most influential design parameters in life cycle GHG emissions and thermal comfort level in the multifamily building design was based on the two-step global sensitivity analysis (GSA) methods, Morris Screening (Morris, 1991) and the Fourier amplitude sensitivity test (FAST) (Andrea Saltelli et al., 2010) (Figure 15,(3)). In the last part of the research, the identified key design parameters from the two-step GSA were optimised using the genetic multiobjective optimisation framework with the Hype genetic algorithm (Bader & Zitzler, 2011), which was based on the three minimisation objectives (functions): a) annual life cycle GHG emissions, b) life cycle cost, and c) initial investment cost (Figure 15,(4)).

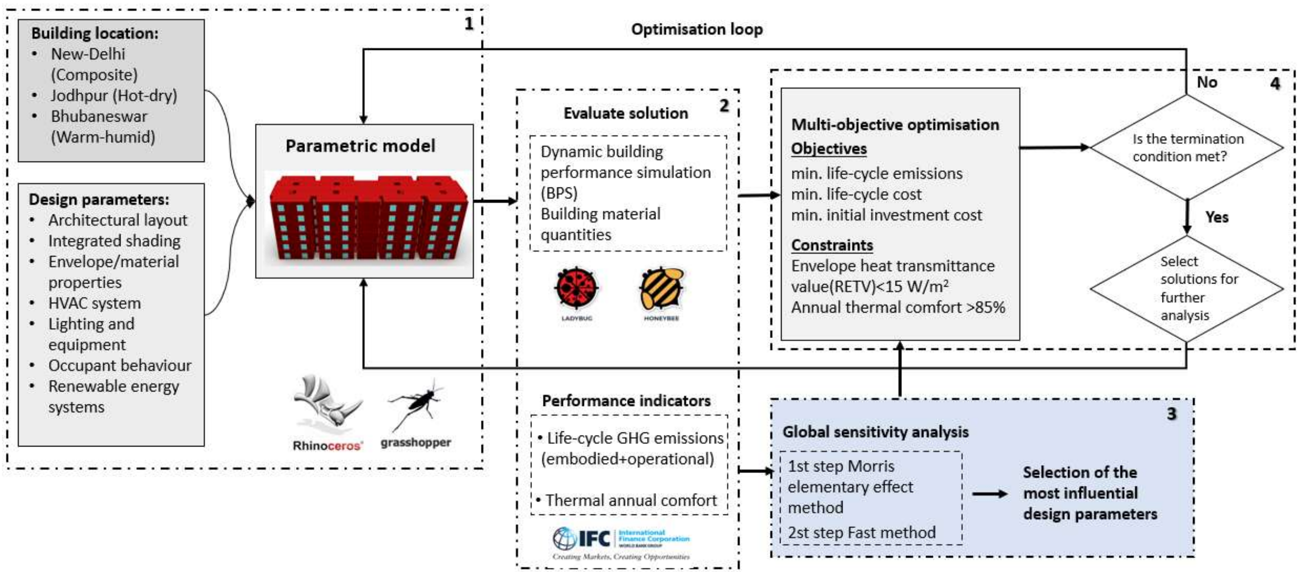


Figure 15 Framework for coupling the parametric building energy simulations, life cycle assessment, global sensitivity analysis and multiobjective optimisation in the Grasshopper environment

Table 8 Range of main design building parameters and design specification of benchmark scenario

Category	Parameter	Abbreviation	Range	Benchmark (base) design scenario	Unit
Architectural layout	Apartment floor area	AA	30–60	30	m^2
	Floor height	FH	2.8–3.2	3.0	m
	Floor numbers	FN	4–12	7	[-]
	Window-to-floor ratio	WFR	ECCRB[1]-50	17	%
	Orientation	O	0–360	0 (N/S)	°
Integrated Shading	Roof overhang/ balcony length	RO/BL	0–3	2	m
	Side-fin length	SFL	0–2	0	m
Envelope/material properties	Construction type (external walls)	CTW	Reinforced concrete, clay brick, autoclaved aerated concrete	Autoclaved aerated concrete	-
	Insulation type	IT	Extruded polystyrene, glass wool, stone wool, wooden fibre insulation	n/a	-
	Insulation thickness walls	ITW	0–15	0	cm
	Solar reflectance	SA	0.4–0.8	0.4	-
	Insulation thickness roof	ITR	ECCRB [2]-15	5	cm
	Window U-value	UW	1.2–4.0	4	W/m^2K
	Window solar heat gain Coefficient	SHGC	0.25–0.7	0.6	-
	Infiltration rate	AT	1.0–5.0	3	1/h (50Pa)
	Concrete type	CT	Standard, low carbon	Standard	-
	Construction type (internal walls)	IWC	Concrete, clay brick, autoclaved aerated concrete, timber	autoclaved aerated concrete	-
HVAC system	Airflow per person (mechanical ventilation)	MVA	0 (natural)–36	0 (natural ventilation)	m3/h person
	Sensible heat recovery efficiency	HRS	0–85	n/a	%
	Latent heat recovery efficiency	HRL	0–70	n/a	%
	Energy efficiency ratio: air-conditioning	SEER	2.5–3.5	3	-
	Energy efficiency ratio: domestic hot water	SCOP	0.9–3.0	0.9	-
	Ceiling fan air velocity	CF	0–0.7	0	m/s

Lighting and equipment	Lighting load	LL	2–10	3	W/m^2
	Equipment load	EQ	5–10	5	W/m^2
Occupant behaviour	Cooling temperature setpoint	TC	24–29	26	°C
	Heating temperature setpoint	TH	20–22	20	°C
	Domestic hot water use	DHW	35–75	35	l/person day
Renewable energy systems	Roof coverage with PV panels	PV	0–90	0	%
	Roof coverage with solar thermal panels	SC	0–90	0	%

[1] Minimum value of window-to-floor area ratio (WFR) is based on Energy Conversation Building Code for Residential buildings (ECCCR) depending on the climate location: Composite climate zone (New Delhi): 12.5%; Hot-Dry (Jodhpur): 10%; and Warm-humid (Bhubaneswar):16.5%. The maximum value was set as 50%
[2] The minimum thickness of the roof insulation should allow the roof's thermal resistance to not exceed 1.2 W/m^2K. The maximum thickness value was set as 15cm

Results

The building performance simulations in each of investigated locations indicated that for the benchmark design scenarios, the annual energy consumption was high, with the highest value of 166 kWh/m^2a being observed in the warm and humid climate zone of Bhubaneswar city, followed by New Delhi (composite climate, 133kWh/m^2a) and Jodhpur (hot and dry climate, 127kWh/m^2a). In all locations, the cooling and dehumidification processes were found to represent a dominant share of the annual energy consumption, contributing 70%, 46% and 45% of the total annual energy consumption in Bhubaneswar, Jodhpur and New Delhi, respectively. Consequently, the life cycle GHG emission profile of the base case buildings in each investigated location was dominated by operational GHG emissions related to energy consumption. The share of embodied GHG emissions from material use and replacement in the total life cycle GHG emissions was less than 5% in each investigated location. This can be explained by the combination of the high energy consumption and high GHG emission factors of India's local electricity grid, whose energy mix is dominated by coal.

The GSA results indicated that for all investigated locations, the apartment's floor area, equipment load, windows-to-floor ratio, mechanical ventilation airflow, and cooling temperature setpoint were the most influential design parameters concerning life cycle GHG emissions. On the other hand, parameters such as mechanical ventilation airflow, cooling, and heating temperature setpoints, and indoor air velocity influenced the annual thermal comfort level most.

Based on the multi-objective optimization, significant reductions in the range of 62-75% in terms of life cycle GHG emissions and 40-54% in terms of life cycle cost were achieved compared to the baseline 7-storey multifamily design scenario based on the minimum requirements of the Indian energy conservation code. At the same time, the initial material investment cost was 25-34% higher.

The performance indicators and design parameter values of the optimal (best) design scenarios, characterised by the lowest life cycle GHG emissions and cost, are presented in Table 9. The most optimal set of design strategies, resulting in the lowest life cycle GHG emissions and life cycle cost, included minimising the apartment's floor area and windows-to-floor ratio, maximising the use of on-site renewable energy, and designing a mechanical ventilation system with ceiling fans, thereby enabling an energy-efficient and thermally comfortable operation of the multifamily building with a high cooling temperature setpoint.

Table 9 Performance indicators and design parameter values of the optimal (best) design scenarios, characterised by the lowest life cycle GHG emissions and cost

	Location and climate zone		
	Bhubaneswar (warm and humid)	**Jodhpur (hot and dry)**	**New Delhi (composite)**
Performance indicators			
Energy consumption [kWh/ m^2year]	57.5	66.9	67.5
Renewable energy generation [kWh/m^2year]	23.8	26.2	23.3
Annual energy balance [kWh/ m^2year]	33.7	40.7	44.1
Total life cycle GHG emissions [kgCO2eq/occupant/year]	404	472	423
Total life cycle GHG emissions [kgCO2eq/m^2year]	38.4	44.8	48
Share of embodied GHG emissions to total life cycle GHG emissions [%]	20	17	16
Life cycle cost [$/occupant]	2097	2206	2280
Share of Life cycle cost from materials production and replacement to total life cycle cost [%]	63	57	55
Materials investment cost [$]	420 743	410 743	407 925
Thermal comfort level [%]	97	92	94
RETV [W/m2]	12.1	7.2	8.6
Optimised design values			
Apartment floor area: AA [m2]	30	30	30
Windows-to-floor ratio: WFR [%]	18	15	13
Ceiling fan air velocity: CF [m/s]	0.7	0.7	0.7
Equipment load: EQ [W/m2]	3	3	3
Cooling temperature setpoint [°C]	29	29	29
Roof coverage with photovoltaic panels (PV) [%]	90	90	90
Mechanical airflow (MVA) [m3/h person]	15	15	15
Solar heat gain coefficient (SHGC) [-]	0.25	n/a	n/a
Infiltration rate: AT [1/h]	1	n/a (3)	n/a (3)
Latent heat recovery (MVL) [%]	n/a (0)	75	75
Heating temperature setpoint (TH) [°C]	n/a (20)	20	20

4. Discussion and outlook

4.1 Main findings related to the research questions

The main findings related to the six research questions posed in the thesis are presented in this section.

Research question 1: *How can the transparency and credibility of net-zero GHG emission-building definitions be improved?*

In Paper I, results of the international expert survey combined with a literature review indicated that among existing net-zero building approaches, there is much confusion about whether the framework's goal is to avoid energy/emissions in absolute terms or achieve net-zero or even a positive balance. The definition of the net-zero approach metric is often confusing, especially regarding the term "(net) zero-emission or carbon", which can be used for both CO_2 and GHG emissions. Consequently, to improve clarity and transparency, a flexible and transparent classification system for the different options for energy or emission balance was developed, which takes into consideration i) system boundaries (embodied, operational, or life cycle), ii) type of balance (absolute or net-zero) and iii) balance metric (energy, CO_2 emissions or GHG emissions).

The analysis showed that the system boundaries and performance requirements might vary significantly among net-zero emission building approaches, leading to comparative confusion. Consequently, a classification framework with 81 possible combinations for the different options for regulations and performance requirements related to operational and embodied parts of a building's life cycle was developed and proposed (Table 2). The developed matrix enables a clear and transparent definition of the performance requirements of the net-zero building approaches.

Despite the developed and proposed systematic frameworks, general recommendations are offered to foster transparency and confirm the credibility of the current and future country-specific net-zero building approaches, which will successfully contribute to the decarbonisation of the building sector. The most important ones include:

- The minimum performance target of the net-zero GHG emission approach should at least include and balance the complete scope of the operational energy use stage module (B6), which consists of B6.1: building-related, regulated operational energy use; B6.2: building-related, unregulated operational energy use; and B6.3: user and use-related operational energy use. The building design and construction should also follow the minimum requirements related to the amount of embodied GHG emissions based on national benchmarks.

- Considering the higher efficiency and credibility compared to other GHG emission compensation options, on-site renewable energy generation should be prioritised as the primary offsetting solution for achieving the net-zero balance.

However, to ensure transparency in published results, net-zero frameworks should prescribe that both sides of the balance (on-site energy generation and amount of exported energy) are always provided separately.

- The use of dynamic, hourly GHG emission factors for the energy grid mix is recommended for a net-zero building performance verification.

Research question 2: *How do local conditions and binding building policies influence GHG emissions and the achievement of the net-zero GHG emission performance target of residential buildings in humid subtropical climate regions?*

The results of the life cycle GHG emission assessment case study, based on the detached single-family building model presented in Paper 2, indicated that the level of energy efficiency requirements present in the local building policy in the referential locations of the humid subtropical climate, including Sydney (Australia), Atlanta (USA), Shanghai (China), and New Delhi (India) is a crucial factor influencing the life cycle GHG emissions and the consequent possibility of achieving net-zero emission building balance. The results found that mandatory minimum energy efficiency requirements present in the local building codes, BASIX and IRC2015 in Sydney and Atlanta, respectively, are much stricter, especially considering the thermal specification of the building envelope, than those in Shanghai (JGJ134-10) and New Delhi, where there is a lack of mandatory requirements for single-family buildings. The high level of building thermal insulation, airtightness, solar protection and minimisation of lighting energy use reduced the operational energy use and the consequential operational GHG emissions in the case study buildings in Sydney and Atlanta. Consequently, achieving the net-zero GHG emission performance target of the case study single-family building was feasible both in Sydney and Atlanta, but with varying ambition levels.

The compensation of GHG emissions by the on-site PV energy system is strictly dependent on the GHG emission factor of electricity when applying the symmetric weighting approach using a constant emission factor for both the import and export of electricity from the building. Considering the higher emission factor of the electricity grid in Sydney as compared to Atlanta and the similar renewable solar energy potential of both places, the compensation potential is much higher in Sydney and enables a higher level of net-zero ambition (ZEB-OM), including balancing embodied GHG emissions from construction materials use and their replacement.

The low level of energy efficiency requirements in the Chinese building code JGJ134-10 for Shanghai and the lack of such requirements in the case of New Delhi resulted in annual energy consumption that was approximately two and four-fold higher, respectively, compared to Sydney. This difference increased significantly when accounting for GHG emissions due to highly carbonised energy mix, leading to higher electricity emission intensity in these locations. Consequently, the ZEB performance balance was not achieved in the case of Shanghai and New Delhi.

Research question 3: *What is the current state and the existing research gaps related to life cycle GHG emissions of residential buildings in tropical and humid subtropical climate regions?*

The results of the systematic literature review presented in the Paper 3 indicated that the number of identified research papers/studies related to life cycle GHG emission assessments and design mitigation measures of residential buildings in humid subtropical and tropical climate zones is limited. The majority of life cycle GHG emission assessments were based in Australia (18) and China (14) and were dominantly located in the humid subtropical climate zone. The results found that the highest life cycle GHG emissions were observed in the rapidly developing residential construction sectors in China, Hong Kong and India. In comparison with other studies, it can be stated that residential buildings located in humid subtropical climates present, on average, 65% higher total GHG emissions than those operating in temperate and continental climate zones.

The share of embodied GHG emissions of total GHG emissions ranged from 16% to 100%, with an average share of 27%. This is similar to previous research, most of which is based on case studies of buildings in cold and temperate climates (Chastas et al., 2018a). The differences in the ratio between embodied and total life cycle GHG emissions are mainly attributable to energy performance, the primary material of the building structure, and the energy mix of the study location. Buildings characterised with "conventional" energy performance presented the highest total GHG emissions, which, on average, were 50% and 80% higher than those in "low" and "zero" energy buildings. The highest embodied GHG emissions resulted from by the use of reinforced concrete and steel as the primary building materials. On average, the multifamily building typology presented nearly 40% higher total life cycle GHG emissions than the single-family one, which was driven mainly by high operational GHG emissions relating to energy use.

Some of the main identified research gaps and the reasons for further research are as follows:

i) More research is needed to assess the GHG emission profile and promising reduction strategies in the residential construction sector in tropical climate zones, especially considering the ongoing efforts towards the redevelopment of existing slum areas and market implementation of governmental housing units in developing Asian economies.

ii) This study identified a research gap related to the development and assessment of GHG emission reduction measures in multifamily buildings, which tends to present higher life cycle GHG emissions compared to single-family buildings.

iii) There is limited existing research on developing prefabricated, sustainable, and affordable housing concepts, with the potential for wide implementation in the Asian market.

Research question 4: *How do off-grid container-based housing units perform in the humid subtropical South-East China context in terms of initial investment cost and life cycle impacts, compared to other more conventional design scenarios?*

The results of paper V indicated that the initial investment cost related to the construction of off-grid housing units with a floor area of 21m^2 in Shanghai was estimated to be around 18,800 USD. Accordingly, this investment cost is 45% and 200% higher than a net-zero and low-energy building design, respectively.

Based on LCA, it was found that the life cycle impacts related to an off-grid design were significantly higher than in the case of a net-zero energy design, with an average increase of 59% in all considered categories. The highest relative increase of 86% was observed for the category of fossil fuel scarcity, followed by a 76% and 69% increase for fine particulate matter formation and global warming potential, respectively. The main driver of this increased environmental impact was the need for an on-site PV system with twice the size of peak power, followed by energy storage based on Li-ion batteries.

Compared to the baseline design, the total life cycle impacts were much lower in the case of an off-grid design in all investigated categories and had a reduction rate between 21% and 76% for freshwater eutrophication and GWP, respectively. These significant reductions, ranging from 89% for stratospheric ozone depletion to 460% for the water use category, were achieved despite the substantial extension of pre-use environmental impacts. Life cycle impact reductions were driven by a decrease in operational energy use and the consequential environmental impact related to the use stage, characterised by high environmental loads associated with Shanghai's energy mix, which primarily involves the use of hard coal. In comparison to the low-energy design scenario, the off-grid design scenario was characterised by lower environmental impacts in most categories, despite the freshwater eutrophication and water consumption-related impacts. Similarly, in most categories, the reduction was driven by a complete reduction of operational energy use in the off-grid scenario. In the freshwater eutrophication and water use categories, higher impacts were mainly attributable to high water consumption processes related to PV cell production and the process of copper mining, which is the primary material used in battery cells and produces a significant volume of toxic wastes.

The comparison with existing studies demonstrates the significant GHG emission mitigation potential of the implementation of off-grid and zero-energy buildings in rural, remote, or post-disaster areas with limited electricity access and energy facilities based on fossil fuels.

Research question 5a: *What are the most influential design parameters and optimal design solutions for low GHG emission multifamily building designs in the warm climate zones of India?*

The global sensitivity analysis (GSA) presented in Paper VI, based on the parametric modelling framework, coupling embodied and operational GHG emission assessment, indicated that the apartment's floor area, equipment loads, windows-to-floor ratio, mechanical ventilation airflow and cooling set-point temperature were the most important design parameters regarding life cycle GHG emissions in a multifamily building design located in each of the investigated warm climate locations (Bhubaneswar-warm and humid; Jodhpur-hot and dry; and New Delhi-composite) in India. Interestingly, the influence of the heating temperature setpoint and the thermal insulation thickness of building partitions on the life cycle of GHG emissions was higher in the Jodhpur and New Delhi locations in comparison with Bhubaneswar climate conditions, which requires more space heating-related energy.

Based on the results of this study, the life cycle GHG emission profile was dominated by operational GHG emissions (95-80% share), even in low-energy multifamily building designs, which is due to the high carbon intensity of the Indian electricity grid (0.91kgCO_{2eq}/kWh).

The multi-objective optimisation results presented in Paper VI showed the highest reduction potential with respect to life cycle GHG emissions and cost when comparing the baseline design to the optimal design and ranged between 62–75% (life cycle GHG emissions) and 40–54% (life cycle cost), respectively, depending on the study location. This can be achieved by:

i) Minimizing the apartment's floor area decreases the building heat transfer surface and the mass of building materials, which directly contributes to the decrease in operational and embodied GHG emissions. However, the design team should carefully study the potential of minimising the apartment's floor area, considering the local conditions. In research presented in Paper VI, the minimum floor area per occupant is defined as 10m^2, following the guidelines (Rao & Min, 2018) and the upper limit (30m^2) of carpet area for the economically weaker section dwelling unit types.

ii) Minimizing the windows-to-floor area ratio (WFR) directly leads to a reduction in solar heat gains and cooling energy consumption, which dominates the energy use profile in each investigated location.

iii) Implementing ceiling fans in the building HVAC system design leads to increased airspeed (0.7 m/s) in air-conditioned (AC) zones, thus enabling the achievement of acceptable thermal comfort levels, according to the PMV model, despite the high cooling temperature setpoint (29 °C). This strategy significantly reduces cooling-based energy consumption, leading to a large reduction in operational GHG emissions.

However, it is important to always follow the detailed design of the ceiling fan system to avoid possible effects related to noise and disturbing lighting effects caused by fan blades passing through the beam or intersecting with an occupant's line of sight to a light source.

iv) The use of a mechanical ventilation system with energy (both sensible and latent heat) recovery and an airflow volume not smaler than $15m^3/h$ per person. Using the mechanical ventilation system reduces both sensible (20-30%) and latent heat gains (20-25%) compared to natural ventilation based on natural infiltration airflow through the windows openings.

v) Maximising roof area coverage with PV panels. Considering both the high solar harvesting potential and the emission-intensive Indian grid, the PV system's renewable energy generation covers 34% (New Delhi) to 40% (Bhubaneswar) of the total energy consumption in the case of the low-energy design solution.

Research question 5b: *What are promising design strategies for GHG emission reduction in residential buildings in tropical and humid subtropical regions?*

The meta-analysis of the data from the systematic literature review presented in Paper III indicated that improving a building's energy-efficiency performance should be the first chosen design strategy when working towards zero/low GHG emission performance targets. This finding is supported by the results from Paper V, where despite the increase in the embodied GHG impacts in low and net-zero energy designs, the increase in residential building energy efficiency led to significant reductions (29% (low energy design) and 86% (net-zero energy design)) in total life cycle GHG emissions compared to the base design scenario with a low-efficiency standard. The improvement of building energy efficiency can be achieved by the integration of passive and active design strategies.

Passive design strategies

From the group of passive GHG emission reduction strategies, it was found that improvement of the building envelope's thermal properties led to significant reductions in energy consumption and a consequent decrease in operational GHG emissions. However, the mitigation potential of this strategy is much higher in humid-subtropical climate locations with space heating requirements than in solely cooling-dominant, tropical climate locations. Additionally, increasing the living space efficiency, decreasing the window area and implementing shading overhangs were identified as effective passive strategies to reduce life cycle GHG emissions.

Active design strategies

From the set of active design strategies, implementing an on-site PV renewable energy system was recognised as the most effective GHG mitigation strategy, considering the highly emission-intensive grid and the high solar energy potential in humid subtropical and tropical climates.

Furthermore, in cooling-dominated climate locations, a decrease in the sensible and latent heat loads is crucial for achieving a building design's low GHG emission performance. Consequently, the active design solution involving integrating personal ceiling fans with the HVAC system, which allows for achieving an acceptable thermal comfort level despite the high cooling temperature setpoint, was a highly effective strategy. However, it is essential to mention that the energy reduction efficiency of this strategy is strictly correlated with the occupant behaviour related to the user temperature set-point. Based on the results from paper VI, the change of the temperature set point from 29℃ to 26℃ leads to the increase of the space cooling energy use in the range between 32% in New-Delhi, (composite climate) up to 40% in Bhubaneswar (warm and humid) climate.

Finally, implementing a mechanical ventilation system with both sensible and latent heat recovery is recommended in humid subtropical and tropical climates, characterised by the high sensible and latent outdoor air loads and high pollution.

Strategies for embodied GHG emissions reduction

Regarding design strategies that decrease embodied GHG emissions, reduction of the apartment's floor area using natural-based materials as well as materials with low embodied carbon and high recycling and reuse potential was found to be the most effective. Table 10 below presents the embodied GHG emission reduction potential of selected design strategies applied in energy efficient design of multifamily building in India (characterised by optimised design values shown in Table 9).

Table 10 Embodied GHG emission reduction potential and investment cost change of the selected design strategies in the energy-efficient multifamily building design located in India

Design strategy for embodied GHG emission reduction	Embodied GHG emission reduction	Initial investment cost reduction (-) or increase (+)
Reduction of apartment floor area from 60m^2 to 45m^2	-22%	-15%
Reduction of apartment floor area from 60m^2 to 30m^2	-39%	-33%
Change of the main exterior walls material from clay brick to aerated concrete block	-9%	-3%
Use of the low-carbon concrete mix	-6%	+4%
Replacement of EPS thermal insulation (10cm) type with wood fibre	-3%	+2%
Replacement of internal walls materials from aerated concrete to timber	-2%	+3%

4.2 Implications for policy

The decarbonisation of the construction sector, which is currently responsible for almost 40% of total GHG emissions, is critical for achieving carbon neutrality in national economies (Dean, Dulac, Petrichenko, & Graham, 2016). Consequently, the global development of transparent and reliable net-zero GHG emission building frameworks that address GHG emissions for the entire building lifespan, along with the further implementation of net-zero performance requirements in mandatory national building codes for the long-term perspective, is crucial to achieving climate targets.

This thesis developed a range of recommendations and systematic frameworks for future progress in developing new country-specific net-zero approaches and updating the existing ones. The following recommendations are particularly relevant for the rapidly expanding economies in the Global South, of which China and India are the leading actors, which lack net-zero emission building approaches and high-level mandatory building energy codes.

Based on the results of Paper III, the first and urgent step should be to develop and introduce mandatory residential building energy codes in countries that lack such requirements. The requirements included in such regulations should not only rely on a single energy indicator for the thermal performance of the envelope but rather be oriented on more holistic indicators such as energy use intensity targets (EUI) that take into consideration the complete scope of building energy use and support the use of renewable energy sources. At the same time, there is a need to gradually strengthen the energy-efficiency requirements in existing mandatory residential energy building codes to reach the level of requirements present in the nearly zero-energy building (nZEB) or passive-house frameworks.

Other short-term term policy-related recommendations, which are in line with conclusions from Paper I, include:

- **Harmonise the life cycle methodology used for calculating the life cycle GHG emissions;** foster research industry collaboration and efforts towards standardisation of parameters, definitions and modelling techniques, including quantifying both building-related life cycle GHG emissions and possible compensations/offsets from different available options.

- **Integrate the net-zero building performance target as the more ambitious goal in popular certification schemes such as BREEAM or LEED** to increase the number of net-zero emission buildings in the national market (transition from current regulation type D2.a to G5.f, Table 3).

- **Develop national benchmarks regarding a building's embodied, operational and life cycle GHG emissions;** based on these values implement gradually more ambitious targets in the mandatory building codes based on the life cycle GHG emission metric.

The long-term policy-related recommendations include the following:

- **Decarbonise and electrify the energy grid;** the research results presented in Papers II-VI indicated that the GHG emission profile of residential buildings in humid subtropical and tropical climates are dominated by operational emissions and highly influenced by energy mix. Consequently, a shift from fossil fuels to renewable energy sources in the energy mix and the complete electrification of buildings for heating and cooking purposes should be supported as a vital decarbonisation strategy to enable the implementation of energy-efficient technologies such as heat pumps or electric stoves.

- **Develop reliable LCI databases;** the lack of widely available, critically reviewed, comprehensive LCI databases is one of the main reasons why building LCAs are frequently dismissed as expensive and time-consuming.

In addition to these higher-level policy-related mechanisms, significant reductions in life cycle GHG emissions in the residential building sector **are impossible without specific research based on practical low GHG emission building concepts and strategies**. The research activities included in this thesis cover some research gaps (identified in Paper II) related to the lack of holistic LCAs of prefabricated single-family housing units in Shanghai, China, with net-zero energy and off-grid design, as well as cost-efficient life cycle GHG emission reduction strategies for multifamily building designs for warm climates in India. Based on this, a set of policies and research recommendations are proposed. Although these recommendations originate from a specific residential building designs in China and India, their applicability can be extended to other rapidly developing economies in humid subtropical and tropical climates.

Governments in developing countries should support a shift from conventional construction methods toward prefabrication, as this strategy holds great potential for guiding urbanisation in a more sustainable direction. This can be done by offering financial incentives for developing and following the example of the Chinese government's long-term goals related to achieving a significant share of prefabricated buildings in the national construction stock. Additionally, the transition towards more energy-efficient technologies and controls in the production facilities, such as waste heat recovery, wastewater reuse or renewable energy use, should be adopted to reduce the environmental impact of manufactured prefabricated building modules or single components. Prefabricated plants should be located close to raw material suppliers and target markets to minimise the environmental impact of transport activities. At the component level, the choice of material for prefabricated housing units should include extensive reuse of building components and high utilisation of recycled and locally sourced materials.

The research results included in this thesis (Paper V) have proven that reusing steel-based shipping containers as the main structural frame of a prefabricated housing unit significantly reduces the embodied environmental impacts, especially in factories located in harbour-hub locations such as Shanghai, which is characterised by the high availability of shipping containers and low transportation distances.

However, to increase the potential of reusing shipping containers in the market and increase the safety of repurposing them for housing units, mandatory policies related to transparent registration and documentation of the primary use of the container and the kind of goods it has transported must be implemented.

Furthermore, research activities (Paper V) related to the development of transportable, prefabricated modular housing units based on reused shipping containers demonstrate the significant potential to mitigate GHG emissions related to the implementation of off-grid and ZEBs in rural, remote, or post-disaster areas with limited electricity access and energy facilities based on fossil fuels. These solutions are particularly promising for temporary housing in Asian and African regions located in the Belt and Road Initiative (BRI) area, which expects significant population and development growth, consequently leading to an increase in primary energy use. This increase, coupled with increased power generation based on the dominant share (75%) of fossil fuels, will lead to a tremendous expansion of GHG emissions, corresponding to 7–17% of the remaining carbon budget for the 1.5–°C climate goal (Tao, Liang, & Celia, 2020). Consequently, a market-wide implementation of sustainable prefabricated housing units that are highly-energy efficiency and exploit renewable energy sources can reduce these harmful environmental impacts. However, it is essential to note that research presented in this thesis (Paper IV and V) based on the single container unit with a limited living space area of 21m^2 is mainly applicable to the temporary, emergency, and remote housing market in Asian locations with limited access to water and energy services.

However, with minor changes in the design (extension of the floor area to 23m^2), the presented housing solution based on a single unit is in line with requirements related to affordable housing in general and in particular for the economically weaker section (EWS) unit type. As such, a modified solution would be appropriate for the redevelopment of the slum areas in India and wider Asia, which is currently suffering from a shortage of more than 20 million units (Gupta, 2008). Nevertheless, to provide a comfortable and standard market housing solution, the design based on shipping containers must combine multiple units to provide sufficient living space. Particularly in China, the floor area can be extended by adding additional modules inspired by a traditional Chinese courtyard house (Figure 16).

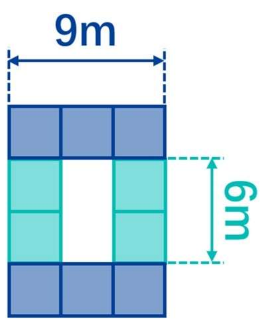


Figure 16 Courtyard house shape, inspired by the traditional Chinese Siheyuan

In the early stages of planning a residential building design in tropical and humid subtropical climates, **the focus should be on finding incentives that will promote an increase in the space efficiency of the apartments and enable comfortable living with a reasonable floor area**. The amount of sufficient space should be based on the local conditions and not be less than $10m^2$-$15m^2$ per occupant. Additionally, when minimising the apartment space, the multifamily building design should include shared spaces such as guest rooms, balconies, and working and storage spaces, which housing occupants often underuse.

Based on the results from Paper VI, the floor area per inhabitant directly affects the material use and the embodied and operational life cycle GHG emissions. Considering the dominant share of cooling-related energy consumption in a total energy profile, the development and implementation of energy-efficient hybrid cooling systems with the use of ceiling fans should be supported. These active strategies should be reinforced using more passive design methods, including providing proper orientation for the building, shading overhangs and glazing that is characterised by a low solar heat coefficient. The installation of on-site renewable energy systems should be achieved with financial subsidies provided by local and national bodies.

So far, and in light of the research results (Papers II), the GHG emission profile of residential buildings located in humid subtropical and tropical climates is dominated by operational GHG emissions. However, since the electricity grids in most countries seem to be set to decarbonise over time, the life cycle contribution of operational emissions will be reduced and replaced by the initial embodied GHG emissions. Consequently, the building design should include approaches and strategies to achieve low embodied energy and GHG emissions. The first design choice should be to replace high carbon-intensive construction materials with more sustainable ones. The extensive use of low-carbon concrete mixes and prefabricated building elements such as aerated concrete blocks, and the increased use of biobased materials in partial walls, finishes and thermal insulation were proven to reduce embodied GHG emissions significantly based on the results of the research papers included in this thesis.

4.3 Scientific contribution of this thesis

The research presented in this thesis has contributed to advancing knowledge related to the definition of a net-zero GHG emission building. The detailed analysis of key methodological parameters, together with the developed systematic frameworks and recommendations for policy, is a good base for the global development of new country-specific net-zero GHG emission building frameworks. This scientific contribution seems to be especially relevant for rapidly developing economies in humid subtropical and tropical climates that have not yet created any specific net-zero GHG emission frameworks.

Besides the scientific contribution to building policy, the research presented in this thesis covered some identified gaps regarding the life cycle and climate mitigation strategies in relation to prefabricated housing units and multifamily building designs located in China and India, respectively. This was done using a holistic case-study approach that combined the assessment of both embodied and operational environmental impacts.

Coupling the assessment of embodied and operational GHG emissions is widely recognised as one of the most challenging endeavours for calculating the total life cycle GHG emission of buildings. This challenge can be related to two different research communities that rarely collaborate. The first group is usually the building energy modelling community, which is primarily focused on the operational or use stage, and the second is the process and industrial engineering community, which heavily focused on the embodied impacts related to building materials production (product stage). Consequently, the holistic case-study approach for assessing both embodied and operational impacts was mostly undertaken in this thesis using different modelling techniques. In addition to the development of a set of energy efficiency and life cycle emission mitigation strategies, practical recommendations were proposed to inform the decision-makers on how to successfully lower the life cycle GHG emission by buildings in humid subtropical and tropical climates in a cost-effective manner.

4.4 Future work

The main limitations of the research covered in this thesis should be addressed in future work by conducting the following research activities:

a) Extend the geographical scope of building LCAs in humid subtropical and tropical climates

Future research should cover the gap related to the limited number of LCA studies of buildings in Africa, South America and Southeast Asia, in which tropical and humid subtropical climates are dominant. Considering the rapid urbanisation and development in these regions, quantifying the life cycle GHG emission profiles and developing design strategies to minimise environmental impacts are crucial.

b) Determine the influence of the compensation options for achieving the net-zero GHG emission performance target

The current frameworks for net-zero GHG emissions of buildings and the existing research on ZEB designs are mostly based on the net-balance approach, where the environmental benefits from exported energy based on on-site renewable energy generation are fully attributed to the building ("potentially avoided emissions"). However, this approach has some major limitations regarding its reliance on the uncertain assumption that exported electricity avoids today's average grid mix production. It also includes the risk of double-counting emission reductions between the producer (building) and the user (purchaser of exported energy) (Lützkendorf & Frischknecht, 2020). Consequently, more research on the technical and economic feasibility of achieving the net-zero GHG emission performance target using the different compensation options or a combination of these, as described in Section 1.4, is needed.

c) Implement a dynamic approach to LCA

The quantification of the life cycle impact profiles and the reduction potential of the different active and passive design strategies in this thesis was based on a static methodological approach to the LCA. This includes the constant emission factor from electricity use and the climate weather data during the building's lifespan.

Future research should evaluate the environmental performance of case study buildings, considering scenarios with gradual decarbonisation of the power sector and the influence of climate change on local weather conditions during the building's lifespan.

d) Compare the process-based LCA with input-output and hybrid methods

The LCAs included in this thesis are based on the process-based methodology, which is sensitive to truncation error and tends to underestimate embodied GHG emissions, compared to the input-output and hybrid methods (Crawford et al., 2018, 2019). Consequently, future research should be performed to explore the variety of embodied impact results considering the different LCA methods.

e) Validate operational energy use and renewable energy generation with on-site measurements

The accuracy of the building performance simulation results depends greatly on the level of detail incorporated in the analysis tool; the accuracy with which building properties are known; and the modeller's skill, experience and available time (Coakley, Raftery, & Keane, 2014). The validation of the BPS models in this thesis was limited due to the lack of measurements for energy use and production from the case studies at the time of the analysis. Future research should reconcile the model outputs with measured data to achieve more detailed and reliable results related to operational energy use and generation.

f) Integrate the climate-resilient approach into net-zero GHG emission building design

The humid subtropical and tropical climates are nearly twice as sensitive to local temperature changes due to global warming, and are thus more affected by related harmful effects compared to cold and temperate climate regions (Ganopolski, Friedrich, Elison Timm, Tigchelaar, & Timmermann, 2016). Considering the status of climate change and the rapid increase in climate-related disasters, designing a built environment for environmental sustainability and resilience to extreme weather events in the context of changing climatic conditions is crucial to face future environmental challenges effectively. However, knowledge gaps in the current understanding of resilience and environmental sustainability dynamics plague the integration of extreme weather resilience and environmental modelling methodologies. Future research should examine the synergies between the design approaches of net-zero GHG emissions and climate-resilient buildings to address these knowledge gaps and develop integrated framework definitions.

5. Conclusions

The humid subtropical and tropical climates are widely recognised as among the most GHG emission-intensive regions in the world, and a large share of their environmental impact comes from the construction sector. Considering the remarkably rapid growth of the population and improved access to electricity, building facilities and services, mitigating GHG emissions from the residential construction stock in these climates is crucial to combat global climate change and its harmful impacts.

The research presented in this thesis advances the development of sustainable, low-emission residential building concepts, particularly for locations in humid subtropical and tropical climates, at the policy and design level. First, a collection of systematisation frameworks, analysis of key methodological features, and recommendations were proposed to improve the credibility and transparency of the net-zero GHG emission-building frameworks with the main aim of accelerating the global development of country-specific net-zero GHG emission-building approaches. Second, the feasibility of achieving a net-zero GHG emission building for a single-family case-building located in various humid-subtropical locations (Sydney, Atlanta, Shanghai, New Delhi) was proven to be highly dependent on the level of energy efficiency requirements present in the local mandatory residential building codes. The low level of energy efficiency requirements in Chinese building standards and the lack of such regulations in India's building standards were identified as significant barriers to the rapid market adoption of single-family buildings characterised by low life cycle GHG emissions.

At the building level, the case study research presented in this thesis aimed to cover the identified research gap related to the lack of a holistic life cycle assessment (LCA) and design strategies for life cycle GHG emission reduction in prefabricated housing units and multifamily buildings located in humid subtropical and tropical climates. Consequently, validated building performance simulations and on-site experiments were combined to explore the relation between energy use, indoor environmental quality, and the economics of the various energy conservation strategies applied to a prefabricated housing unit based on a shipping container constructed and tested in Shanghai, China. Relaxed cooling and heating temperature setpoints outside building occupancy hours, increased thermal insulation thickness, upgrade to 3-layer glazing, and implementation of the hybrid ventilation system were found to provide the most significant energy use savings. The improved "low-energy" design of the housing unit was further compared with conventional, net-zero energy and off-grid design scenarios, while considering the life cycle environmental impacts and the initial investment cost. The initial investment cost related to the construction of low-energy, zero-energy and off-grid housing modules was estimated to be 37%, 99% and 205% higher than that for the conventional design scenario, respectively. The life cycle environmental impacts were the lowest for the zero-energy scenario, with an 86% reduction of GHG emissions compared to the conventional scenario. The off-grid design presented substantially higher environmental impacts in all investigated categories (by an average of 59%) than the zero-energy scenario. However, environmentally, it still performs significantly better than the low-energy scenario despite the identified increase in impacts on water consumption and freshwater eutrophication categories. Comparison with existing literature demonstrates the significant GHG emissions mitigation potential of implementing off-grid and ZEB in rural, remote, or post-disaster areas with limited electricity access and energy facilities based on fossil fuels.

The global sensitivity analysis (GSA) based on the multifamily building designs located in the warm climate locations of New Delhi (humid subtropical), Bhubaneswar and Jodhpur (tropical) indicated that apartment floor area, equipment loads, windows-to-floor ratio, mechanical ventilation airflow and cooling set-point temperature were the most important design parameters influencing the life cycle GHG emissions in multifamily buildings located in each of investigated warm climate locations. The multiobjective optimisation based on the above parameters identified that the strategies related to increasing the space efficiency of building apartments, minimising the windows area and the solar heat gain coefficient, implementing the hybrid cooling system with the use of ceiling fans, and maximising energy generation from the on-site PV system provided the best life cycle performance including GHG emissions and life cycle cost. A reduction rate between 44–53% was found for life cycle GHG emissions compared to the baseline design.

These findings advance the net-zero and low GHG residential building designs in developing economies in warm climates, especially in humid subtropical and tropical zones, which are critical for global climate change mitigation efforts.

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Part B

Scientific papers

PAPER I

How to define (net) zero greenhouse gas emissions buildings: The results of an international survey as part of IEA EBC Annex 72, published in *Buildings and Environment (2021).*

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

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ABSTRACT

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

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

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

1. Introduction

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

As part of the way forward for sustainable development, actors in the built environment, including the related upstream and downstream economic sectors, strive to protect their traditional business interests, along with fulfilling their responsibility towards society and the environment. They orient themselves, among other things, towards the internationally recognised sustainable development goals (SDGs) [1–3]. Any specific decision may affect not only the achievement of economic goals but also society and the environment. ISO 26000 [4] on corporate social responsibility (CSR) forms the basis for this. It expressly includes the task of assuming product responsibility. For construction product manufacturers and the actors involved in the design, construction, use, financing, and management of buildings, this means that the characteristics and properties of the use of resources and undesirable impacts on the global and local environment; biodiversity; and the health of construction workers, building users, and neighbours must be documented, assessed, and influenced in a targeted manner, as well as communicated to third parties. These topics together can be summarised

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as the environmental performance of buildings.

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

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

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

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

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

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

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

1.3. Focus and aim of the research

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

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

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

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

2. Theoretical basis

2.1. Object of assessment and system boundaries

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

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

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

2.1.1. System boundaries—operational part

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

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

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

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

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

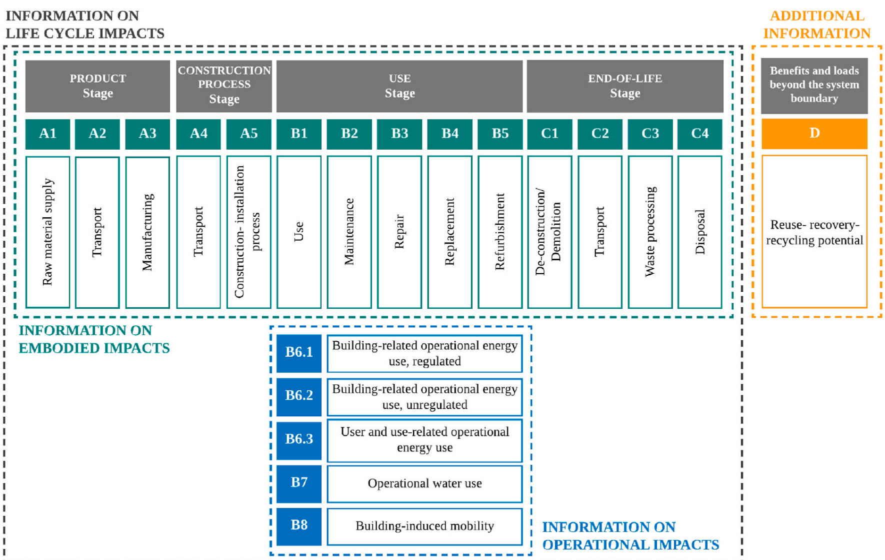

Fig. 1. System boundaries of building life cycle (modified from EN 15978 and Lützkendorf (2019)).

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

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

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

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

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

2.1.2. System boundaries: embodied part

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

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

2.2. Indicators and metrics of balance

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

The use of energy and the consumption of energy carriers play an essential role in the description, assessment, and targeted influencing of environmental performance. The energy performance is one aspect of the environmental performance. Embodied energy can become a factor in the energy performance if a life cycle-based approach is considered. For a long time, the consideration of the resource use, and the use of non-renewable primary energy resources, dominated the discussion as a single indicator/metric by which to assess and benchmark buildings' environmental performance. Still, today the requirements for climate protection are expressed in goals for improving the energy efficiency of buildings.

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

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

2.3. Principles for an environmental impact assessment of electricity use

Generally, environmental impact evaluation methods for the electricity mix can be divided into two main distinct concepts: average and marginal. The use of the "average electricity" principle presents the statistical average emissions, which are usually given as the gram carbon dioxide equivalent per kWh (gCO_2eq/kWh) from the entire electricity mix and usually contain several interconnected regional zones. In contrast, the "marginal electricity" principle is defined as marginal changes in GHG emissions caused by changes in non-baseload electricity generation due to daily or hourly variation in the electricity consumption profile. Consequently, this principle takes into consideration the local and actual effects of different actions on the power grid.

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

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

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

2.4. Aspect of time—static versus dynamic approach

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

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

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

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

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

The extensive development and use of hourly and regionally specific (marginal) GHG emissions factors are important for a reliable and accurate representation of the benefits related to the implementation of GHG emission reduction strategies, such as on-site renewable energy systems.

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

2.5. Options for compensation

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

The most important questions are discussed below.

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

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

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

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

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

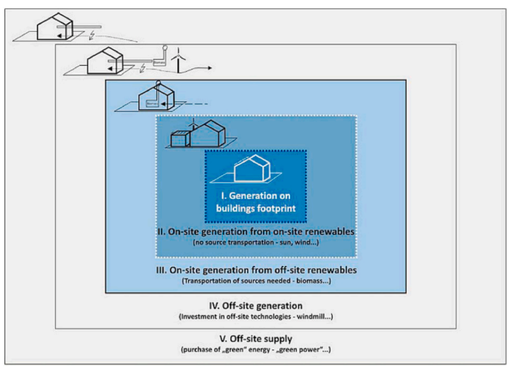

Fig. 2. Overview of the possible renewable supply options by Marszal et al., 2011 [16].

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

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

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

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

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

2.5.2. Negative GHG emissions through technical measures

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

2.5.3. Purchasing of off-set certificates

The purchase of eligible off-set units supports projects that reduce or remove emissions from the atmosphere and compensate for emissions generated elsewhere. The general framework of the measurement and validation of carbon off-set programs which can be traded in a marketplace was established under the development mechanism (CDM) developed under the Kyoto Protocol. Off-set certificates/units are considered as an essential tool to improve sustainability and boost global decarbonisation by financing initiatives related to carbon reduction in developing countries. On the other hand, compensation by off-set units may lead to controversy regarding effectivity and reliability [52].

2.5.4. Typology of options

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

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

Type B: Economic compensation;

Type C: Technical reduction;

Type D: Absolute zero approach.

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

3. Materials and methods

3.1. Proposal for a systematic approach

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

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

In order to deliver clarity, limit misunderstanding, and avoid potential greenwashing, it is therefore important to state the chosen term very clearly and specifically. The same applies to the term "(net) zero emission", which is used for both 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.

The authors propose a system which clearly distinguishes the contribution of (1) energy balance, (2) CO_2 balance, and (3) GHG emissions balance in the chosen framework (code). It must be declared whether the goal is to avoid, in absolute terms, non-renewable primary energy consumption and emissions, or whether the goal is to achieve a net zero balance or possibly even a positive balance. While, for the operational part, in the areas of both non-renewable primary energy and CO_2 emissions, there are at least theoretical possibilities of absolutely avoiding any impacts, this is currently not possible for the entire scope of GHG emissions and the embodied part. Even though it is theoretically possible to achieve an absolute zero during operation or in the full life cycle, there are strong influences due to the system boundaries. This depends on whether the focus is on the direct use of energy and direct emissions and whether and to what extent upstream processes are included.

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

Table 1
Framework of different options for an energy or emissions balance.

	Energy use (specified by energy carriers) representing use of natural resources *[MJ primary energy, non ren.]* A	CO_2 emissions representing impacts to global environment *[kg CO2]* B.1	GHG emissions representing impacts on global environment *[kg CO_2eq.]* B.2
1.1 **Operational part of energy consumption and GHG emissions**	a) **absolute zero** b) net zero	a) **absolute zero** b) net zero	a) absolute zero b) **net zero**
1.2 **Embodied part of energy consumption and GHG emissions**	a) absolute zero b) **net zero**	a) absolute zero b) **net zero**	a) absolute zero b) **net zero**
2 **Balance, considering full life cycle**	a) absolute zero b) **net zero**	a) absolute zero b) **net zero**	a) absolute zero b) **net zero**

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

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

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

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

3.2. Systematic review of building assessment approaches—key features

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

In the second step, the current study excludes the energy metric-based approaches whose methodology and approach have been extensively described in previous research [16–19]. Consequently, the main analysis focuses on 13 building assessment approaches from 11 countries, which are based on a GHG emissions metric. To provide a detailed review and analysis of the methodology occurring in the GHG emissions-based building assessment approaches, the general data from the first step of the data extraction were complemented by the extraction of detailed data covering features related to the operational and embodied modules and possibilities of GHG emission compensation, as presented in Table 3 below.

4. Results and discussion

4.1. State of the art

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

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

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

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

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

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

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

Table 2
Classification framework for system boundaries and performance requirements in building assessment approaches.
Note: for primary energy (**PE**), delivered energy (**DE**), CO_2 (**C**), or GHG emissions (**G**) metric.

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

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

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

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

The requirement for net zero GHG emissions from the operational life cycle module (type G5. a, G5. d) is implemented in building assessment approaches from four countries: Australia, South Africa, New Zealand, and the USA (LEED zero carbon [78]). In all these assessments approaches, the GHG emissions from embodied life cycle modules are outside of the assessment scope (Type G5. a), except New Zealand (Type G5. d), where all new buildings need to be constructed with 20% fewer embodied GHG emissions relative to the baseline scenario by 2025.

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

The more ambitious performance target requirement can be found in

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

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

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

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

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

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

In 8 of the 13 analysed building assessment approaches, the complete scope of operational energy use modules including the B6.1 B6.2, and B6.3 submodules is covered. 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 the Sweden (Local Roadmap Malmo [84]) framework, while the non-regulated building-related energy consumption module (B6.2) is outside of the scope in the framework from Norway and Canada.

Further, the performed review indicates that among the analysed building assessment approaches, there is inconsistency in terms of including the GHG emissions from operational water use (B7), with 7 of the 13 frameworks having a B7 module in the operational impact assessment scope. The impact of building-related mobility caused by the location (B8) is included only in the scope of the building assessment

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

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

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

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

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

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

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

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

4.2.2. Life cycle embodied modules

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

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

A static approach to the "time" factor in embodied GHG emissions assessment during the building lifespan is evident in most of the analysed building assessment approaches (Table 7), except for Sweden (NollCO$_2$ scheme), where the GHGs emissions from the end-of-life stage (C1–C4) are assumed to be zero, due to the assumption of carbon neutrality when taking into account the life cycle of all activities up to 2050. The only exception from the static approach suggested in the Norwegian approach is the environmental impact caused by the replacement of PV modules. Here, based on the continuous improvement of new technologies and material use, as well as prospective LCA studies, a 50% reduction in the GHG emissions relative to product stage impact (A1-A3) is applied as a rule of thumb [44,83].

4.2.3. Options and principles of GHGs emissions compensation

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

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

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

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

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

X: included with details; ✓: included without details; n/c: not clear.
[1] only as additional information.

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

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

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

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

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

5. Conclusions and recommendations

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

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

Based on the current review of 35 building assessment approaches, the present authors identified 13 voluntary frameworks from 11 countries, characterised by net zero-carbon/GHG emissions performance targets. There is a significant variance in the methodological principles and approaches between these frameworks. In order to rule out misunderstandings and greenwashing, the key methodological factors from the building assessment approaches were identified, explained, and analysed. One of the proposals suggested by the authors is to extend the scope of the operational energy module (B6) and develop a systematic approach which defines the performance target of the building on the basis of a different energy or emissions system balance.

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

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

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

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

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

X: Allowed option.
[a] Reforestation, carbon reduction programs in developing countries, carbon sequestration investments.
[b] On-site renewable generation is prioritised.
[c] Life cycle GHG emissions can be compensated by implementing energy efficiency measures in other existing buildings.
[d] Carbon capture and storage.
[e] Renewable energy projects, reforestation projects, and landfill gas-to-energy projects where the methane would otherwise be released to the atmosphere.

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

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

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

Outlook

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

Declaration of competing interest

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

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Appendix A. Supplementary data

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

Explanation of the authors' contributions

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

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Appendix Paper I

Table A1. Overview of the key methodological parameters from 35 building assessment approaches.

Note: the highlighted approaches 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
Australia (AU)	Climate active, carbon neutral standard for buildings, [76]	Voluntary, 2019	Government	Buildings and neighborhoods	GHG emissions	G5.a
Austria (AT)	OIB-300.6-009/2015, Guideline 6 (EPBD), [55]	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Belgium (BE)	Energieprestatie en Binnenklimaat (EPBD), [56]	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Brazil (BR)	Zero energy standard, [69]	Voluntary, 2017	Brazil Green Building Council	Buildings	Delivered energy	DE7.a
Canada (CA)	Zero-carbon building standard, [80]	Voluntary, 2020	Canada Green Building Council	Buildings	GHG emissions	G5.f
China (CN)	Technical standard for nearly zero-energy buildings, [54]	Voluntary, 2019	Government	Buildings	Primary energy	PE4.a
Czech Republic (CZ)	Energy management act, 78/2013 Coll (EPBD), [57]	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a
Denmark (DK)	Danish building regulations (EPBD), [58]	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Finland (FI)	Method for the whole-life carbon assessment of buildings, [75], and Finnish regulatory life cycle carbon limits of buildings	Draft, 2020	Finish Green Building Council	Buildings	GHG emissions	G4.e
France (FR)	France E+C-, [59]	Draft, 2020	Government	Buildings	Primary energy	PE4.a
	France EQUER, [81]	Voluntary, 2017	Research	Buildings	GHG emissions	G5.f

Germany (DE)	Framework for “carbon neutral buildings and sites” [82]	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, [89]	Public framework, 2015	Government	Building stock	Primary energy	PE4.a
Hungary (HU)	Decree on the determination of the Energy Efficiency of Buildings (EPBD), [60]	Mandatory, 2016	Government	Buildings	Primary energy	PE4.a
India (IN)	Net zero energy rating system [70]	Voluntary, 2018	Indian Green Building Council	Buildings	Delivered energy	DE7.a
Italy (IT)	Law 90/2013 and decree 26/06/2015 (EPBD) [61]	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Japan (JP)	Japan’s strategic energy plan, [62,63]	Mandatory, 2014	Government	Buildings	Primary energy	PE4.a
Netherland (NL)	Almost energy-neutral building requirements (EPBD), [64]	Mandatory, 2019	Government	Buildings	Primary energy	PE4.a
New Zealand (NZ)	CarboNZero Building Operations pilot scheme as part of the Zero Carbon Road Map for Aotearoa’s Buildings, [79]	Voluntary, 2019	New Zealand Green Building Council	Buildings	GHG emissions	G5.d
Norway (NO)	Zero emission building (ZEB) definition ,[83]	Voluntary, 2014	Research	Buildings	GHG emissions	G5.f
	Zero emission neighborhoods in smart cities, [90]	Voluntary, 2019	Research	Neighborhood	GHG emissions	G5.f
Poland(PL)	Buildings and their location: Polish technical conditions (EPBD), [65]	Mandatory, 2018	Government	Buildings	Primary energy	PE4.a
Portugal(PT)	Art. 16 of DL 118/2013 (EPBD), [66]	Mandatory, 2013	Government	Buildings	Primary energy	PE4.a

Slovenia(SI)	Action plan for nZEB until 2020, [67]	Mandatory, 2015	Government	Buildings	Primary energy	PE4.a
Spain(ES)	Net zero-energy buildings, [71]	Voluntary, 2019	Spanish Green Building Council	Buildings	Delivered energy	DE7.a
South Korea (KR)	The green building promotion act, [72]	Mandatory, 2013	Government	Buildings	Delivered energy	DE7.a
South Africa (ZK)	Net zero and net positive certification scheme, [77]	Voluntary, 2019	South Africa Green Building Council	Buildings	GHG emissions	G5.a
Sweden (SE)	NollCO2, [86]	Voluntary, 2020	Sweden Green Building Council	Buildings	GHG emissions	G5.h
	Local Roadmap Malmö, [84]	Draft, 2020	Malmö municipality with industrial partners	Buildings	GHG emissions	G5.f
Switzerland (CH)	Net zero-energy building (MINERGIE-A), [68]	Voluntary, 2012	Minergie Association	Buildings	Primary energy	PE7.d
Singapore (SG)	Green mark for super-low-energy buildings, [73]	Voluntary, 2018	Building and construction authority (BCA) of Singapore	Buildings	Delivered energy	DE7.a
United Kingdom (UK)	Net zero-carbon building, [85]	Voluntary, 2019	UK Green Building Council	Buildings	GHG emissions	G5.f
USA (US)	Zero-energy building, [74]	Voluntary, 2015	Government	Buildings and neighborhood (campus)	Delivered energy	DE7.a
	LEED zero carbon, [78]	Voluntary, 2016	United States Green Building Council (USGBC)	Buildings	GHG emissions	G5.a
	Zero-carbon building, [87]	Volontary, 2019	International Living Future Institute	Buildings	GHG emissions	G5.h

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

Table A2. Overview of the multiple performance levels in the analysed GHG emissions-based building assessment approaches.

			Regulation type[2]			
Country	Building assessment approach	Level of performance[1]:	Type G5. a	Type G4. e	Type G5. f	Other
Australia	Carbon-neutral buildings	Base building operation	X			
		Whole building operation	X			
Germany	Carbon-neutral buildings	Climate neutral by 2050		X		
		Carbon neutral in the ongoing operation	X			
		Carbon neutral through life cycle			X	
Norway	Zero-emission building	ZEB: O-EQ, ZEB:O	X			
		ZEB: OM, ZEB: COM, ZEB: COME			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				G1. f
		Net zero-carbon operational energy	X			
		Net zero-carbon for whole life			X	

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

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

Among the 13 building assessment approaches from 11 countries characterised by the GHG emission-based metric, in the five frameworks from Australia, Germany, Norway South Africa, and the UK the relative standard introduces different levels of building performance targets, providing some flexibility in the design and construction of net zero-GHG emissions buildings (Table A2).

The differences between performance levels in the Australia and South Africa frameworks are attributed to the scope of operational life cycle boundaries and presented in Section 3.2.

The German framework defines three levels of performance, while the net zero-emission building standards in Norway provide 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 the embodied life cycle system boundary scope. The experiences from the pilot building projects in Norway show that reaching the highest level of ambition for ZEB (Type G5.f), which includes 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 an additional implementation of renewable energy sources, which increases the initial energy generation in the range of 82% to 182% [20].

In the UK net zero-carbon standard, there is the possibility of achieving two different performance levels or a combination of those, which takes into consideration the whole life cycle approach.

Table A3. Overview of the verification requirements in the 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 building 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					
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	CarboNZero Building Operations pilot scheme as a part of the 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	X	X			

	(occupant emissions)					
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	

PAPER II

Towards Zero-Emission Residential Buildings (ZEBs) in a Humid Subtropical Climate. Analysis Emissions from Energy Use and Embodied Emissions from Materials in Referential Locations According to Obligatory Residential Energy Codes and Using Generic LCA Data Sources, *Published in Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)*

Authors: **Daniel Satola,** Aoife Houlihan-Wiberg and Arild Gustavsen

Towards Zero Emission Residential Buildings (ZEBs) in a Humid Subtropical Climate. Analysis Emissions from Energy Use and Embodied Emissions from Materials in Referential Locations According to Obligatory Residential Energy Codes and Using Generic LCA Data Sources

Daniel Satola, Aoife Houlihan Wiberg and Arild Gustavsen

Abstract The primary objective of this paper is to investigate whether is it possible to achieve a zero greenhouse gas emission residential building (ZEB) operating in a humid subtropical climate. Sydney, Atlanta, Shanghai and New Delhi, recognised as main regional policymaker centres, were included in the scope of analysis as referential locations. Calculations of annual energy consumption, embodied emissions from production (A1-A3) and replacement (B4) of construction materials, as well as on-site renewable energy production, were performed on the basis of mandatory energy standards, building performance simulations and generic, process-based life cycle data. All calculations were based on a single-family building model with timber construction. All building's thermal energy demands are provided by electrical air-to-water heat pump with a backup from an electric coil heater. Additionally, the roof-mounted photovoltaic system is used specifically to reduce GHG emission from building operation and materials. The preliminary results of this study show that zero emission ambition level for residential building is obtained in Sydney and Atlanta, where mandatory energy codes enforced high standards of building energy performance. The paper presents and discusses the results of the environmental impact for a model residential building in each of the specific humid subtropical climate locations. Additionally, general adjustments of the energy codes requirements that could enable higher ZEB ambitions are proposed.

Keywords Zero emission residential building · Energy policy · Humid subtropical climate

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1 Introduction

1.1 Life Cycle-Related Environmental Impacts Caused by Residential Buildings

Buildings and the related construction industry contribute to over 36% of total global final energy consumption and about 39% of all energy-related carbon dioxide emissions when upstream power generation is included [1]. Moreover, emissions related to residential buildings contribute to over 60% of all global construction emissions [1]. This may double or potentially even triple by 2060 due to the increased access for billions of people in developing countries to adequate housing, electricity and improved facilities [2]. Global greenhouse gases (GHGs) attributable to the building energy use, together with the embodied emission from materials production stage and their replacement during building lifespan, contribute to over 90% of total life cycle emissions [3].

1.2 Humid Subtropical Climate as Main Global Energy Consumer and GHG Emitter

The humid subtropical climate is one of the major climate types of Köppen–Geiger classification and can be characterised by long, hot-humid summers and mild winters [4]. This climate type is found on the eastern sides of all continents and is located poleward from adjacent tropical climates. The challenging summer conditions engender significant energy consumption and related GHG emissions connected with cooling and dehumidifying needs, in addition to the heating loads in winter [5]. The main contributing regions can be found in: hot summer and cold winter (HSCW) China climate zone, North and Northeast India, American gulf and east coast states of USA and east coastal strip of Australia.

1.3 Concept of Zero Emission Buildings (ZEBs)—An Opportunity for Deep and More Effective Reduction of GHG Emission in the Construction Sector

In contrast to energy standards requirements or widely distinct methodologies like Passivhaus or zero/nearly zero energy buildings, a zero emission building (ZEB) design approach focuses [6] more on the environmental impact caused by buildings during their entire lifespan. The different ambition levels of ZEB are based on and founded on life cycle assessment boundaries as in EN15978 and defined in progressive ZEB ambition levels as below:

The lowest ambition level—**ZEB-O-EQ**—describes the building where on-site renewable energy production compensates greenhouse gas emission related to the operation of the building—O (ventilation, heating, hot water, lighting), excluding energy required for user equipment and plug loads (EQ);

The next ambition level—**ZEB-O**—describes a building where on-site renewable energy production compensates greenhouse gas emission related to the operation of the building—O—including energy for user equipment and plug loads;

The ambition level—**ZEB-OM**—describes the building where on-site renewable energy production compensates greenhouse gas emission related to the operation of building, as well as emission from production (A1-A3) and replacement (B4) of building materials.

2 Methodology

2.1 Calculation of Annual Energy Consumption and Related GHG Emission

The annual energy consumption for each location was evaluated using dynamic and multi-zone building performance simulations. The energy model for the case building in each location was developed by using IDA Indoor Climate and Energy Software (IDA ICE 4.8) [7]. In each location, information including building geometry, thermal performance of the building fabric, HVAC system efficiency and internal gains was integrated into the case building multi-zone thermal model. The building performance was studied in typical weather years (IWEC 2.0 data files). The results of the annual energy consumption, together with electricity emission impact factors, are served as the basis for estimating GHG emissions related to the energy use stage.

2.2 Residential Building Model

2.2.1 Architecture and Functionality

For research purposes, the building is characterised as a detached, single-family house typology with a timber-framed load bearing structure and a timber floor construction. The building consists of two adjoining rectangular cells (12.5 $\times$ 4.1 m), with elongated facades facing north and south. The roof is built of two parts: one part tilted with an angle of 30 °C and the other flat. A building-integrated PV system is installed on the tilted part. The living space includes two bedrooms, an office, a living room/kitchen, a bathroom, as well as an entrance hallway and technical room. The case building is designed for three persons. The ground floor has a heated area of 105 m^2 and a volume of 315 m^3. The total window and door surface are 47 m^2, which gives a window/door-to-floor area ratio of 46%.

2.2.2 Thermal Specification of the Building Fabric

The thermal specification of building envelope used in each of the referential locations depends on the minimum requirements included in the mandatory residential energy codes of: Sydney—BASIX [8], Atlanta—IRC2015 [9] and Shanghai—JGJ134-2010 [10]. In the case of New Delhi, where there is no residential code in place, the specification was assumed according to business as usual values [11] with no use of thermal insulation. The thermal properties of each part of the envelope were set as minimal requirements.

2.2.3 Building Services

Ventilation system
The choice of building ventilation system relies on requirements included in country's building energy codes. In the Atlanta location, a mechanical ventilation system with energy recovery use is mandatory in all new built residential buildings. In locations of Sydney, Shanghai and New Delhi, building ventilation is characterised as natural.

Thermal services
An air–water heat pump is the primary source of meeting building energy needs connected with space heating, domestic hot water production and space cooling. The system does not provide heat recovery, during the cooling period, so required energy for producing hot water is covered by the backup electric coil. Heat pump size parameters depend on case building energy needs. Seasonal efficiency is set up as a minimum value according to the efficiency standards [8–11] applied in the specific location (Table 4). Domestic hot water production energy needs were calculated by using daily average hot water consumption [l/day] for three-person occupancy in the specific location.

Operating temperatures/relative humidity
The operative indoor temperature was defined as 20 °C during heating period and 26 °C during cooling period in accordance with indoor environment requirements included in referential, residential energy codes. The indoor relative humidity was not controlled.

Lighting and equipment energy consumption
The energy consumption related to the lighting system use was based upon the current efficiency requirements—included in the energy code in the example of Sydney, Atlanta and Shanghai. The average time of lighting system use was estimated as

6 h/day. The energy consumption related to equipment use was estimated using energy consumption surveys in each location.

2.2.4 Assessment of Renewable Energy Generation Potential

A total of 24 modules are included in the PV plant. The modules are grouped in two strings, leading to a total DC installed power of 6 kW. The predicted energy production from the solar cells in selected locations was calculated using the PVsyst software [12]. Annual energy generation was simulated as 9295 kWh in New Delhi, 8694 kWh in Sydney, 8580 kWh in Atalanta and 6318 kWh in Shanghai.

2.2.5 Calculation of Embodied Emissions from Materials

The life cycle inventory data [13] has been accessed from SimaPro Analyst version 8.5 with the use of EcoInvent 3.0 Rest-of-the-World (RoW) data set [14]. The RoW data sets represent activities with uncertainty adjusted which are considered to be an average and are valid for all countries in the world. To attain more accurate and allocated data, conversion by using local electricity grid emission factors in accordance with the selected location where building model has been evaluated. The IPCC GWP 100-year scenario method has been applied for the environmental impact assessment of the material inventory. Building lifespan was assumed as 60 years.

3 Results and Discussion

3.1 Embodied Emissions from Materials Production (A1-A3) and Replacement (B4) Stage

The calculated results of GHG emissions related to the production phase (A1-A3) and replacement stage (B4) for the construction materials used in each building case study are found in Fig. 1. The total embodied emissions from materials vary from 18.90 $kgCO_{2EQ}/m^2$ year in Sydney to 14.40 $kgCO_{2EQ}/m^2$ year in Shanghai. The higher results seen for Sydney and Atlanta, compared to Shanghai and New Delhi, are mainly caused by the requirements for substantial insulation and sealing materials necessary to meet mandatory and more stringent building code requirements. The results differ by 6% (i.e. 0.75 kg/CO_{2EQ}) between buildings in Shanghai and New Delhi, which present particularly the same material quantity. This is due to the higher carbon intensity of the medium voltage electricity network in New Delhi (1.50), as compared to Shanghai (1.13) which directly affects the emission factors of the respective materials.

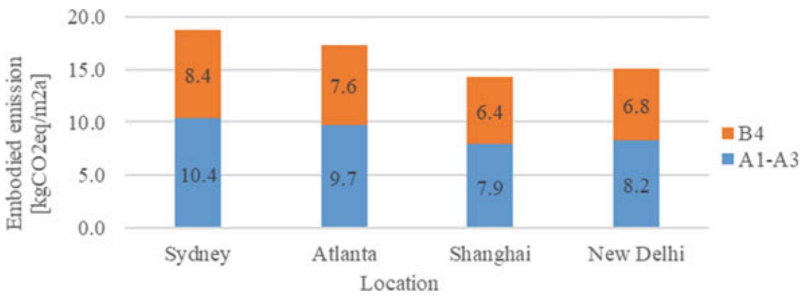


Fig. 1 Calculation results of embodied GHG emissions related to materials production phase (A1-A3) and replacement stage (B4)

3.2 *Final Energy Consumption—Electricity Demand*

Annual electricity delivered categorised by building services demand in each location is shown in Figs. 2, 3, 4 and 5. The annual energy consumption varies from 52 kWh/m^{2}a (i.e. 5460 kWh/m^2 year) in Sydney up to 187 kWh/m^2/a (i.e. 19,635 kWh/a) in New Delhi. Low energy demand for the Sydney location (Fig. 2) is due to the

Fig. 2 Annual electricity consumption of the case residential building in Sydney

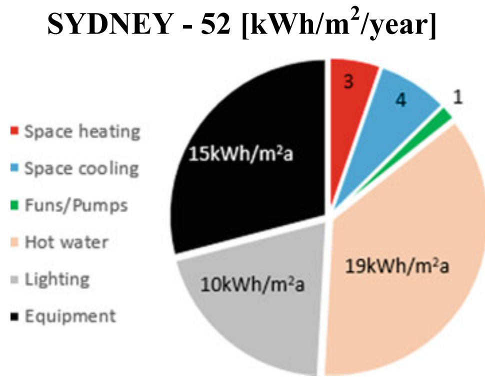
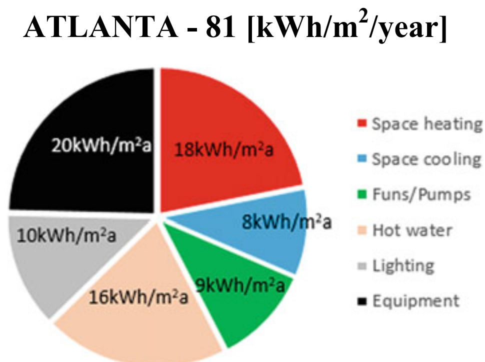


Fig. 3 Annual electricity consumption of the case residential building in Atlanta



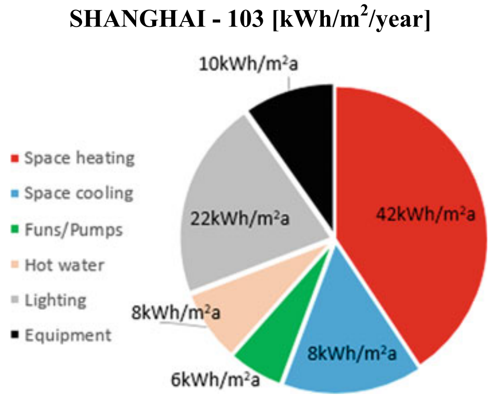


Fig. 4 Annual electricity consumption of the case residential building in Shanghai

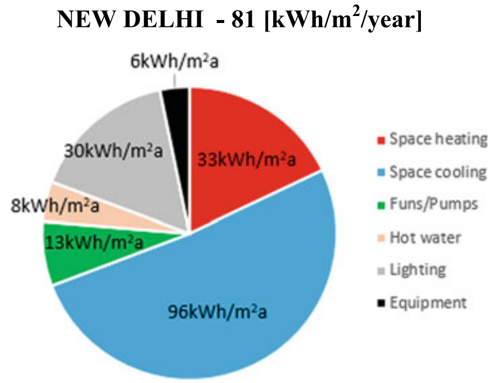


Fig. 5 Annual electricity consumption of the case residential building in New Delhi

residential building having high thermal performance building envelope and the thermal energy demand covered by a heat pump. The largest share in annual electricity consumption is that of the production of domestic hot water—37% (i.e. 19 kWh/m^2 year). The needs connected with lighting and equipment contribute to 49% of the total building energy demand. Due to highly energy efficient building partitions and windows, space cooling and heating demands are only 12% (i.e. 7 kWh/m^2/year) of the annual electricity consumption. Annual energy consumption in Atlanta (Fig. 3) amounts to 81 kWh/m^2a (i.e. 8505 kWh/m^2a) and is approximately 55% higher than in that of Sydney. This is because of more challenging climate conditions as well as the lower building fabric thermal requirements in Atlanta. The largest energy demands are connected with equipment use—25% (i.e. 20 kWh/m^2 year), space heating—22% (i.e. 18 kWh/m^2 year) and production of domestic hot water—20% (i.e.16 kWh/m^2 year). In the Shanghai (Fig. 4), annual energy consumption has been evaluated to 103 kWh/m^2a (i.e. 10,815 kWh/m^2 year). Thermal demands are responsible for 64% (i.e. 66 kWh/m^2a) of total energy demands, with the highest demand related to space heating—41% (i.e. 42 kWh/m^2a). Production of domestic hot water contributes to only 8% (i.e. 8 kWh/m^2a). This is the result of a smaller DHW daily use in comparison with Sydney or Atlanta, as well as higher share of heat pump activity than electric coil operation in DHW production. The New Delhi (Fig. 5) case holds the highest values of annual energy consumption—187 kWh/m^{2}a (i.e. 19,635 kWh/year) from among all referential locations. This is mainly because of the lack of a residential energy code. This enables construction and operation of dwellings with a poorer thermal performance than in the other locations. Despite being affiliated to a humid subtropical climate, New Delhi is situated within a semi-arid climate and is annually highly influenced by monsoon weather. Hence, the climate sees a long cooling period and also very high outdoor temperatures. Thus, electricity consumption related to space cooling holds the highest share—51% (i.e. 96 kWh/m^2/year) in the total energy demand balance.

3.3 Residential Building Balance of Global Greenhouse Gases Emission in Selected Locations

The individual GHG emissions [kgCO_{2EQ}/m^{2}a] related to operational energy use by building services (O-EQ), equipment (EQ), materials embodied emissions (M), as well as emissions reduction connected with renewable energy generation from the roof PV plant (PV), are seen in Figs. 6, 7, 8 and 9 (left side). On the right side of each figure, the results from the final GHG emission balance are presented.

The total GHG emissions related to operation and embodied emission from materials vary from 69.3 kgCO_{2EQ}/m^{2}a in Atlanta to 338 kgCO_{2EQ}/m^{2}a in New Delhi. In contrast, emission reduction from PV plant energy generation is the highest in New Delhi—153.1 kgCO_{2EQ}/m^{2}a and the lowest in Atlanta—52.3 kgCO_{2EQ}/m^{2}a. In Sydney, a ZEB-OM balance of building was achieved, where emission related to operational energy use and embodied emissions from materials are balanced by renewable production. Additionally, owing to the fact that the PV system can compensate for more emissions than is used for construction, operation and materials, a more ambitious level of building operation such as ZEB-COM can be considered. In Atlanta, the ambition for a ZEB-O building was accomplished; however, it was not possible to balance emissions from materials in addition. In Shanghai and New

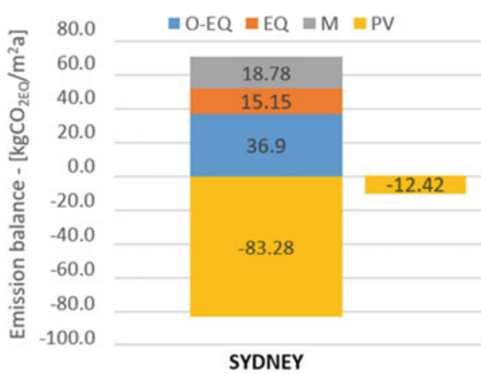


Fig. 6 Emission balance of the case in Sydney

Fig. 7 Emission balance of the case residential building residential building in Atlanta

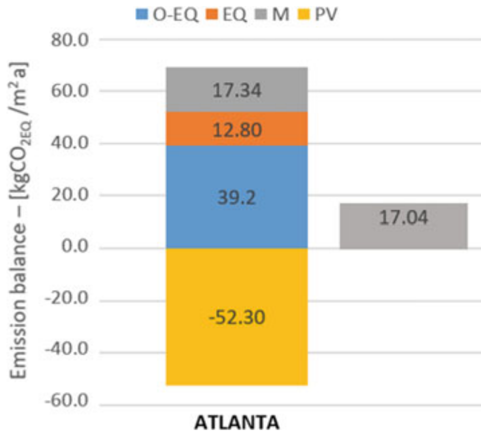


Fig. 8 Emission balance of the case residential building in Shanghai

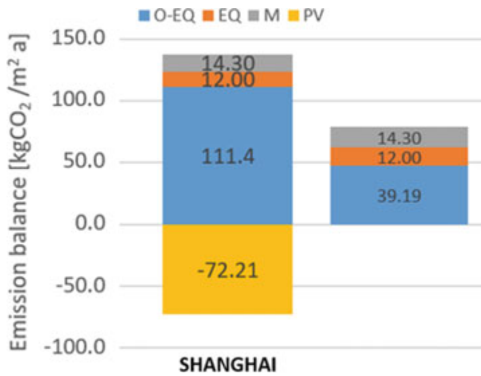
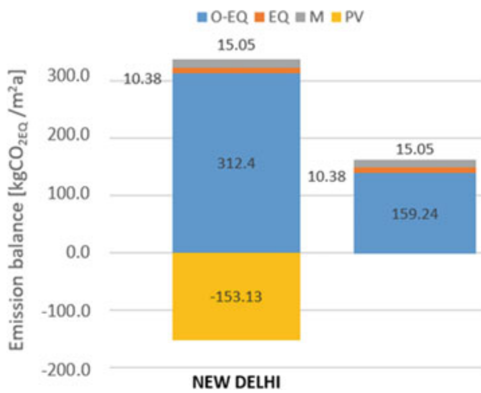


Fig. 9 Emission balance of the case residential building in New Delhi



Delhi, even the lowest zero emission ambition [ZEB (O-EQ)] was not achieved. Nevertheless, the renewable PV energy generation was able to compensate for emissions from operational energy use (O) by 59% in Shanghai and 47% in New Delhi.

4 Conclusions

Mandatory energy residential codes with high requirements of thermal properties of building fabric and energy efficiency of technical systems are crucial to achieve a zero emission ambition in residential buildings. The BASIX standard that regulates energy efficiency of residential buildings in Sydney and imposes the use of complex annual building performance simulation in the early stage of design process is the state-of-the-art of residential energy policymaker.

Mandatory codes of Sydney (BASIX) and Atlanta (IRC) should require the use of renewable solar energy in order to reduce domestic hot water energy demand and should also support the application of energy efficient equipment. Highly intensification of requirements contained in the JGJ134-2010 operating in Shanghai's hot summer and cold winter climate zone is needed. Implementing and enforcing residential mandatory energy codes construction are crucially needed for rapidly developing construction sector in India.

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Appendix Paper II

Building materials inventory related to building design in selected locations

Groundwork and foundations			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Concrete	Ready-mix concrete production (ROW) | Cut-off, U	m^3	9.33			
PVC	polyvinylchloride production (ROW) | Cut-off, U	kg	14.51			
Aluminium	Aluminium alloy (ROW) production | Cut-off, U	kg	9.33			
XPS Insulation	Polystyrene production, extruded (ROW) | Cut-off, U	m^3	4.74			0.0
Steel Rebar	Reinforcing steel (ROW) production | Cut-off, U	kg	571.15			
Gluelam Timber	Glued laminated timber (ROW) production | Cut-off, U	m^3	0.31			

Superstructure			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Gluelam Timber	Glued laminated timber (ROW) production | Cut-off, U	m^3	10.78			
Timber		m^3	1.96			
I-Beam (400mm)	Sawnwood, beam, raw, dried (ROW) production | Cut-off, U	m^3	0.50			

External walls			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Plywood	Plywood, production (RoW) | Cut-off, U	m^3	1.26			
Mineral wool	Glass wool mat production (RoW) | Cut-off, U	m^3	13.21	7.26	0.66	0.00
Vapour Barrier	Vapour memberane OEKOBAU generic data	m^2	7.42	7.42	5.56	0.00
Wind Barrier	Wind memberane OEKOBAU generic data	m^2	16.36	16.36	12.27	0.00
Timber Cladding	Wood cladding, softwood production (RoW) | Cut-off, U	m^3	4.89			
Ceramic tiles (bathroom)	Ceramic tile (RoW) production | Cut-off, U	kg	203.73			
Windows		Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Windows frame timber-metal	Window frame, wood-metal, U=1.6 W/m2K, production (RoW)| Cut-off, U	m^2	5.98			
Glass (2 pane)	Glazing double, U<1.1Wm2K, production (RoW)| Cut-off, U	m^2	23.93		0	**0**
Glass (1 pane)	Glazing single, production (RoW) | Cut-off, U	m^2	0	0	23.9	

Internal walls			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Plywood and Doors	Plywood, production (RoW)|Cut-off, U	m^3	3.97			
Skirting Board and Doors	Sawnwood, hardwood, dried (RoW) production|Cut-off, U	m^3	0.10			

Slab structure			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Chipboard	Plywood, production (RoW) | Cut-off, U	m^3	5.53			
Mineral wool	Sawnwood, hardwood, dried (RoW) production | Cut-off, U	m^3	13.8	15.0	0.0	0.0
Anhydrite Screed	Anhydrite floor, production (RoW) | Cut-off, U	kg	173			
Vapour barrier	Vapour memberane OEKOBAU generic data	m^2	105			
Timber Parquet Flooring	Sawnwood, hardwood, dried (RoW) production | Cut-off, U	m^3	1.8			
Ceramic Tiles	Ceramic tile (RoW) production |Cut-off, U	kg	52.99			

Roof			**Location**			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Plywood	Plywood, production (RoW) |Cut-off, U	m^3	4.22			
Mineral wool	Sawnwood, hardwood, dried (RoW) production |Cut-off, U	m^3	19.0	23.8	3.7	0.0
Vapour Barrier	Vapour memberane OEKOBAU generic data	m^2	13.7	13.7	10.3	0.0
Wind Barrier	Wind memberane OEKOBAU generic data	m^2	17.0	17.0	12.8	0.0
Timber Cladding	Wood cladding, softwood production (RoW) |Cut-off, U	m^3	2.5			
EPS Insulation	Polystyrene foam slab for perimeter insulation production (RoW) | Cut-off, U	m^3	26.7	32.0	0.8	0.0
Chipboard	Particle board, production (RoW)| Cut-off, U	m^3	0.7			
Aluminium Flashing	Aluminium alloy (ROW) production|Cut-off, U	kg	255.0			

Fixed inventory			Location			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Plywood	Plywood, production (RoW) |Cut-off, U	m^3	2.34			
Hardwood	Sawnwood, hardwood, dried (RoW) production|Cut-off, U	m^3	0.5			
Pine Steps and Decking	Pine wood production (RoW) |Cut-off, U	m^3	21.64			
Steel Frame for Stairs	Steel low-aloyed, production (RoW)| Cut-off, U	kg	1880			

PV system			Location			
Material	Background data	Unit	**Sydney**	**Atlanta**	**Shanghai**	**New Delhi**
Photovoltaic Panels	Photovoltaic panel, multi-si wafer production (RoW)|Cut-off, U	m^2	34.00			
Inverter and controling board	Inverter 2.5kW, production (RoW)|Cut-off, U	kg	26.0			

PAPER III

Life cycle GHG emissions of residential buildings in humid subtropical and tropical climates: Systematic review and analysis*, published in Buildings (2020)*

Authors: **Daniel Satola,** Martin Röck, Aoife Houlihan-Wiberg and Arild Gustavsen

buildings

MDPI

Review

Life Cycle GHG Emissions of Residential Buildings in Humid Subtropical and Tropical Climates: Systematic Review and Analysis

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Abstract: Improving the environmental life cycle performance of buildings by focusing on the reduction of greenhouse gas (GHG) emissions along the building life cycle is considered a crucial step in achieving global climate targets. This paper provides a systematic review and analysis of 75 residential case studies in humid subtropical and tropical climates. The study investigates GHG emissions across the building life cycle, i.e., it analyses both embodied and operational GHG emissions. Furthermore, the influence of various parameters, such as building location, typology, construction materials and energy performance, as well as methodological aspects are investigated. Through comparative analysis, the study identifies promising design strategies for reducing life cycle-related GHG emissions of buildings operating in subtropical and tropical climate zones. The results show that life cycle GHG emissions in the analysed studies are mostly dominated by operational emissions and are the highest for energy-intensive multi-family buildings. Buildings following low or net-zero energy performance targets show potential reductions of 50–80% for total life cycle GHG emissions, compared to buildings with conventional energy performance. Implementation of on-site photovoltaic (PV) systems provides the highest reduction potential for both operational and total life cycle GHG emissions, with potential reductions of 92% to 100% and 48% to 66%, respectively. Strategies related to increased use of timber and other bio-based materials present the highest potential for reduction of embodied GHG emissions, with reductions of 9% to 73%.

Keywords: GHG emissions; life cycle assessment; residential buildings; design strategies; humid subtropical climate; tropical climate

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1. Introduction

1.1. GHG Emissions along the Life Cycle of Buildings

Climate change is one of the most challenging science and policy issues of the current time, the negative effects of which are driven by constantly increasing emissions of anthropogenic greenhouse gases (GHGs). The importance of reducing GHG emissions is a subject of numerous global commitments [1] and is globally recognised in the Sustainable Development Goals [2]. The building and construction sector plays a key role in global climate change, contributing about 39% of GHG emissions [3,4]. These emissions could potentially increase threefold by 2060 due to the increased need for adequate housing, electricity and improved facilities for billions of people in developing economies of the Global South [5]. In the past, the assessment of building energy use and related GHG emissions was mainly focused on the energy used for operation [6–8]. So-called embodied GHG emissions, which are associated with construction material production, construction and transport processes, maintenance and replacement and end-of-life treatment, were hardly considered. However, as recent studies have shown, the success in reducing operational energy demand and related GHG emissions through increased energy efficiency of building envelopes and building systems has been accompanied by an increase in embodied GHG emissions in both relative and absolute terms [9]. Hence, to effectively reduce global energy use and GHG emissions by buildings and construction, a life cycle perspective is required when analysing and optimising buildings [10]. Hence, environmental targets such as "carbon budgets" are increasingly being formulated for building construction and operation [11].

Existing studies analysing energy and GHG emissions across the life cycle of buildings provide insights for residential and office buildings but are limited in their geographic scope, i.e., the climate regions studied (Table 1). One study [12] showed that the primary life cycle energy of buildings could mostly be attributed to operational use (80–90% share), compared to a much smaller share (10–20%) related to embodied energy. The results of a review [13] indicated that life cycle GHG emissions are lower in passive and low-energy types of buildings, in comparison to buildings with conventional energy. Another review [14] indicated that the existing literature dealing with life cycle assessment and energy analysis was difficult to compare due to the specific type, climate and local regulations of building-based case studies. These studies were not equally distributed in the world; only a few studies were located in tropical or humid subtropical climate areas. Similar findings can be found in [15], suggesting that most of the investigated case studies did not consider the site specificity or geographic and climatic site conditions, which produced vast differences in the results.

Additionally, several studies indicate that life cycle assessment (LCA) calculation assumptions and calculation methods differ significantly depending on the specific research approach, leading to differences in the results and increased uncertainty in the analyses [8,13,16–18]. The use of different functional units, system boundaries or methodological frameworks may result in uncertainty in life cycle assessment as a decision-making support tool for building design or policymaking processes [14,19]. A meta-study [9] reviewed more than 650 building LCA case studies to analyse life cycle-related GHG emissions. In that study, the authors showed, based on the final data sample consisting of 238 case studies, that building life cycle GHG emissions are decreasing due to energy efficiency improvements. However, it was found that embodied GHG emissions have increased in both relative and absolute terms and are dominating the time frame relevant to reaching climate targets. While this study provides crucial insights into building life cycle-related GHG emissions, it is also limited in its geographic scope to cases from temperate and continental climate regions.

Table 1. Overview of literature review articles analysing life cycle greenhouse gas (GHG) emissions of buildings.

Reference	Number of Cases Analysed	Typology (Residential, Office, etc.)	Climate Region Focus	Life Cycle Stages (Embodied, Operational, Full Life Cycle)	Indicators
Ramesh et al., 2010 [12]	73	Residential and office buildings	Temperate (C), continental (D)	Embodied and operational	Primary energy
Cabeza et al., 2014 [14]	38	Residential, office and industrial buildings	Temperate (C), continental (D)	Embodied and operational	Primary energy, GHG emissions
Säynäjoki et al., 2017 [19]	116	Residential, office and communal buildings	Temperate (C), continental (D)	Embodied	GHG emissions
Chastas et al., 2018 [13]	95	Residential	Temperate (C),	Embodied and operational	GHG emissions
Röck et al., 2020 [9]	238	Residential and office buildings	Temperate (C), continental (D)	Embodied and operational	GHG emissions

1.2. Research Gap for Warm and Humid Climate Zones

As presented in the previous sections, and summarised in Table 1, the existing body of literature mostly analysed buildings located in cold and temperate climates. Hence, there is a research gap regarding GHG emissions across the life cycle of buildings located in warm and humid, subtropical and tropical climate regions. This gap in the literature is appalling, considering the geographic extent of these climate regions and the number of people inhabiting them. By 2060, more than half of new residential buildings are expected to be constructed, with remarkably rapid growth, in Africa, Asia and Latin America, regions that have humid subtropical and tropical climates [20].

The importance of studying buildings in these regions is further emphasised, as warm climates are nearly twice as sensitive to local temperature changes due to global heating and, hence, more affected by related harmful effects than cold or temperate climate regions [21]. Consequently, there is an urgent need to address environmental impacts related to the rapid growth of buildings in these regions, especially in the residential construction sector, by implementing building design strategies that enable significant reduction of GHG emissions.

1.3. Research Questions

This paper studies GHG emissions profiles and design strategies for reducing GHG emissions of residential buildings in humid subtropical and tropical climates based on a systematic review and analysis of published building LCA studies. The selected studies assess both embodied and operational GHG emissions, i.e., GHG emissions across the full building life cycle. The two main research questions guiding this study are the following:

1. What is the current state of life cycle GHG emissions of residential buildings in tropical and subtropical climate regions?
2. Which building design strategies are effective for reducing both operational and embodied GHG emissions for residential buildings in the selected regions?

The primary target audience of this paper is building design professionals interested in investigating the relevant drivers of and effective strategies for reducing life cycle-related GHG emissions of residential buildings in humid subtropical and tropical climates.

2. Materials and Methods

2.1. Data Collection

The analysis presented in this paper is based on a systematic review of the scientific literature [22]. In order to be transparent and reproducible, the systematic literature review (SLR) follows a step-by-step approach.

First, based on the formulated research question(s), a set of keywords is defined for searching the scientific databases. Second, all of the studies identified through the database search are screened for their relevance to the research question(s) and excluded if they are out of scope. In the first exclusion phase, studies are screened based on their title and, in the second phase, based on the abstract. In the third phase, the remaining studies are analysed in full. In this phase, the information relevant to the research question(s) is systematically extracted and documented for further analysis.

The details of the procedure applied in this study are described in the following and graphically presented in Figure 1. Based on the research questions (previous section), the keyword string was defined as: (LCA OR life cycle assessment AND residential* AND warm climate). The database search was conducted using Scopus, searching abstract, title and keywords, limited to articles in the English language and excluding grey literature (books, theses, etc.). The search was conducted on 5 October 2020.

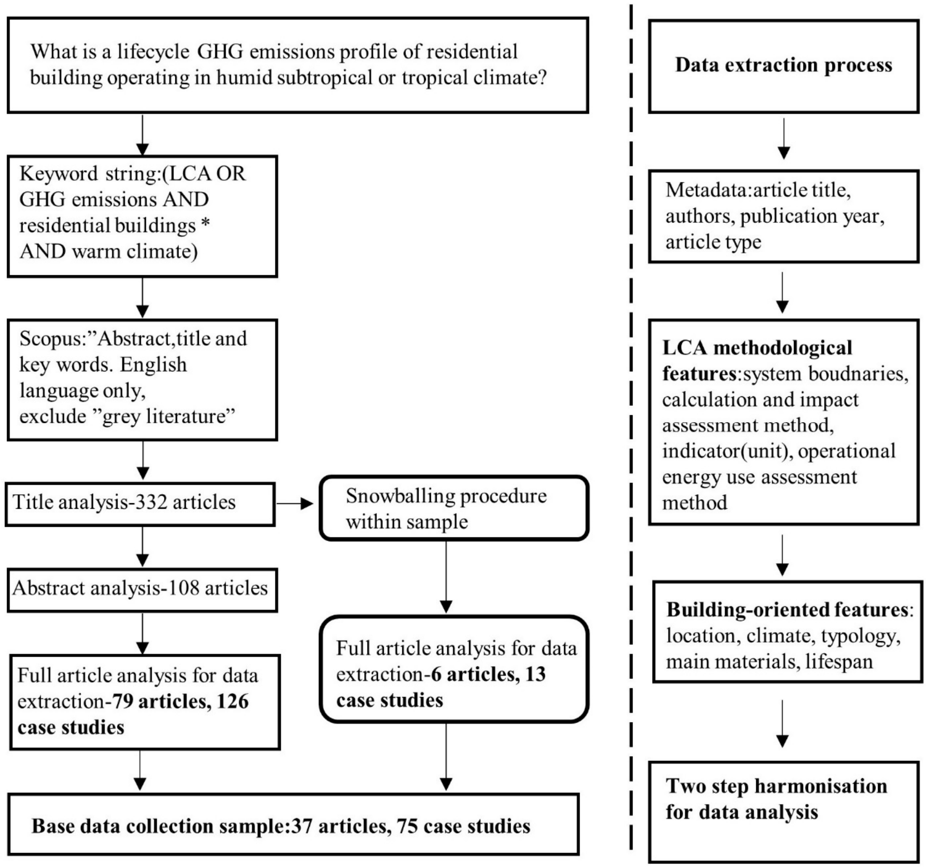


Figure 1. Systematic review of the literature flowchart. GHG: greenhouse gas and LCA: life cycle assessment.

The initial sample of 332 articles was screened and excluded by title, reducing it to 108 articles. Screening and exclusion by abstract led to a selection of 79 articles presenting 126 case studies for full-paper analysis. The full-paper analysis and data extraction included documentation of metadata and methodological and building-oriented features (Section 2.2).

The collection of 31 articles identified as relevant after the full-paper analysis was used as a base to perform a complementary snowballing procedure [23]. In addition, another six articles describing 13 case studies were identified as relevant to the research based on the screened literature. The final data sample consists of 37 articles representing life cycle GHG emission assessments of 75 case studies of residential buildings operating in humid subtropical or tropical climates.

The articles were published between 2004 and 2018. This collection serves as the base sample, the basis of the data extraction process and analysis presented in the following chapters. The data collection procedure is similar to the approach proposed by Röck et al. [9]. However, a specific focus on prevailing climate conditions in this research resulted in the collection of 24 articles covering 47 case studies that were not taken into consideration in the previous analysis.

2.2. Data Extraction Features

Articles in the base sample were analysed based on the full paper to extract data on building-related features, as well as methodological aspects that could significantly influence the value and comparability of life cycle GHG emissions results. An overview of selected criteria documented for the collected studies is presented in Table 2.

Table 2. Overview of methodological and building-related criteria influencing the life cycle.

Feature	Description
Methodological Features	
Life cycle calculation method	Description of life cycle calculation methodology: process-based, input-output or hybrid
System boundaries	Processes included in life cycle assessment (LCA) study
Impact assessment method	Life cycle impact assessment method and category/indicator employed in study
Operational energy assessment methodology	Method, software and data source used for assessing operational energy use
Building Related Features	
Location/climate	Location (country, city) of case building and climate type according to Koppen-Geiger classification
Building type/function	Residential building type: single-family (SF) or multi-family (MF)
Gross floor area	Total area of building measured between exterior walls
Main structural materials	Primary type of materials used for building construction
Lifespan	Life expectancy of building
Electricity mixes	Factor applied for evaluating greenhouse gas (GHG) emissions from local electricity grid ($kgCO_2eq/m^2/kWh$)

The overview of the methodological and building-related features among 75 case studies (base sample) is presented in Appendix A, Tables A1 and A2, respectively. All case study buildings have been assigned with a unique ID, noted in the following text (see Table A1 for details).

3. Meta-Analysis and Data Harmonisation

3.1. Meta-Analysis of the Data Sample

Information was extracted from the studies in the data sample based on the defined features and analysed to prepare for the harmonisation in the next step. Similarities and differences in building-related and methodological characteristics were investigated within a comprehensive meta-analysis, which is available in Appendix A.

Selected findings are presented below.

3.1.1. Geographic Location of Case Studies

Studies in the final sample span of 75 case studies within 13 countries (Table 3). Most of the case studies (49) are in Asia, followed by Oceania (18), South America (4) and North America (4).

3.1.2. System Boundaries

A detailed analysis of life cycle processes and stages among the case study sample can be found in Appendix A (Table A3). That analysis indicates that, among the 75 case studies, 60 are characterised by cradle-to-grave system boundaries. Moreover, an in-depth analysis of the energy use stage module (B6) scope shows that the complete coverage of building energy use from space heating, ventilation, space cooling, domestic hot water production, lighting and appliances is present in 55 case studies. The simplification and minimisation of system boundaries while omitting some building life cycle processes can lead to differences in estimated life cycle GHG emissions [13,17].

The discussion about this issue based on the analysed collection of case studies is presented in Appendix B.1.1.

3.1.3. Main Structural Materials

The primary structural material of case study buildings varies between timber, steel, concrete, reinforced concrete, masonry (brick), stone, mud and different combinations of these (Figure 2). Reinforced concrete is the most common material, followed by timber and concrete.

Table 3. Geographic location of 75 residential construction case studies from the literature data sample.

Geographic Region	Location	Quantity
Oceania	Australia (AU)	18
South America	Brazil (BR)	3
	Colombia (CO)	1
Asia	China (CN)	14
	Hong Kong (HK)	5
	India (IN)	3
	Indonesia (ID)	6
	Japan (JP)	5
	South Korea (KR)	8
	Malaysia (MY)	1
	Taiwan (TW)	2
	Thailand (TH)	5
North America	USA (US)	4

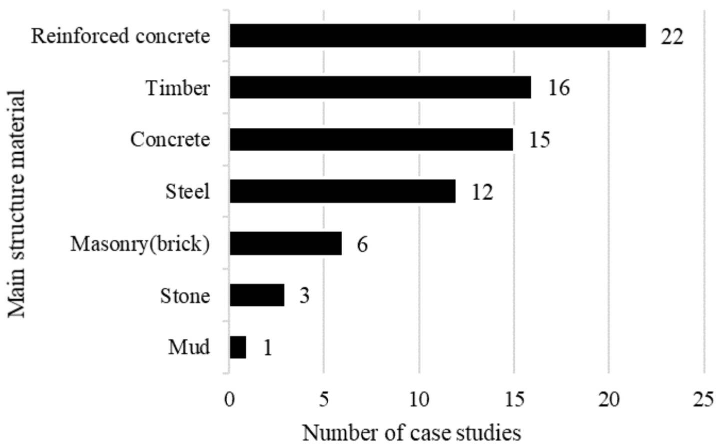


Figure 2. Main structural materials of 75 residential buildings.

3.1.4. GHG Emissions from Electricity Mix

Regarding the analysed case buildings, the value of the GHG emission factor of electricity is clearly stated in 37 case studies (Figure 3) and varies from 0.23 kgCO_2eq/kWh in Colombia (CS22CO) to 1.20 kgCO_2eq/kWh in China (CS27CN). In other studies, the GHG emission factor of the local electricity mix is not documented, leading to difficulties in interpreting the results. Additionally, only eight case studies, CS1-2AU, CS22CO, CS27CN and CS33-36CN, clearly define the system boundaries of the presented GHG emission electricity factor that consider both direct and indirect emissions from electricity generation and transportation.

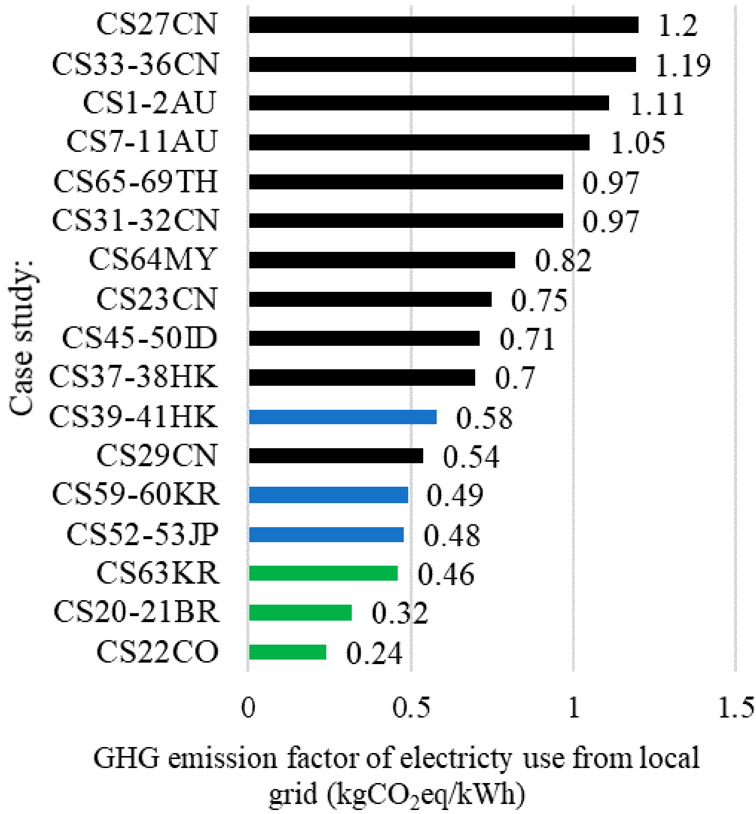


Figure 3. GHG emission factor of electricity from local grids identified in 37 case studies (colour of bars indicates dominant source in energy mix: black, fossil fuel; blue, nuclear and green, renewable).

The GHG emissions factor of the electricity grid is the highest in Australia, China, Hong Kong, Malaysia and Thailand, where the energy mix is mostly based on fossil fuels, with a dominant share of coal or lignite. GHG emissions from the electricity grid are decreasing in countries like Japan and South Korea, where the energy mix is based on a dominant share of nuclear energy sources, and is the lowest in Brazil and Columbia, characterised by an energy mix based on renewable energy sources (Figure 3).

The use of scientifically unconfirmed electricity GHG emission factors can lead to unreliability of the whole life cycle GHG assessment. The analysis of CS29CN indicates that the electricity GHG emission factor of 0.54 $kgCO_2eq/kWh$ is not reliable for the energy mix in Nanjing, China, which is dominated by hard coal and presents significantly higher values of GHG emissions [24,25].

3.2. Harmonisation of GHG Emission Values

The preliminary examination of assessment methods showed the need for harmonisation of life cycle GHG emissions results from the different case studies to allow comparisons. Hence, as shown in Figure 4, a two-step harmonisation procedure was applied to normalise the reference study period (RSP) and to ensure consistency of system boundaries, amongst other aspects.

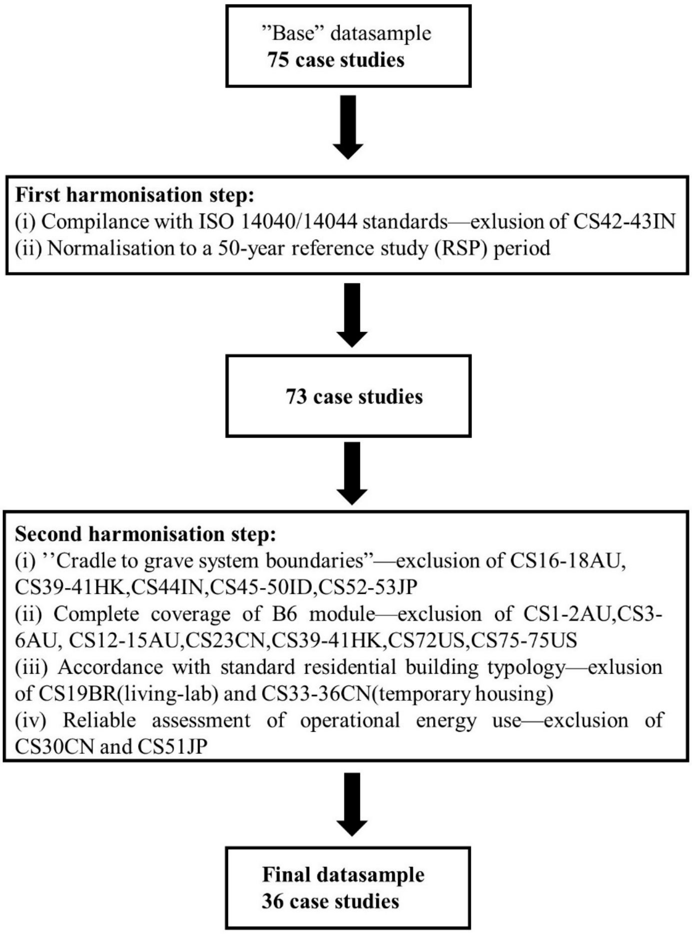


Figure 4. Flowchart showing harmonisation procedure.

In the first harmonisation step, the cases were: (i) checked for compliance with the necessary inclusion of the main LCA phases based on the ISO14040/14044 standards and (ii) harmonised to a 50-year RSP and the reference unit of $kgCO_2eq/m^2$ gross floor area (GFA) by using Equation (1):

$$GHG_{harm} = GHG \times \left(\frac{RSP}{50}\right) \tag{1}$$

where GHG_{harm} is the harmonised life cycle GHG emissions value after the 50-year normalisation ($kgCO_2eq/m^2{}_{RSP=50years}$), GHG is life cycle GHG emissions before harmonisation extracted from full-paper analyses ($kgCO_2eq/m^2$) and RSP is the reference study period considered in the analysed case study. The choice of the RSP relates to the predominant choice of building lifetime among the collected data sample, in which nearly 60% of case studies employ a 50-year time frame (Figure A4 in Appendix B.2.2).

The second harmonisation step (i) excluded all case studies in which the system boundaries did not follow the cradle-to-grave definition; (ii) limited studies to those for which the operational energy stage (B6) incorporated all building energy connected with space heating, cooling, ventilation, domestic hot water and lighting/appliances; (iii) limited studies to only standard residential building typology (excluding temporary housing type) and (iv) excluded case studies in which the methodology regarding the operational energy use assessment was not transparent.

Consequently, the sample used for the final analysis consisted of 20 articles describing 36 case studies, the locations of which are presented in Figure 5.

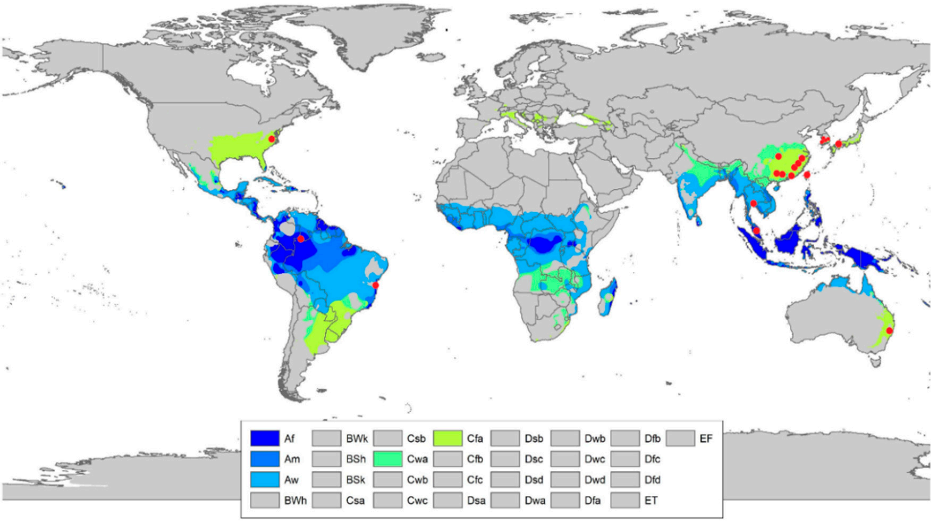


Figure 5. Locations of 36 case studies in the final sample.

4. Analysis of Life Cycle GHG Emissions and Relevant Features

4.1. Embodied and Life Cycle GHG Emissions Results

The performed harmonisation allowed a substantial reduction in the variation in life cycle GHG emissions results (see Appendix C) and enabled a comparison of the harmonised results in the final data sample (36 case studies), which is presented in this section.

As shown in Figure 6, the lowest value of life cycle GHG emissions is 491 $kgCO_2eq/m^2$ in CS69TH, and the highest is 4811 $kgCO_2eq/m^2$ in CS27CN. The variation of embodied GHG emissions ranges from 122 $kgCO_2eq/m^2$ in the timber-based structure CS54JP to 2103 $kgCO_2eq/m^2$ in CS31CN, which is based on the aluminium frame structure. The GHG emissions related to the operational energy used varied from 0 $kgCO_2eq/m^2$ in the zero energy buildings CS19BR, CS67 and 69TH to 3956 $kgCO_2eq/m^2$ in highly energy-intensive building CS37-38HK. The main causes of such a large range are related to the buildings' energy performances and the GHG emission intensity of electricity from the local grid.

The range of harmonised GHG emissions from 36 residential buildings analysed in the current review is similar to that of another study [13], whose data sample consisted of 31 residential case studies mainly located in temperate climates. In that study, the range of total GHG emissions varied between 518 and 4475 $kgCO_2eq/m^2$. However, an in-depth comparison between review articles indicated a significant difference in the maximum value of the harmonised embodied GHG emissions range. In the comparative study, these emissions varied between 180 and 1050 $kgCO_2eq/m^2$. That difference is caused by the inclusion of CS31CN in the current review, whose high value of embodied GHG emission (2103 $kgCO_2eq/m^2$) is related to the combination of extensive use of photovoltaic (PV) systems characterised by high embodied GHG emission load and low floor area (30 m^2). The analysis of the results shows that the range of embodied GHG emissions (122–782 $kgCO_2eq/m^2$) defined by cradle-to-grave system boundaries related to single-family constructions operating in the developed economies of Australia, Japan and the US are comparable to the embodied GHG emissions (378–672 $kgCO_2eq/m^2$) presented in the International Energy Agency (IEA) Annex 57 report [26].

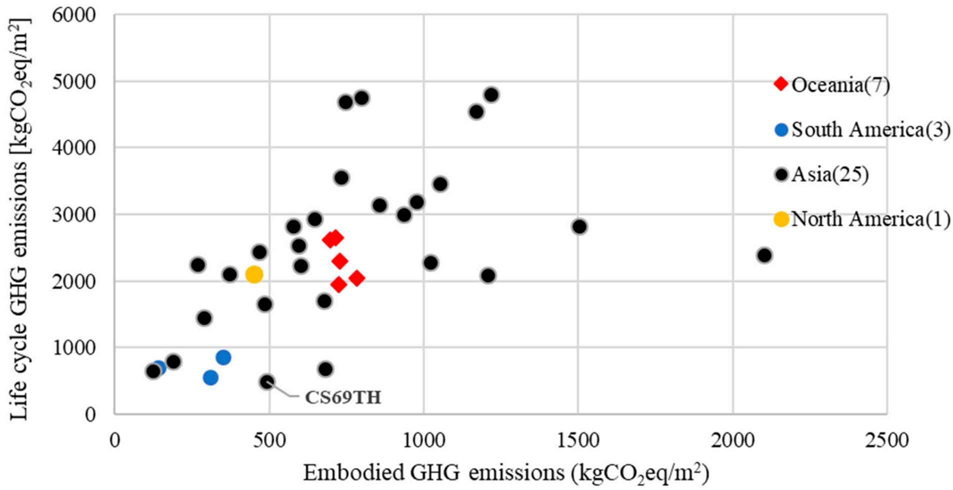


Figure 6. Harmonised embodied and life cycle GHG emissions from 36 case studies.

4.2. Influence of Energy Performance

Determining the energy performance level of the case study buildings was required to examine the influence of energy efficiency on embodied and operational GHG emission values. The classification of energy performance of the buildings in this research was based on the passive and low energy standards of the Passive House Institute [27], which are implemented globally in the residential construction sector. The definition of a low-energy building is based on a limit value of annual primary energy use related to heating, cooling, ventilation, domestic hot water and plug loads. However, in most of the 26 case studies, the annual energy use of the buildings was based on the final energy use. To overcome this limitation, the final energy use values were transformed into their primary form by implementing primary electricity conversion factors, which were obtained from existing research and local government reports [28–33]. As a result, the residential buildings CS20-21BR; CS22CO [34]; CS31CN and CS65, 66 and 68TH were defined as low-energy, with the total annual primary operational energy use not exceeding 120 kWh/m^2a. The solar-powered houses CS67 and 69TH, with an annual renewable energy generation higher than the annual energy needs, are classified as net-zero energy buildings. The rest of the buildings, which did not fulfil the low or net-zero energy requirements, were defined as conventional type.

The results of the present study indicate the existence of different GHG emission trends related to the energy performance of buildings. Zero-energy buildings present the lowest total GHG emissions among all case studies considered (Figure 7), with a 100% share of embodied to total GHG emission value (Figure 8). Low-energy buildings present a percentage of embodied GHG emission of 20–56% (Figure 8), except for CS31CN, which shows an extreme amount (82%) caused by the combination of extensive use of PV modules, aluminium-based construction characterised by high embodied GHG emissions load and low floor area (30 m^2).

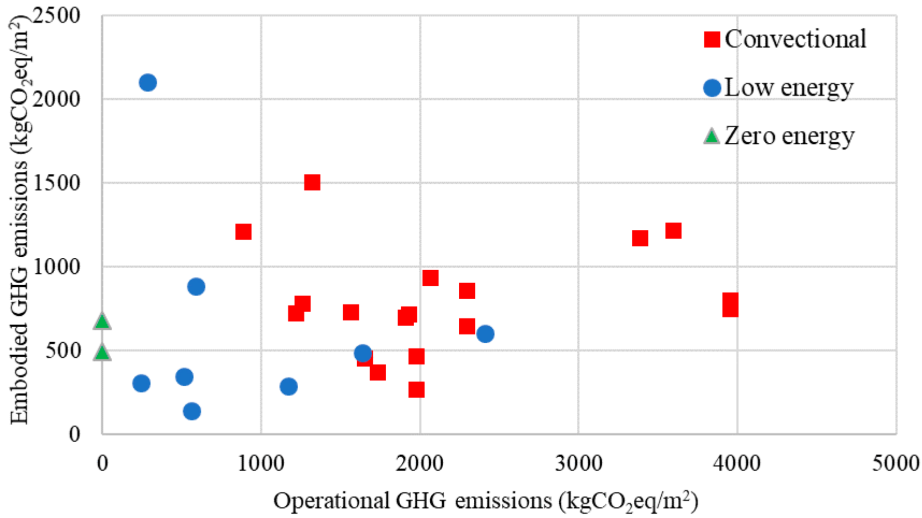


Figure 7. Operational and embodied GHG emissions in relation to the energy performances of 26 case buildings.

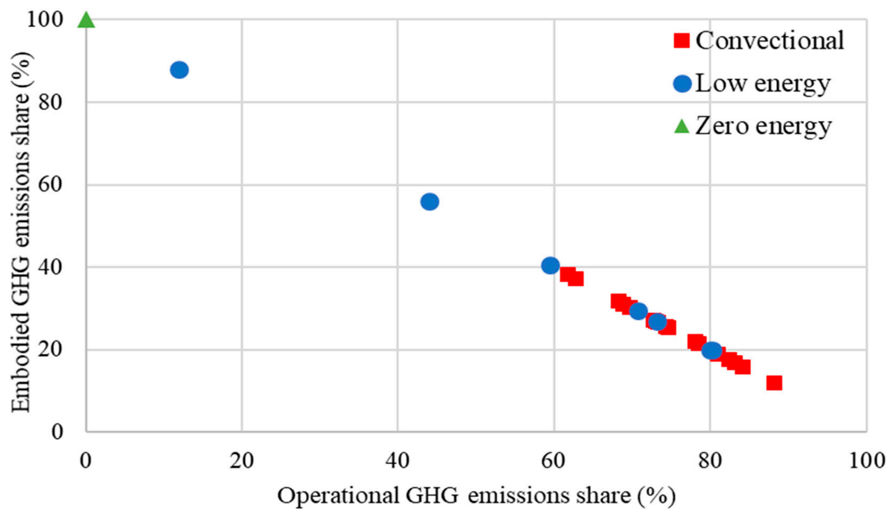


Figure 8. Share of embodied and operational-to-total GHG emissions in relation to the energy performances of 26 case buildings.

Convectional residential buildings contribute to the highest total GHG emissions, which, on average, are 51% and 80% higher than low- and zero-energy buildings, respectively (Figure 7). The observed share of embodied-to-total GHG emissions is between 12% and 38% (Figure 8). The electricity factor of GHG emissions has a strong influence on the emission profile of buildings. This can be observed by comparing low-energy buildings (CS65, 66 and 68TH) in Thailand with low-energy houses (CS22CO and CS21BR) in Colombia and Brazil. These buildings present similar values of embodied GHG emissions (242–601 $kgCO_2eq/m^2$), as well as annual primary operational electricity use (69–102 kWh/m^2a). However, the difference in the electricity emission factor leads to high variations in the share of embodied-to-total GHG emissions, with a 20–29% share in buildings in Thailand and 41–56% share in single-family buildings in Colombia and Brazil, respectively.

4.3. Influence of Building Typology

To study the influence of different residential building types, we plotted the embodied, operational and life cycle GHG emission values for single-family (SF) and multi-family (MF) buildings (Figure 9). The MF type is characterised by 40% higher total life cycle GHG emissions, on average, than the single-family type.

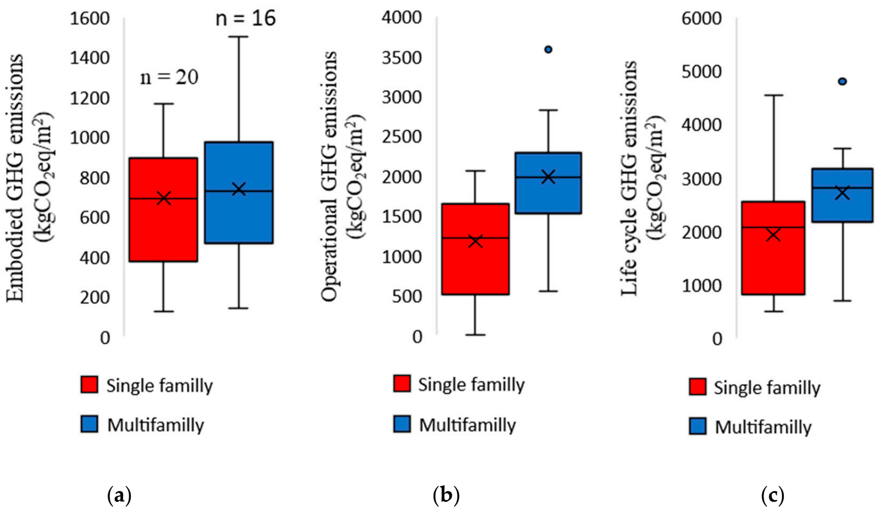


Figure 9. (**a**) Embodied, (**b**) operational and (**c**) total life cycle GHG emissions in relation to the residential building typology. n, number of case studies with a specific building typology.

The variation in total life cycle GHG emissions is high in both residential building types, with MF ranging between 700 $kgCO_2eq/m^2$ (CS20BR) and 4811 $kgCO_2eq/m^2$ (CS27CN) and SF ranging between 491 $kgCO_2eq/m^2$ (CS69TH) and 4554 $kgCO_2eq/m^2$ (CS32).

Both types of residential construction present similar average values of embodied GHG emissions: 650 and 740 $kgCO_2eq/m^2$ for SF and MF, respectively. These results are similar to findings from the Base Carbone database, which investigates GHG emission profiles of residential buildings in France.

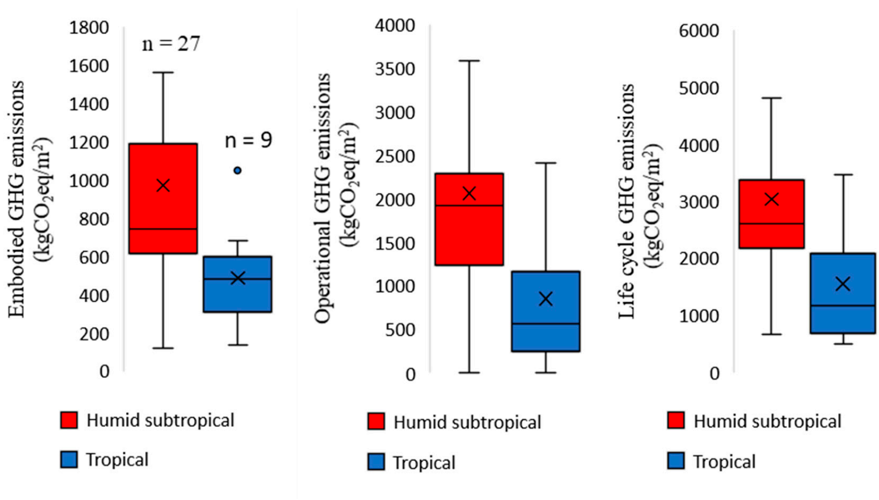
However, the multi-family type of building presents higher lower and upper limit values than a single-family type. This can be attributed to the inapplicability of timber-based structure and oversized reinforced concrete structure in high-rise multi-family buildings.

The main difference in total life cycle GHG emissions between residential building types is driven by operational GHG emissions, which, on average, are 78% higher in multi-family buildings. This is contrary to the findings from the US residential energy use survey in 2009 [35] and a study by Obrinsky and Walter in 2016 [36]. The main reason of this is that case studies of multi-family buildings included in the final sample are mostly based on existing stock and characterised by the "convectional" energy performance with the limited implementation of energy efficiency measures. This leads to twofold higher annual energy use, on average, compared to case studies based on single-family buildings.

4.4. Influence of Building Location and Climate Zone

As shown in the final sample (36 case studies; Figure A5 in Appendix C), the highest life cycle GHG emissions are found in Mainland China (CN), Hong Kong (HK) and South Korea (KR), characterised by a low energy-efficient multi-family construction sector. In contrast, the lowest impacts can be observed in Japan (JP), Colombia (CO) and Brazil (BR), characterised by low-energy performances or low-GHG emission grids based on renewable or nuclear energy sources (Figure 3).

Based on the current systematic literature review, it can be stated that residential buildings operating in humid subtropical climates on average present 60% higher embodied GHG emissions than those operating in the tropical climates (Figure 10). This can be attributed to the fact that most of the case study buildings in tropical climate zones are characterised as lightweight single-family constructions with the extensive use of local natural materials. In contrast, the residential construction sector in humid subtropical climate areas is dominated by heavily reinforced concrete multi-family buildings. Moreover, the data analysis indicates that constructions in humid subtropical climate areas are characterised by 75% higher total life cycle GHG emissions, on average, than those in tropical climate areas (Figure 10). Higher emissions are driven by the operational GHG emissions part, which is found to be, on average, 225% higher in humid subtropical than tropical climates. One of the main contributing factors of higher operational GHG emissions is demanding climate conditions in the humid subtropical zone (Figure A6 in Appendix C), which, compared to the tropical climate, leads to the significant energy-related use of both space heating and cooling. Climate conditions in tropical areas enable the use of a bioclimatic design approach for residential buildings, as in CS22CO, where no space heating or cooling is needed to meet adaptive thermal comfort requirements, leading to a significant reduction in operational GHG emissions.



(**a**) (**b**) (**c**)

Figure 10. (**a**) Embodied, (**b**) operational and (**c**) total life cycle GHG emissions in relation to the climate zone. n, number of case studies with a specific climate location.

Comparing the current results with a previous harmonised analysis of 15 residential case studies by Chastas et al. [11], it can be stated that residential buildings operating in humid subtropical climates present, on average, 65% higher total GHG emissions than those operating in temperate and continental climate zones. One of the biggest contributing factors is the dominant share of buildings characterised by highly efficient performances (passive and low-energy) in developed economies located in temperate and continental climate zones.

4.5. Influence of Main Structural Materials

Among the harmonised final data sample, the dominant construction materials used for load-bearing structures vary between reinforced concrete (RC), concrete (C), steel (S), masonry brick (M) and wood (W), combined with secondary materials (All). The highest embodied and life cycle GHG emissions are induced by using reinforced concrete and steel as the primary building materials (Figure 11).

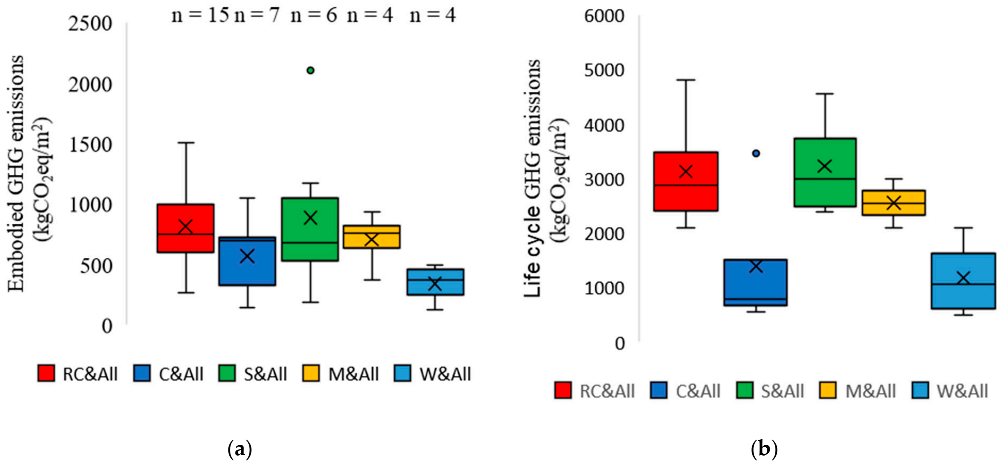


Figure 11. (**a**) Embodied and (**b**) total life cycle GHG emissions in relation to the primary structure materials. RC, reinforced concrete; C, concrete; S, steel; M, masonry brick; W, wood and All, secondary materials. n, number of case studies with a specific primary structure material.

Embodied GHG emissions in the building structures based on reinforced concrete range from 267 $kgCO_2eq/m^2$ in CS58KR to 1503 $kgCO_2eq/m^2$ in CS61KR, and the total life cycle GHG emissions range from 2093 $kgCO_2eq/m^2$ in CS62KR to 4811 $kgCO_2eq/m^2$ in CS27CN. The relatively low value of embodied GHG emissions in CS58KR is due to the extensive use of high-strength concrete, which results in a decreased quantity of concrete and rebar. As a result, embodied GHG emissions were reduced by 43% compared to the same high-rise building design (CS57KR) when utilising standard reinforced concrete. Embodied GHG emissions related to steel-based buildings present a high variation, with values between 188 $kgCO_2eq/m^2$ in CS55JP and 2103 $kgCO_2eq/m^2$ in CS31CN, nearly half of which comes from extensive use of PV modules. The use of concrete and masonry (brick) materials in the structure evidenced a similar variation, with concrete structures ranging between 349 $kgCO_2eq/m^2$ in CS22CO and 1050 $kgCO_2eq/m^2$ in CS64MY and masonry (brick) structures varying between 369 $kgCO_2eq/m^2$ in CS24CN and 933 $kgCO_2eq/m^2$ in CS28CN. The use of wood as the primary structural material led to the lowest embodied and total life cycle emissions. Embodied GHG emissions range between 122 $kgCO_2eq/m^2$ in CS54JP and 491 $kgCO_2eq/m^2$ in CS69TH, and the life cycle GHG emissions vary between 491 $kgCO_2eq/m^2$ in CS69TH and 2100 $kgCO_2eq/m^2$ in CS73US.

5. Building Design Strategies for Reducing GHG Emissions

To compare building design strategies for GHG reduction in the analysed case studies, strategies were categorised into seven main groups (detailed description in Table 4): maximisation of timber use (S1), improvement of thermal properties (S2), use of materials with lower embodied GHG emissions (S3), increased use of local materials (S4), extension of building lifespan (S5), form optimisation (material efficiency) (S6) and implementation of renewable energy generation, i.e., on-site PV energy system (S7). The reduction potential of embodied, operational and life cycle GHG emissions relative to the baseline design scenario in each recognised strategy is presented in Figures 12 and 13.

Table 4. Overview of GHG emission reduction strategies.

Reduction Strategy	Case Study	Description	GHG Emission Reduction (−) or Increase (+) (%) Relative to Baseline Scenario		
			Embodied	Operational	Total Life Cycle
S1: Maximise use of timber	CS1 AU	Replacement of steel structure frame (base design CS2AU) with timber frame	−30%	−4%	−17%
		Replacement of concrete slab (base design CS2AU) with elevated timber floor	−21%	−3%	−12%
		Replacement of brick veneer (base design CS2AU) with weatherboard cladding	−9%	−1%	−5%
	CS13 AU	Switch concrete sub-floor, double brick wall covering and roof steel frame (base design CS12) to timber products	−44%	−1%	−16%
	CS15 AU	Switch concrete sub-floor, double brick wall covering and roof steel frame (base design CS14) to timber products	−69%	−1%	−21%
	CS32 CN	Replace aluminium panel wall (base design CS31CN) with timber wall	−6%	0%	−5%
S2: Improve thermal properties	CS4 AU	Implement reflective insulation for non-insulated carpet floor (base design CS3)	+10%	−7%	−1%
	CS5 AU	Replace non-insulated carpet floor (base design CS3) with insulated hardwood timber floor	+5%	−44%	−26%
	CS66 TH	Replace non-insulated reinforced concrete structure (base design CS65TH) with insulated steel frame	−19%	−29%	−26%
S1+S2: Maximise use of timber + improve thermal properties	CS69 TH	Replace non-insulated reinforced concrete structure (base design CS65TH) with insulated timber frame	−52%	−29%	−35%
S3: Use lower EC materials	CS58 KR	Replace standard concrete (base design CS57KR) with non-cement concrete panels and amorphous steel fibre concrete (low GHG emission)	−25%	0%	−7%
	CS61 TW	Replace reinforced concrete structure (base design CS66TW) with lightweight steel frame	−34%	−18%	−25%
S4: Increase use of local materials	CS51 JP	Replace standard timber construction with (a) locally produced timber, (b) no laminated wood, (c) natural and locally produced insulation materials	−73%	−41%	−48%
S5: Extend building lifetime	CS58 KR	Extend 50-year building lifespan (base design CS57KR) to 100 years by replacing standard 24 MPa strength concrete (base design CS57KR) with high-strength (40 MPa) concrete	−50%	0%	−8%
S6: Optimise form (material efficiency)	CS62 KR	Optimise building form and design by using T-type instead of flat-type concrete blocks (base design CS61KR)	−21%	−30%	−25%

Table 4. *Cont.*

Reduction Strategy	Case Study	Description	GHG Emission Reduction (−) or Increase (+) (%) Relative to Baseline Scenario		
			Embodied	Operational	Total Life Cycle
S7: Implement PV systems (on site)	CS31 CN	Implement on-site PV system of 2.8 kW in reference to design scenario CS32CN	+79%	−92%	−48%
	CS67 TH	Implement on-site PV system of 5 kW in reference to design scenario CS66TH	+41%	−100%	−59%
	CS69 TH	Implement PV system of 5 kW in reference to design scenario CS68TH	+70%	−100%	−66%

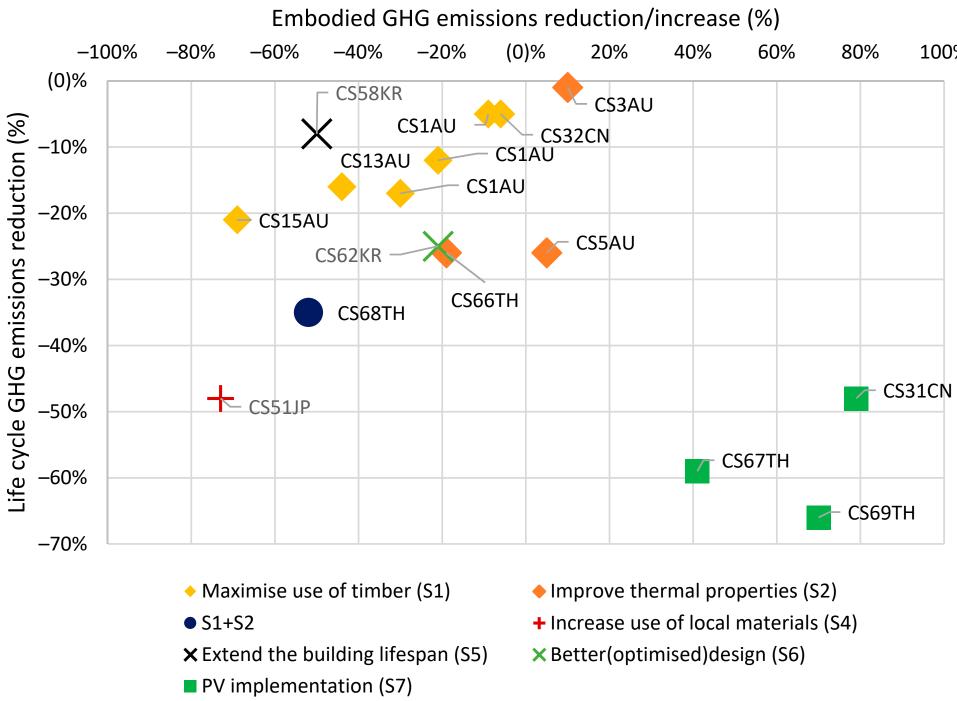


Figure 12. Embodied and life cycle GHG emission reduction potentials of the identified design strategies.

Strategy S1, related to maximisation of timber used in the building structure, is the most common among case study buildings and presents an emission reduction potential of 5% (CS1AU and CS32CN) to 69% (CS15AU) and 1% (CS32) to 21% (CS15AU) for the embodied and total life cycle GHG emissions, respectively. The influence of S1 on the reduction of operational GHG emissions is marginal (1–4%; Figure 13) and related mostly to the lower thermal conductivity of timber compared with steel, concrete or brick. In this strategy, both the embodied and total GHG emission reduction potentials are strictly correlated with the extent of timber use, which is the lowest in CS32CN, where only the external aluminium wall is replaced with a timber-based wall, while the highest reductions occur in CS15AU, where timber was implemented entirely as the primary structural material.

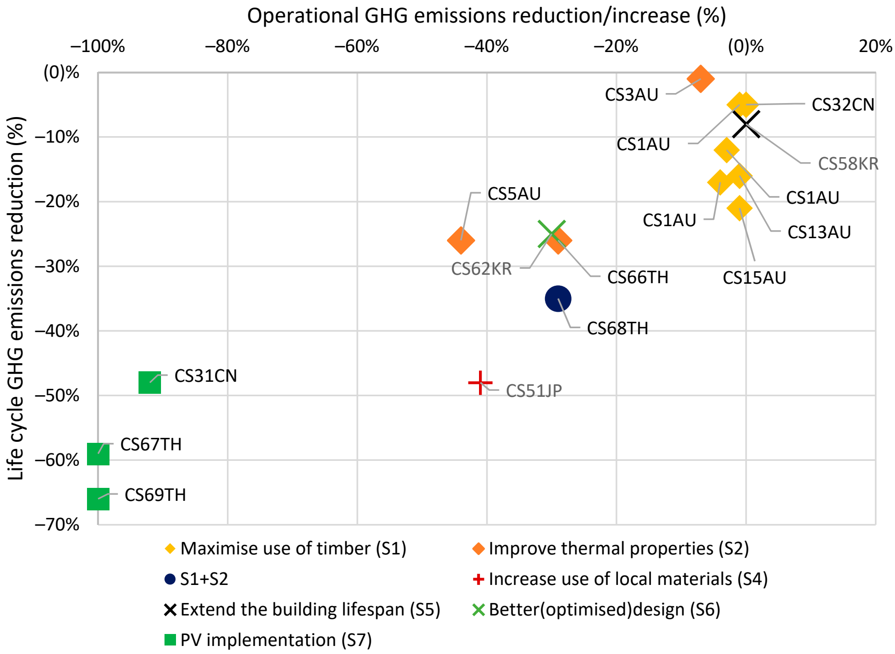


Figure 13. Operational and life cycle GHG emission reduction potentials of the identified design strategies.

Additionally, the use of the different methods related to the accounting of carbon-storage credits from timber-based product leads to discrepancies in the reduction efficiency potentials among the analysed case studies. The highest benefits are for CS13-15AU, in which the carbon-storage benefits are included in the life cycle assessment results. Excluding that component, the embodied GHG emission savings would have been reduced twofold.

Strategy S2, related to improving the thermal properties of the building, e.g., by insulating building partitions or complete frames, presents a substantial potential for reducing operational GHG emissions in the range of 7–44%, which can be mainly correlated with a decrease of space heating energy demand. Implementing additional insulation materials may lead to increased embodied GHG emission values relative to the baseline design scenario, as in CS3AU (+10%) and CS5AU (+5%). Despite the increased embodied GHG emissions, the strategy presents a life cycle GHG emission reduction potential of 1% (CS3AU) to 26% (CS66TH).

A combination of strategies S1 and S2, identified in CS68TH, leads to a reduction in terms of both embodied and operational GHG emissions, increasing the total life cycle GHG emission reduction potentials to 35% relative to the baseline scenario.

Among all available GHG emission reduction strategies, implementing renewable energy sources based on the extensive use of solar energy generated by photovoltaic panels (S7) is identified as the most efficient in terms of life cycle emission reduction, with a range of efficiency between 48% (CS31CN) and 66% (CS69TH). In this strategy, the significant increase of embodied GHG emissions (41–79%) is overcome by a massive compensation (92–100%) of operational GHG emissions. The life cycle GHG reduction potential is the highest in locations characterised by high emissions related to electricity use from the local grid.

The GHG emission factor of electricity has a dominant influence on life cycle GHG emissions and is a key parameter for choosing the most effective design strategies toward low-emission buildings, which is in-line with the findings of [37,38].

In addition, the implementation of strategies in the analysed sample is dominated by the single-family building type. Based on this, it was found that there is little research on GHG reduction strategies implemented in multi-family buildings, which are dominant in developing economies and characterised by higher life cycle GHG emissions.

6. Contributions and Limitations of the Current Review

The current review is an effort to fill the research gap in systematic identification and assessment of the existing literature on GHG emissions along the life cycle of residential buildings in humid subtropical and tropical climate regions. The results show the influence of building-oriented factors on GHG emission profiles and allow the identification and discussion of promising strategies for reducing the environmental impact.

The most important limitations of this study are related to the following:

- The possible omission of existing studies in the data collection procedure.
- The underestimation of embodied GHG emissions among case studies, taking into consideration the dominant use of the process-based assessment method, which is sensitive to truncation error.
- The application of linear harmonisation of the embodied GHG emissions to the reference study period of 50 years is a straightforward approach to increase the comparability of the results. However, the replacement of construction materials and the associated environmental impacts during the study period occurs in a discrete period of time. Scaling these impacts linearly induces errors.

7. Conclusions and Outlook

Within the collection of 71 case studies, most of the life cycle GHG emission assessments were performed for buildings located in humid subtropical climates. The highest life cycle GHG emissions were found in the rapidly developing residential construction sectors of China, Hong Kong and India. The results of this study demonstrate that residential buildings with net-zero or low-energy performances have the potential to reduce the total life cycle GHG emissions by 50–80% compared to the most common conventional energy performance. The share of embodied GHG emissions among total GHG emissions ranges from 16% to 100%, with an average share of 27%, which is similar to previous research mostly based on case studies of buildings located in cold and temperate climates. The differences in the ratio between the embodied and total life cycle GHG emissions are mainly attributable to the choice of material in the building structure, energy performance and electricity emission factor for the grid mix used in the calculation of emissions from the operation.

The results indicate that the design strategy connected with the implementation of renewable energy sources in the form of photovoltaic systems provides the best reduction in terms of life cycle GHG emissions.

Furthermore, analysing the geographic locations of the buildings showed that most studies were located in humid subtropical climates, with only 15 case studies in tropical climates. This finding highlights the need for future research on the life cycle assessment for GHG emission reduction strategies in the tropical residential construction sector, especially taking into consideration ongoing efforts towards the redevelopment of slums and market implementation of governmental housing units in developing economies. This study furthermore identified a research gap related to developing and assessing the GHG emission reduction measures in multi-family buildings, which present higher life cycle GHG emissions than single-family buildings.

Several additional aspects were identified that future research efforts should focus on. The study identified the significant GHG emission reduction potentials by substituting high-emission materials such as steel and concrete with bio-based low-carbon materials. Further research and development of such materials, such as timber-based products or bamboo for construction, is needed to support market implementation. The analysis of promising design strategies should be advanced to develop specific design guidelines for low-emission, carbon-neutral buildings in warm and humid climate regions. Such guidelines will be crucial in enabling decarbonisation of building construction and operation, for both the refurbishment of new buildings and renovation of existing buildings. Science-based targets and guidelines are needed to inform effective policies and implement related requirements in building codes and standards. To that effect, harmonising building life cycle assessment studies in terms of methodology and results and reporting is important. Efforts for such harmonisations are under way in international research collaborations such as the IEA EBC Annex 72 project.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. List of Case Studies and Basic Properties

Table A1. Overview of 75 case studies: methodological principles.

Case Study	Reference	Calculation, Impact Assessment Method (Impact Indicator)	Operational Energy Assessment Methodology (Software/Data Source)
CS1AU CS2AU	Carre, 2011 [39]	PLCA/AIA, GWP (kgCO_2eq)	BPS (Accurate)
CS3AU CS4AU CS5AU CS6AU	Islam et al., 2015 [40]	PLCA/AIA, GWP (kgCO_2eq)	BPS (Accurate)
CS7AU CS8AU CS9AU CS10AU CS11AU	Holloway et al., 2007 [41]	IO/n/s, GWP (kgCO_2eq)	Statistical data (Energy suppliers local, data)
CS12AU CS13AU CS14AU CS15AU	Ximenes and Grant, 2013 [42]	PLCA/n/s, GWP (kgCO_2eq)	n/s
CS16AU CS17AU CS18AU	Lawania and Biswas, 2016 [43]	PLCA/IPPC (2007), GWP (kgCO_2eq)	BPS (Accurate)
CS19BR	Gomes et al., 2018 [44]	PLCA/CML2001, GWP (kgCO_2eq)	BPS (Energy +)
CS20BR CS21BR	Evangelista et al., 2018 [45]	PLCA/ILCD (2011) GWP (kgCO_2eq)	Statistical (National data)

Table A1. *Cont.*

Case Study	Reference	Calculation, Impact Assessment Method (Impact Indicator)	Operational Energy Assessment Methodology (Software/Data Source)
CS22CO	Ortiz-Rodríguez et al., 2010 [34]	PLCA/CML GWP ($kgCO_2eq$)	Statistical (Energy suppliers' data)
CS23CN	Zhan et al., 2018 [46]	Hybrid, IPPC (2006) GWP ($kgCO_2eq$)	n/s
CS24CN	D. Li et al., 2016 [47]	PLCA/n/s CO_2 ($kgCO_2$)	Statistical (National/local data)
CS25CN CS26CN	Wu et al., 2017 [48]	PLCA/n/s, GWP ($kgCO_2eq$)	BPS (Dest) and meter data
CS27CN	Huang et al., 2018 [49]	PLCA/ReCiPe Midpoint GWP ($kgCO_2eq$)	Meter data
CS28CN	Yang et al., 2018 [50]	PLCA/IPPC (2007), GWP ($kgCO_2eq$)	BPS (Design Builder)
CS29CN	D. Z. Li et al., 2013 [51]	PLCA/n/s, CO_2 ($kgCO_2$)	Statistical (Local and field survey data)
CS30CN	Zeng and Ren, 2012 [52]	Hybrid, IPPC (2007) GWP ($kgCO_2eq$)	n/s
CS31CN CS32CN	Dong et al., 2018 [53]	PLCA/n/s, CO_2 ($kgCO_2$)	BPS (Energy +)
CS33CN CS34CN CS35CN CS36CN	Satola et al., 2020 [54]	PLCA/ReCiPe Midpoint GWP ($kgCO_2eq$)	BPS (Trnsys)
CS37HK CS38HK	Yim et al., 2018 [55]	PLCA/IPPC (2007) GWP ($kgCO_2eq$)	Statistical (National data)
CS39HK CS40HK CS41HK	Gan et al., 2018 [56]	PLCA/n/s GWP ($kgCO_2eq$)	BPS (DOE-2 software)
CS42IN CS43IN	Chel and Tiwari, 2009 [57]	n/s/n/s, CO_2 ($kgCO_2$)	BPS (n/s)
CS44IN	Ishaq et al., 2019 [58]	PLCA/n/s, CO_2 ($kgCO_2$)	BPS (DOE2)
CS45ID CS46ID CS47ID CS48ID CS49ID CS50ID	Surahman et al., 2015 [59]	IO/n/s, CO_2 ($kgCO_2$)	Meter data
CS51JP	Tonooka et al., 2014 [60]	IO/n/s, CO_2 ($kgCO_2$)	n/s
CS52JP CS53JP	Ohta, 2017 [61]	IO/n/s, CO_2 ($kgCO_2$)	BPS (n/s)
CS54JP CS55JP	Gerilla et al., 2007 [62]	IO/CML, GWP ($kgCO_2eq$)	Statistical (n/s)
CS56KR	S. Tae et al., 2011 [63]	PLCA/n/s, CO_2 ($kgCO_2$)	Statistical (National data)
CS57KR CS58KR	S. Tae et al., 2016 [64]	IO/n/s, CO_2 ($kgCO_2$)	
CS59KR CS60KR	Cho and Chae, 2016 [65]	PLCA/n/s, CO_2 ($kgCO_2$)	Statistical (National benchmark data)

Table A1. *Cont.*

Case Study	Reference	Calculation, Impact Assessment Method (Impact Indicator)	Operational Energy Assessment Methodology (Software/Data Source)
CS61KR CS62KR	Baek et al., 2016 [66]	IO/n/s, CO_2 ($kgCO_2$)	BPS (Ecodesigner)
CS63KR	Roh et al., 2016 [67]	PLCA/n/s, CO_2 ($kgCO_2$)	BPS (n/s)
CS64MY	Rashid et al., 2017 [30]	PLCA/CML2(2001) GWP ($kgCO_2eq$)	BPS (Open studio)
CS65TH CS66TH CS67TH CS68TH CS69TH	Bukoski et al., 2017 [68]	PLCA/ReCiPe Midpoint V.1.1, GWP ($kgCO_2eq$)	BPS (Design Builder)
CS70TW CS71TW	Chang and Lee, 2013 [69]	PLCA/IPPC (2007) GWP ($kgCO_2eq$)	BPS (DOE-2 software)
CS72US	Fesanghary et al., 2012 [70]	PLCA/n/s, GWP ($kgCO_2eq$)	BPS (Energy +)
CS73US	Mosteiro-romero et al., 2014 [71]	PLCA/BEES, GWP ($kgCO_2eq$)	BPS (RemDesign)
CS74US CS75US	Winistorfer et al., 2005 [72]	PLCA/Athena, CO_2 ($kgCO_2$)	n/s

n/s, not stated; GWP, global warming potential; PLCA, process-based LCA; IO, input-output and BPS, building performance simulation. Meter data refers to direct end-use energy measurements.

Table A2. Overview of 75 case studies: building-oriented features.

Case Study	Location/Climate	Type	GFA (m^2)	Main Materials	RSP (Years)
CS1AU CS2AU	Sydney/HST	SF	202	W,C S,C	50
CS3AU CS4AU CS5AU CS6AU	Brisbane/HST	SF	101	W,C	50
CS7AU CS8AU CS9AU CS10AU CS11AU	Sydney/HST	SF	174 164 323 219 213	C C,M M,C C M	65
CS12AU CS13AU CS14AU CS15AU	Sydney/HST	SF	221 221 296 296	C,M W C,M W	50
CS16AU CS17AU CS18AU	Perth/HST	SF	243	M C W	50
CS19BR	Campinas/HST	LL	1005	S,C	50
CS20BR CS21BR	Salvador/TR	MF SF	10,778 561	C,S C,W	50
CS22CO	Pamplona/TR	SF	125	C,S	50

Table A2. *Cont.*

Case Study	Location/Climate	Type	GFA (m^2)	Main Materials	RSP (Years)
CS23CN	Guangzhou/HST	MF	4235	RC	70
CS24CN	Nanjing/HST	MF	1839	M,C	50
CS25CN CS26CN	Shanghai/HST	MF	138,048 67,063	RC RC	50
CS27CN	Fuzhou/HST	MF	29,910	RC	50
CS28CN	Baiguoba/HST	SF	423	M,C	50
CS29CN	Nanjing/HST	MF	1459	M,C	70
CS30CN	Shanghai/HST	MF	2831	RC	50
CS31CN CS32CN	Nanjing/HST	SF	30	S(Al),PV S(Al)	20
CS33CN CS34CN CS35CN CS36CN	Shanghai/HST	SF	27	S S S,PV S,PV,ES	25
CS37HK CS38HK	Hong Kong/HST	MF	33,078	RC	50
CS39HK CS40HK CS41HK	Hong Kong/HST	MF	38,360	RC	50
CS42IN CS43IN	New Delhi/HST	SF	94	RC Mud	50
CS44IN	Uttar Pradesh/HST	MF	5664	RC	30
CS45ID CS46ID CS47ID CS48ID CS49ID CS50ID	Jakarta/TR Bandung/TR	SF	45 95 207 57 127 300	ST,M C,M	20 35 50 20 35 50
CS51JP	Tokyo/HST	SF	126	W	100
CS52JP CS53JP	Kameyama/HST	SF	147	W	50
CS54JP CS55JP	SagaHST	SF	150	W S,RC	35
CS56KR CS57KR CS58KR	Busan/HST	MF	3440 14,424	RC RC	60 50 100
CS59KR CS60KR	Gwangju/HST	MF	1078	RC	30
CS61KR CS62KR	Pohang/HST	MF	11,401 19,303	RC RC	40 80
CS63KR	Seoul/HST	MF	208,393	RC	40
CS64MY	Kuala Lumpur/TR	SF	246	C,M	50

Table A2. *Cont.*

Case Study	Location/Climate	Type	GFA (m^2)	Main Materials	RSP (Years)
CS65TH CS66TH CS67TH CS68TH CS69TH	Bangkok/TR	SF	148	RC S S,PV W W,PV	50
CS70TW CS71TW	Hsinchu/HST	SF	326	RC S	30
CS72US	Baton Rouge/HST	SF	186	C	25
CS73US	New Jersey/HST	SF	317	W	65
CS74US CS75US	Atlanta/HST	SF	202	C W	75

GFA, gross floor area; RSP, reference study period; HST, humid subtropical climate; TR, tropical climate; SF, single-family; MF, multi-family; LL, living laboratory; W, wood; S, steel; S(Al), steel (aluminium) stone; C, concrete; RC, reinforced concrete; M, masonry (brick); PV, photovoltaic and ES, energy storage.

Appendix B. Meta-Analysis

Appendix B.1. Methodological Features

Appendix B.1.1. System Boundaries

Table A3. Life cycle processes and stages (EN 15978) of 75 life cycle GHG emission assessments of the residential buildings.

	Product Stage			**Construction Stage**		**Use Stage**							**End of Life**				**Benerfits**
Case Study, CS	**Raw Material Supply, A1**	**Transport, A2**	**Manufacturing, A3**	**Transport, A4**	**Installation, A5**	**Use, B1**	**Maintenance, B2**	**Repair, B3**	**Replacement, B4**	**Refurbishment, B5**	**Operational Energy Use, B6**	**Operational Water Use, B7**	**Deconstruction Demolition, C1**	**Transport, C2**	**Waste Processing, C3**	**Disposal. C4**	**Reuse–Recovery–Recycling, D**
1 to 2 AU	x	x	x	x	x		x		x		H,V,C		x	x	x	x	X
3–6 AU	x	x	x	x	x		x		x		H,V,C		x	x	x	x	X
7–11 AU	**x**	**x**	**x**	**x**	**x**				**x**		**H,V,C, DHW,L,A**	**x**	**x**				
12–15AU	x	x	x	x			x		x		H,V,C			x	x	x	X
16–18AU	x	x	x	x	x						H,V,C, DHW,L,A						
19BR	x	x	x	x	x		x		x		H,V,C, DHW,L,A		x	x			
20 to 21BR	**x**	**x**	**x**	**x**	**x**				**x**		**H,V,C, DHW,L,A**	**x**	**x**	**x**	**x**	**x**	

Table A3. *Cont.*

	Product Stage			Construction Stage		Use Stage							End of Life				Benefits
Case Study, CS	**Raw Material Supply, A1**	**Transport, A2**	**Manufacturing, A3**	**Transport, A4**	**Installation, A5**	**Use, B1**	**Maintenance, B2**	**Repair, B3**	**Replacement, B4**	**Refurbishment, B5**	**Operational Energy Use, B6**	**Operational Water Use, B7**	**Deconstruction Demolition, C1**	**Transport, C2**	**Waste Processing, C3**	**Disposal. C4**	**Reuse–Recovery–Recycling, D**
22CO	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	
23CN	x	x	x	x	x		x		x		H,V,C,L		x	x	x	x	X
24CN	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
25 to 26CN	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
27CN	**x**	**x**	**x**	**x**	**x**				**x**		**H,V,C, DHW,L,A**		**x**	**x**		**x**	
28CN	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	
29CN	x	x	x	x	x		x		x		H,V,C, DHW		x	x	x	x	X
30CN	x	x	x	x	x		x		x		H,V,C, DHW,L,A		x	x	x	x	X
31 to 32CN	**x**	**x**	**x**	**x**					**x**		**H,V,C, DHW,L,A**		**x**	**x**		**x**	
33–36CN	x	x	x	x	x		x		x		H,V,C, DHW,L,A		x	x	x	x	X
37 to 38HK	**x**	**x**	**x**	**x**					**x**		**H,V,C, DHW,L,A**		**x**	**x**		**x**	
39–41HK	x	x	x	x							H,V,C						
42 to 43 IN	x	x	x								H,V,C						
44 IN				n/c							H,V,C,L				n/c		
45–50 ID	x	x	x						x		H,V,C, DHW,L,A						
51 JP	x	x	x				x		x		H,V,C, DHW,L,A		x	x	x	x	X
52 to 53 JP	x	x	x	x	x						H,V,C, DHW,L,A						
54 to 55 JP	**x**	**x**	**x**	**x**			**x**		**x**		**H,V,C, DHW,L,A**					**x**	
56–58KR	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**

Table A3. *Cont.*

	Product Stage			Construction Stage		Use Stage							End of Life				Benefits
Case Study, CS	Raw Material Supply, A1	Transport, A2	Manufacturing, A3	Transport, A4	Installation, A5	Use, B1	Maintenance, B2	Repair, B3	Replacement, B4	Refurbishment, B5	Operational Energy Use, B6	Operational Water Use, B7	Deconstruction Demolition, C1	Transport, C2	Waste Processing, C3	Disposal. C4	Reuse–Recovery–Recycling, D
59 to 60KR	**x**	**x**	**x**	**x**	**x**		**x**				**H,V,C, DHW,L,A**				**x**	**x**	**X**
61 to 62KR	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
63KR	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
64MY	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
65–69TH	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
70 to 71TW	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	
72US	x	x	x	x	x		x		x		H,V,C		x	x	x	x	
73US	**x**	**x**	**x**	**x**	**x**		**x**		**x**		**H,V,C, DHW,L,A**		**x**	**x**	**x**	**x**	**X**
74 to 75US	x	x	x	x	x		x				H,V,C		x	x	x	x	

x, process included in system boundaries; n/c, not clear; H, space heating; V, ventilation; C, space cooling; DHW, domestic hot water; L, lighting and A, appliances. The 36 case studies in bold are those included in the final sample.

Sensitive analysis of 40 case studies characterised by cradle-to-grave system boundaries with a complete B6 scope indicates that excluding the energy demands of domestic hot water, lighting and appliances leads to the highest deviation of total life cycle GHG emissions in the range of 19–81%. Excluding the construction stage (A4–A5) results in a variation between 0.1% and 26.7%. Herein, the most extensive deviation value occurs in CS19BR, and it is mainly caused by the removal and transportation of a large volume of earth to the building site to create a vertical bridge between two wings of the building. Excluding this study, the deviation is reduced to a range of 0.1%–5.3%. Excluding the maintenance (B2) and replacement process (B4) modules resulted in a deviation range between 0.9% and 9.9%. This variation is primarily caused by a high uncertainty surrounding future replacement and maintenance scenarios. Excluding the entire end-of-life module (C1–C4) resulted in a deviation ranging between 0.5% and 4.2%.

Appendix B.1.2. Calculation Method of the Life Cycle GHG Emission Assessment

The life cycle GHG emission assessment embodies a process-based (PLCA), input-output-based (IO) or hybrid-based calculation method. The selection of the approach depends mostly on data availability and quality, and each method always presents varying degrees of completeness and reality. While the process-based method covers the GHG emissions and material inputs to each system process, the complexity of this arrangement may produce a misleading life cycle assessment [73]. Additionally, the PLCA method inherently suffers from a truncation error made in the selection of system boundaries, which may not cover significant environmental impacts associated with the inputs and outputs located outside the system boundaries [74–77]. The recently published Australian EPiC database [78] shows an average truncation error of ~60% across 131 building materials.

The input-output methodology uses economic input-output data for the entire construction sector, but applying this method can lead to problems with data aggregation and unreliability [79]. Additional factors contributing to the uncertainty of the IO method are the homogeneity and linearity assumptions [80].

The hybrid method is a combination of the PLCA- and IO-based methods. In this case, the process-based methodology is used up to the stage where reliable and complete information is no longer available, and then, the IO-based method is used, with the aim of reducing the negative features of the two basic calculation methodologies.

In most of the 52 collected case studies, the life cycle GHG emission assessment was calculated using the PLCA methodology, while the IO methodology was applied in 20 case studies (Figure A1). In contrast, the hybrid-based method was only utilised in two case studies, CS23CN and CS30CN.

The literature shows that IO and hybrid-based assessments tend to report higher impacts than PLCA due to higher system completion [81–83]. Furthermore, Crawford and Stephan [84] and Crawford et al. [85] found that a hybrid LCI can produce embodied energy figures two to four times larger at a whole-building level compared to using process analysis data only.

Under this review, it is made evident that, on average, case studies CS7-11AU, which applied the IO calculation method, provided nearly 110% higher embodied GHG emissions compared to the PLCA-based results of the Australian single-family buildings (CS12 and14 and 16 and 17AU) with similar structure types. However, assessing the direct impact of PLCA or IO methodology on the embodied GHG emission value is challenging, taking into consideration other factors such as the simplification of the material inventory and outdated IO construction data in IO-based case studies. Overall, the implementation of hybrid methods improves the system resolution and leads to higher emissions than the PLCA method [75]. This comes from looking at the hybrid-based CS23CN case study, where the embodied GHG emission was 145% higher than that in a comparable multi-family building from case study CS29CN, which was assessed using the process-based methodology.

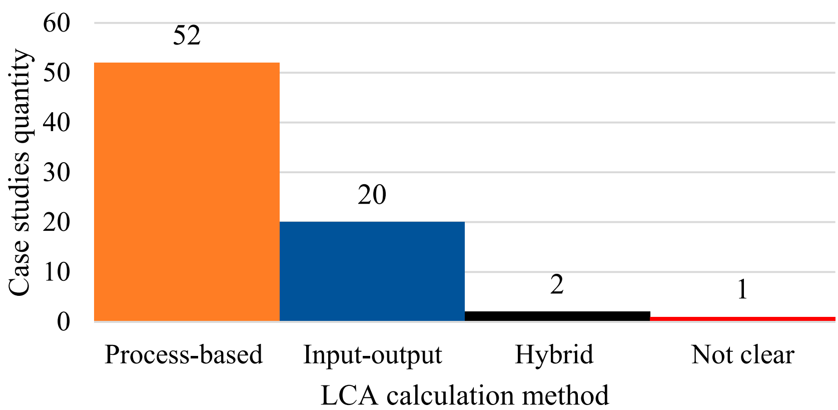


Figure A1. Life cycle assessment calculation method employed with 75 case studies.

Appendix B.1.3. Impact Assessment Method and Indicators

The choice of impact assessment method varied among the examined case studies (Table A1). In 39 case studies, the method was not clearly stated. In contrast, in CS22CO, the authors indicated that different impact assessment methods could deliver results with the same order of magnitude if the same life cycle inventory databases were used. The midpoint indicator of the global warming potential, GWP (CO_2eq), was used in 44 case studies in the sample. In other case studies, the life cycle impact was based only on the CO_2 emissions. Due to the complexity of the procedure and lack of available data, the uncertainty related to a different choice of impact assessment method and scope of GHG emissions could not be estimated in this review.

Appendix B.1.4. Operational Energy Use Assessment Methodology

Operational energy use can be defined as the energy required to preserve the comfort conditions inside the building and needed in day-to-day maintenance [12]. This notion incorporates the energy needs connected with heating, ventilation and air-conditioning (HVAC), domestic hot water (DHW), lighting (L) and appliances (A). A critical review of the collected literature indicates that the assessment methodology of GHG emissions related to the energy use stage (B6) is mainly based on a multiplying relation between the annual final energy annual consumption and the GHG emission factors of energy carriers. An in-depth analysis of the operational energy stage (B6) is then crucial for a complete life cycle GHG emission assessment due to its dominant contribution compared to other life cycle stages.

The collected case studies employed various operational energy use assessment methodologies (Table A1), which generally can be divided into two main groups—namely, engineering or statistical methods. Engineering methods are based on building performance simulations or direct on-site measurements via energy meters. The building performance simulation is used in most of the case studies (40), followed by statistical methods (19) and on-site measurements (7) (Figure A2). The accuracy of the building performance simulation results depends mainly on the accuracy of the building model, experience of the user and simulation software, which applies different methods in integrated or separated simulation engines [86].

This study indicates that the methodology for the building performance simulation (BPS) assessment among the analysed sample is mostly simplified, which makes an uncertainty analysis challenging. Moreover, it can be pointed out that CS42 and 43IN, CS52 and 53JP and CS63KR lack a clarification of the used BPS software or simulation engine, which leads to the uncertainty of the simulation outcomes in the form of the annual, final energy use. The use of metered energy data provides the most reliable energy use results. Still, its implementation is limited to already-constructed buildings.

The source of statistical data in the collected literature sample is based on energy suppliers, government data, construction energy benchmarks and survey field databases, which cover local or national data ranges. However, in CS54 and 55JP, the data source used for the statistical method is not clear, whereas in CS12-15AU, CS23CN, CS30CN, CS51JP and CS74 and 75US, the operational energy use assessment method is not stated, leading to uncertainty in the results.

The performed analysis indicated that none of the investigated case studies included the possible effects of climate change during the building lifespan in the assessment's calculations. This can be identified as a significant uncertainty factor, especially taking into consideration that the location of the case study buildings is in the humid subtropical or tropical climate regions, which are the parts of the world likely to be affected by global warming impacts the most [87]. This will lead to significant increases in the building operational energy use and related GHG emissions [5]. This was deeply investigated in the research of [88] by simulating the impact of climate change scenarios in two cities in Brazil with humid subtropical and tropical climates, respectively. They found that the mean annual outdoor temperature is likely to increase by 4.6 °C and 5.1 °C (respectively) by

2060. The total energy demand and related operational GHG emissions from heating and cooling in residential case-buildings located in humid subtropical and tropical climates can thus increase by 99% and 48%, respectively, compared to the 2020 figures. In addition, the related climate changes in the temperature and humidity profiles in humid subtropical and tropical climates can lead to a significant increase in the peak sensible and latent cooling loads [89,90]. As a result, the embodied emissions related to replacement of the technical systems may increase due to the need to provide more extensive cooling and ventilation system capacities.

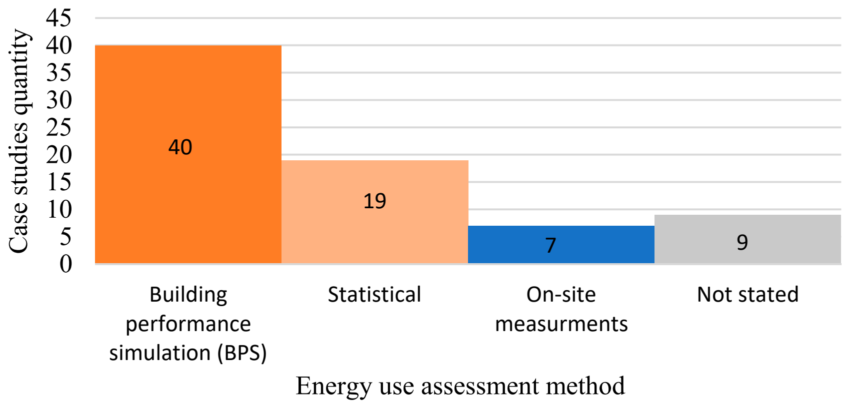


Figure A2. Energy use assessment methodology employed among 75 case studies.

Appendix B.2. Building-Related Features

Appendix B.2.1. Building and Climate Types

Globally, residential construction sectors differ in terms of energy efficiency and GHG emissions related to building types, construction materials, fabrication processes and transportation activity [91]. Moreover, different climate conditions have a direct impacts on the building design and operational energy use [92] and significantly contribute to GHG emissions. This systematic literature review focuses on the residential construction sector and contains 52 single-family (SF) buildings, 22 multi-family (MF) buildings and one zero-energy residential living laboratory (LL) case study building (Figure A3).

Most of the analysed case studies (43) are based on existing building stock, while the others (32) are based on the assessment of GHG emissions of newly built or designed residential buildings. Based on the collected case studies, it seems that there is a lack of life cycle GHG emission assessments of refurbished building stock. This can be identified as a research gap, since the need for GHG emission reduction in the existing building stock is apparent and urgent in both developing and developed economies [93].

The analysis further indicates that the number of case studies analysing residential buildings in tropical climates is limited. The collected literature data sample includes 18 case studies describing buildings located in tropical climate areas, while 57 case studies are based on constructions operating in humid subtropical climate areas (Table A2).

Appendix B.2.2. Building Lifespan

The building lifespan is a key factor that influences the total GHG emissions related to the building life cycle [94]. The estimation of a building's lifespan is mostly based on national regulations, research literature or construction market estimations. Particularly, the lifespan of a building directly influences the recurring GHG emissions by maintenance, repair, refurbishment or replacement in the building use life cycle stage [13].

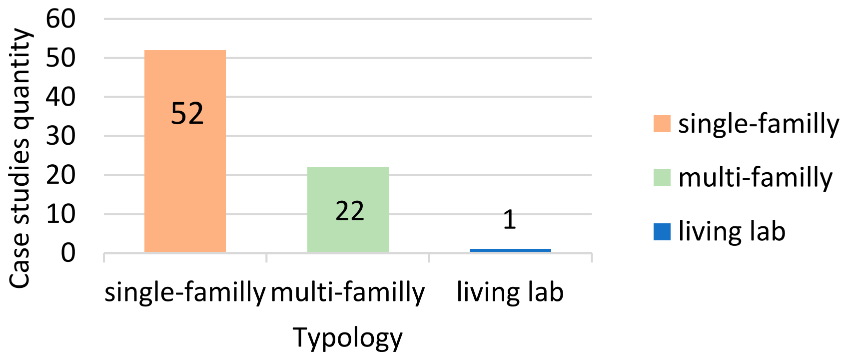


Figure A3. Residential building type distribution among 75 case studies.

The building lifespans in the collected case studies vary between 20 and 100 years (Figure A4), with 58% (41 case studies) having a 50-year lifespan. Case studies CS1 and 2AU, CS3-6AU, CS27CN and CS51JP emphasise, with a sensitivity analysis, the difficulties related to forecasting the precise building lifespan by testing the initial assumption. As an example, in CS1 and 2AU, changing the building service life from 50 to 75 years imposes a 12% reduction of annualised embodied GHG emissions. The estimated building lifespan can also depend on the housing quality class, especially in developing economies with high social and economic disparities, as in CS45-50ID, where low, medium and luxury housing classes have estimated building service lives of 25, 35 and 50 years, respectively. Studies CS57 and 58KR indicate that material durability is an essential factor influencing the lifespan of high-rise multi-family buildings. In these studies, changing the concrete from normal to a high-strength type resulted in an extension of the estimated building service life from 50 to 100 years and produced an 8% reduction of the annualised embodied GHG emissions.

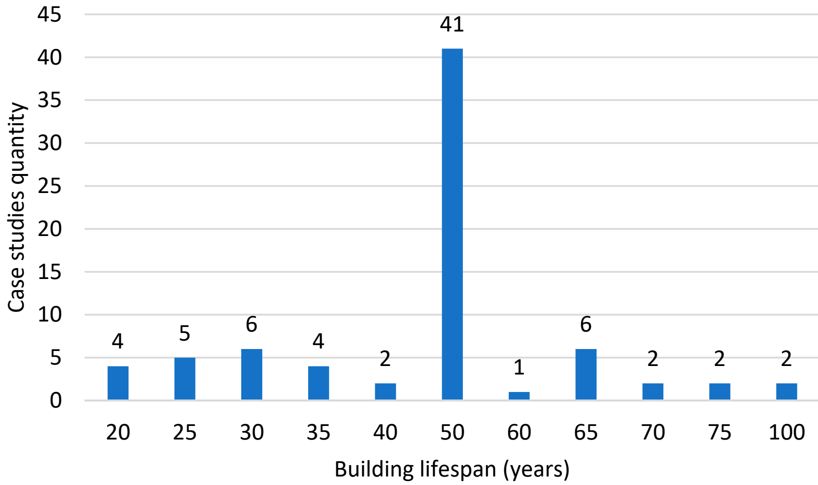


Figure A4. Building lifespan distribution among 75 residential buildings.

Appendix B.2.3. Building Structural Materials

The use of specific materials in building structures depends on the building type, construction regulations, local access and cost. The extensive literature indicates that reinforced concrete and steel-based building structures have the highest environmental impacts among traditional materials, while timber-based structures are widely characterised by low values of embodied GHG emissions [95–99].

In this literature review focusing on residential buildings, the primary structural materials vary between timber, steel, concrete, reinforced concrete, masonry (brick), stone, mud and different combinations of these (Figure 2).

The focus of bio-based materials applied in building structures is on industrialised types of wood, and the collected literature lacks a consideration of other bio-based forest or agricultural materials that are extensively accessible in tropical and humid subtropical climate regions [100]. This gap can be related to the economic development of bio-based materials, which is still in the early stages and faces several challenges in the construction industry related to scepticism from architects, insurers and contractors [101]. However, including bio-based building materials can effectively reduce the environmental impact of the construction sector.

The embodied GHG reduction potential related to the use of bamboo as a primary structural material was investigated by Yu et al. [102]. The results showed that the bamboo-based structures of residential buildings in Shanghai provided a 48% reduction compared to traditional clay brick-based structures.

Furthermore, a study performed by Zea Escamilla et al. [103] concluded that the transition to a low-carbon residential sector in the tropical Philippines would be much faster with the implementation of industrialised bamboo production than with industrialised wood production. Adding to this, the sustainable validity of bio-based agricultural products used in residential constructions in Argentina was investigated [104]. In that study, the life cycle analysis results showed that external walls based on straw bales and straw clay blocks had four- and threefold lower GHG emissions than fired-brick walls and had significantly better thermal performances.

One of the biggest uncertainties related to life cycle GHG emission assessments of buildings with extensive uses of bio-based materials is in assessing the biogenic carbon flows related to the sequestration and storage of carbon dioxide within a product. Currently, there is no scientific consensus on which accounting method is the most appropriate [105]. The most recent LCA calculation guidelines recommend separately including compensative GHG emissions in "additional benefits and loads beyond the system boundary" (module D) only if bio-based materials come from sustainably managed forests or cultivations in which total carbon pools can be assumed to be stable or increasing.

Appendix C. Result Harmonisation

The first step of the harmonisation procedure resulted in a narrowing of the initial literature sample, with 73 case studies that had a wide variety of total life cycle GHG emissions, between 310 $kgCO_2eq/m^2$ in CS1AU and 8407 $kgCO_2eq/m^2$ in CS33CN (Figure A5). The embodied GHG emissions varied between 66 $kgCO_2eq/m^2$ in CS15AU and $kgCO_2eq/m^2$ in CS36CN, and the GHG emissions connected with operational energy use varied from 0 $kgCO_2eq/m^2$ in zero-energy buildings CS19BR, CS35 and 36CN and CS67 and 69TH to 7111 $kgCO_2eq/m^2$ in CS33CN. The main causes of such a large range are related to the energy performance of the building and the GHG emission intensity of the electricity from the local grid, which varies between 0.23 $kgCO_2eq/kWh$ in Colombia (CS22CO) [34] to 1.20 $kgCO_2eq/kWh$ in Fuzhou (Figure 3).

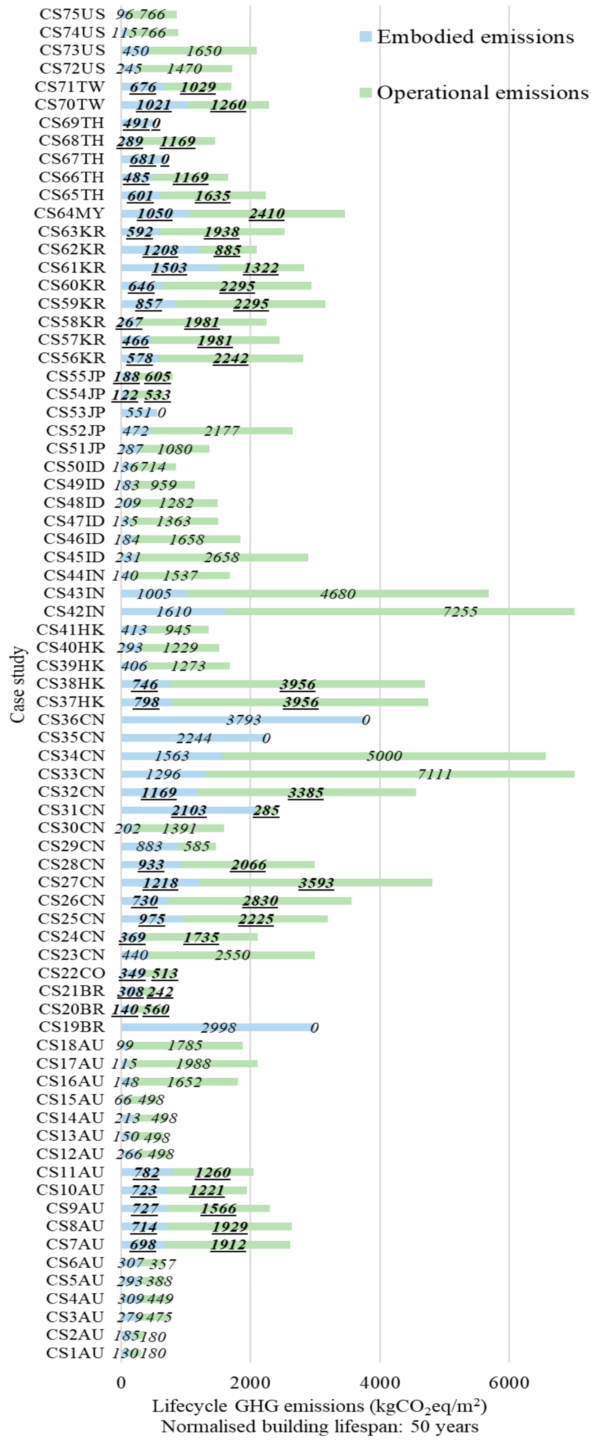
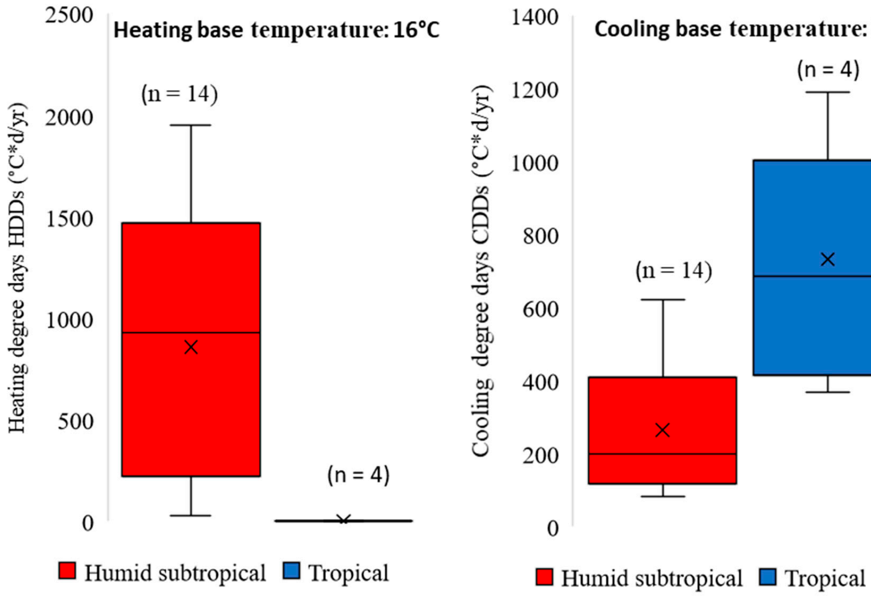


Figure A5. Harmonised embodied and operational GHG emissions from 75 case studies (bold and underlined values refer to the 36 case studies included in the final sample).



(**a**) (**b**)

Figure A6. Annual (**a**) heating and (**b**) cooling degree days in relation to the climate zone, based on 18 case study locations.

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PAPER IV

Feasibility study of an off-grid container unit for industrial construction. *Published in Sustainable Cities and Society (2020).*

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Feasibility study of an off-grid container unit for industrial construction

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ABSTRACT

This article presents solutions for improved energy efficiency by adapting a shipping container building in Shanghai for off-grid operation. While this prototype is based on a single unit, larger buildings made from multiple units constructed at factories is the ultimate goal. Previous studies of container buildings have revealed gaps concerning the quality of construction and thermal comfort. In this study, the heat transfer resistance of a typical container building wall has been improved from 1.0 m^2K/W to around 3.7 m^2K/W by installing Vacuum Insulation Panels (VIP), verified through measurements. VIPs reduce the temperature dependence of the heating need and the thermal bridges from the steel beams. Through validated building performance simulation using the software IDA ICE, the energy use and indoor air quality were examined for different ventilation scenarios and indoor temperature setpoints in Shanghai. A wider range of heating and cooling setpoints outside operation hours, lowering the heating setpoint at night and upgrading to triple glazed windows were found to be the most economic energy saving measures. Combined with roof rainwater harvesting, the possibility of achieving near self-sufficiency of water and electricity in the suburbs of Shanghai shows promise in the quest for a higher degree sustainable living.

1. Introduction

It is predicted that 60 % of the world's population will live in cities by 2030, increasing to 70 % by 2050 (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019). Worldwide, a 30 % increase in energy need for buildings is expected by 2040 (IEA, 2016). A recent review by Kristiansen, et al. (Kristiansen, Ma, & Wang, 2019), which this article builds on, reveals how Photovoltaics (PV) powered shipping container homes can provide affordable and decent zero energy homes with a 5–10 % reduction in material use. Compared to on-site construction it is also more sustainable because fewer leftover materials are left on site, more waste is recycled, transport to site is minimized and there are fewer accidents (Ferdous et al., 2019). Moreover, numerous studies claim that modular construction reduces the construction time by 50–60 % (Ferdous et al., 2019).

As China is projected to build a lot of substantial infrastructure works in the coming years through 'Belt-and-Road' initiatives, there is a need for transportable, decent, temporary housing. Constructing modular container modules that can be rearranged and upgraded and become permanent houses has become a viable alternative (Hui Ling, Tan,

Abbreviations: ACH50, Air Changes per Hour at 50 Pa pressure difference; AIVC, The Air Infiltration and Ventilation Centre (AIVC) is the International Energy Agency's information centre on energy efficient ventilation of buildings; CLO, The clothing insulation in clo, where 1 clo equals 0.155 m^2K/W [1]; DHW, Domestic Hot Water; EE, Embodied Energy; g, Solar Heat Gain Coefficient (commonly referred to as SHGC); GHG, Greenhouse Gas; HFM, Heat Flow Meter; HV, Hybrid Ventilation; HVAC, Heating, Ventilation and Air Conditioning; IEA, The International Energy Agency; IWEC, International Weather for Energy Calculation (database); LCA, Life Cycle Assessment; MBE, Mean Bias Error; MET, Metabolic rate in metabolic units where 1 met equals 58 W/m^2 [1]; MV, Mechanical Ventilation; NPV, Net Present Value; NV, Natural Ventilation; NZEB, Net Zero Energy Building; PM2.5, Particulate Matter with a diameter of less than 2.5 micrometers; PCM, Phase Change Material; ppm, Parts per million; PV, Photovoltaics; RMSE, Root Mean Square Error; SEER, Seasonal Energy Efficiency Ratio defined according to the European Union standards EN14511 and EN14825 as described in chapter 2.4.1.2 in [2], corresponding to China's domestic standard GB21455; SFP, Specific Fan Power; SCOP, Seasonal Coefficient of Performance, defined according to the European Union standards EN14511 and EN14825 as described in chapter 2.4.1.2 in [2], corresponding to China's domestic standard GB21455; VIP, Vacuum Insulation Panel; ZEB, Zero Energy Building

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& Saggaff, 2019)? Governments should see these as potential cities of tomorrow. In the suburbs of cities there is enough land to build single-story homes, which benefit from the space for PV on the roof.

A container home is selected for this case study, in which the steel provides fire resistance, longevity and high load-bearing capacity which allows large spacing between the columns (Dara, Hachem-Vermette, & Assefa, 2019; Ferdous et al., 2019). Steel structures can be as sustainable as wood, as long as the structural steel is reused (Dara et al., 2019; Tavares, Lacerda, & Freire, 2019). A container-based structure makes it easier to transport the building back to the factory for reuse and recycling at the end of its lifetime. A literature review by McConnell and Bertolin (McConnell & Bertolin, 2019) indicates that shipping containers are significantly cheaper than other prefabrication alternatives, and that they have high heat resistance with simple modifications. Still, the operational energy requirements is dominant topic in most studies of container buildings (Dara et al., 2019; McConnell and Bertolin (2019), although Tumminia, et al. (Tumminia et al., 2018) demonstrated that for a Net Zero Energy Building the material production dominates. Design solutions based on the reuse and recycling of buildings tend to win proposals because they reduce costs and environmental impact (Ginelli, Pozzi, Lazzati, Pirillo, & Vignati, 2020).

Based on the presentation of ZEB definitions in the review by Kristiansen, et al. (Kristiansen et al., 2019) it was chosen to focus on ZEB rather than Net ZEB or near ZEB, since this definition is easier for the public to understand and assures that the goal is to rely fully on solar energy in operation. Recently, off-grid container buildings have also been suggested more frequently lately (Bowley & Mukhopadhyaya, 2017; Daniel Satola, Dziedzic, & Gustavsen, 2019; Ginelli, Pozzi et al., 2020, 2020b), due to the potential of self-sufficiency. Although grid connection would be more economical in most cities [Bagalini et al., 2019], off-grid solutions are welcomed because they strengthen the focus on energy efficiency and motivates users to pay more attention to their energy use. The majority of the zero energy research projects have been located in Europe or the USA, where most researchers have focused on grid-connected net zero energy buildings that are built on site (Attia et al., 2017; Cao, Dai, & Liu, 2016; D'Agostino & Parker, 2018; Wells, Rismanchi, & Aye, 2018). There is, therefore, a need for studies on factory-made, off-grid zero energy buildings.

Shanghai is suitable as the location of a container home factory since Shanghai is the busiest harbor in the world (Wikipedia, 2020). Furthermore, 90 % of the world's shipping containers are produced in China (Olivares, 2010). The Chinese government strongly promotes building prefabricated buildings and has mandated that 15 % of the nation's annual new construction be built in a prefabricated manner by 2020 and 30 % by 2025 (Chang et al., 2018; Zhu et al., 2018). Certainly, prices for such buildings will fall as production increases. For example, Irulegi, et al. (Irulegi, Torres, Serra, Mendizabal, & Hernández, 2014) demonstrated that the unit cost was reduced by almost 30 % by increasing the production from 18 units to 489 units.

1.1. Water harvesting

While the global population has increased by 300 % during the 20th century, water demand has increased twice as fast (Şahin & Manioğlu, 2019). In India, several states have consequently made it mandatory to install rainwater harvesting systems on the roofs of new buildings in urban areas (Meera & Ahammed, 2006). The payback period for such systems is typically 2–6 years (Bashar, Karim, & Imteaz, 2018).

For arid regions, vapor compression condensing or an adsorption process can be used to extract water from the air. Atmospheric water-harvesting has seen clear progress during the last two decades (Tu, Wang, Zhang, & Wang, 2018). It is now considered a reasonable way to obtain water in arid or desert areas (Entezari et al., 2019). A review of atmospheric water harvesting by Tu et al. (Tu et al., 2018) points out that tank delivery or bottled water is expensive, while desalination depends on high operation and low maintenance costs to be viable for small scale applications. Through co-operation with solar energy, atmospheric water harvesting can provide a more sustainable solution. The optimal commercially available solution has an electricity use of around 250 Wh/kg. During periods with excess PV generation, this energy may be used to extract water from the air.

1.2. State of the art and research gaps

In the existing studies of buildings made from shipping containers and similar modular steel structures, control of heat gain through the windows and natural ventilation are often mentioned (Bohm, 2018; Cornaro et al., 2017; Irulegi et al., 2014; Taleb, Elsebaei, & El-Attar, 2019; Tumminia et al., 2018; Vijayalaxmi, 2010; Wang, Shi, Zhang, & Zheng, 2016). An overview of studies related to container buildings is included in Table A1. On the other hand, research has shown that hybrid ventilation can result in considerable energy conservation in warm and humid climates, in comparison to natural ventilation and mechanical ventilation for stand-alone systems (Axley & Axley, 2001; Haase & Amato, 2009). There appears to be no studies that focus on ventilation scenario assessment in container buildings. Therefore, it is necessary to clarify the interrelations between ventilation scenario, energy demand, peak loads, and indoor air quality in container buildings.

A recent study of a container home for the hot and humid climate in Port Said showed a problem with thermal comfort. Five different models with different 100 mm insulation layers all showed around 4000–5000 discomfort hours per year (Elrayies, 2017). Another study of a container building in a hot and humid tropical climate in India showed that the thermal indoor climate performance was as good as a traditional building with brick walls and cement mortar. However, this can largely be attributed to the attached cement shading roof with an overhang (Islam, Zhang, Setunge, & Bhuiyan, 2016). Consequently, it is not directly comparable. It is also not transportable and has higher embodied GHG emissions because of the concrete.

One reason for the thermal discomfort is often the high infiltration of outdoor air. The airtightness of four container buildings commonly used for temporary housing in Turkey was measured in a study, with Air Changes per Hour at 50 Pa pressure difference (ACH50) between 9-25 h^{-1} (Tanyer, Tavukcuoglu, & Bekboliev, 2018). An airtight building would have a leakage number in the range of $0.6-2$ h^{-1} for ACH50, which indicates the need to increase the quality of container sealings.

There is also a gap in the quality of construction. A container wall is more challenging to insulate than an ordinary wall. Foam insulation can be used to level the surface and create a seamless moisture barrier to prevent corrosion, but it is more expensive than ordinary insulation methods (Woods, 2020). If mineral wool is placed outside the foam insulation, an ordinary moisture barrier would not only reduce the diffusion of moisture from the room into the mineral wool, but also make the drying process very slow. A smart moisture barrier is probably the best solution, since it allows the wall to dry towards the inside during periods with low indoor humidity. The diffusion rate for a smart moisture barrier depends on the relative humidity on each side of the moisture barrier. During the winter, the relative humidity inside the building is higher than inside the external wall and the smart moisture barrier works like an ordinary moisture barrier (Dalehaug, 2017; Geving, 2012).

Various studies have tried to map energy efficiency in buildings (Evans et al., 2014; He, Yang, & Ye, 2014; Juan & Weijun, 2018; Shan, Wang, Li, Yue, & Yang, 2015; Wu, Zheng, You, & Wei, 2019), based on surveys performed in a variety of provinces in China. Out of the surveyed homes, 80 % had energy inefficient, single-pane windows (Evans et al., 2014; Wu et al., 2019). As for the wall construction layers, brick walls with a U-value of 1 W/m^2K were typically used (Shan et al., 2015). For cooking purposes, about 49 % of the surveyed households from the study of Wu, et al. (Wu et al., 2019) used a firewood-based stove, while the rest used gas-based (22 %) and electric stoves (19 %).

Poor indoor air quality is caused by the use of inefficient stoves and insufficient ventilation (Li et al., 2017). Based on measurements of indoor PM2.5 and CO_2 concentration, improvements in indoor air quality is found to be critical (Wang, Wang, & Wang, 2016).

To improve the thermal resistance of the envelope, Vacuum Insulation Panels (VIP) is considered. VIPs ($3-8$ mW/(mK)) have 5–10 times lower thermal conductivity compared to mineral wool, which makes it possible to achieve high thermal resistance without considerably reducing the already limited width of the container (Jelle, 2011). The design approach also involves a tiny and well-insulated space, similar to refrigerators, where VIPs are more commonly used. Because the area is small, the additional cost of using a more expensive insulation material will be less than in most buildings.

1.3. Aim and innovations

The aim of this article is to evaluate solutions for improved energy efficiency in a shipping container building. The goal is to work towards ZEB in an off-grid operation. By experiments and simulations, the performance of various designs are investigated. The targeted audience of the paper are architects, engineers working on building design, and HVAC and policymakers, who make regulations to ensure sustainable urban development. Due to the growing need for water supply in urban areas, rainwater harvesting is also investigated. Among the innovations are:

- The change in thermal resistance for a standard container building with 50 mm mineral wool insulation after adding VIPs is verified.
- Studies of different ventilation strategies for container buildings are missing in the literature. Therefore, natural, mechanical, and hybrid ventilation is simulated and compared.
- The relative energy use reduction and Net Present Value of several energy conservation measures are compared.
- Roof Rainwater harvesting is estimated to be able to supply the whole annual water demand in the container building.

2. Materials and methods

In this study, SketchUp, IDA Indoor Climate, and Energy (IDA ICE) software were used in the process, from developing the first 3D model of the building to simulating the energy need, indoor air quality, and thermal comfort. The floor plan was taken as input in IDA ICE 4.8 (EQUA, 2020a). IDA ICE is a whole-year detailed and dynamic multi-zone simulation application for the study of thermal indoor climate as well as for the energy use of an entire building (EQUA, 2020b). Building performance was assessed for a typical weather year in Shanghai (IWEC 2.0). The model does not take into consideration the local wind and shading conditions. Also, the energy use connected with equipment use was minimized, assuming that the occupants live a simple lifestyle for economic and environmental reasons.

2.1. Case study

The Shanghai climate entails an average outdoor temperature of 27 °C during the warmest months, while winters can be described as mild, with mean temperatures in the coldest month above 0 °C. During the entire year, relative humidity is high, usually over 70 %. The challenging summer conditions engender significant energy use and related GHG emissions connected with cooling and dehumidifying needs, in addition to the heating loads in winter (Goto, Ostermeyer, & Wallbaum, 2014).

As can be seen from Fig. 1, the south facade of the structure is shaded from the high summer sun, while the heat gain from the low winter sun can be utilized.

The energy demand for cooling and ventilation was reduced by utilizing cross ventilation through the window and door (Fig. 2). The indoor heat pump unit provides the space heating and cooling. To make our building independent of a sewage grid and to save water, a composting Separett waterless toilet was chosen (Separett, 2020). It is known to be clean and prevent odor (Morrison, 2020).

Table 1 presents the most important characteristics of the container building depicted in Fig. 2.

The dehumidification strategy is to lower the heat pump setpoint in order to provide dehumidification when excess PV power is available. A passive solar dehumidification concept based on multilayer moisture-permeable panels was investigated for possible future implementation, but the experimental test was not completed before the construction of the building (Cao, Tu, & Wang, 2019). The wooden furniture was also chosen to provide a buffer for the humidity. To reduce the accumulation of humidity inside the building from showering, a shower cabinet and extract ventilation from the bathroom was installed.

The PV system has a theoretical peak power of 5.5 kW and consists of 20 solar panels arranged in two rows of ten modules each. A total of 24 lead-carbon batteries were connected in a series, giving the pack an overall capacity of 48 V and 24 kW h.

2.2. Experimental activity

2.2.1. Test of VIP performance

To provide input data for the simulation, the thermal resistance of the VIP was measured. To independently test the performance of VIP in a container building, a standard container building was purchased (Fig. 3a) and VIP panels were taped to its walls and roof with double-sided tape (Fig. 3b). The thermal performance test and energy use analysis was conducted in Shanghai during the winter. The thermal resistance of the standard container building with 50 mm mineral wool insulation and without VIP had previously been verified to 1.0 m^2K/W. According to the parameters provided by the manufacturer (Panasonic, 2020), the theoretical thermal resistance of the VIP panels is 2.67 m^2K/W. The total thermal resistance of the wall, R_T, after installing the VIP was therefore expected to be 3.67 m^2K/W. To verify R_T, measurements and calculations were done according to ISO 9869 (ISO 9869-1:2014, 2014), except that the temperature sensors had an accuracy equal to instead of smaller than 0.5 K, meaning that:

- The temperature difference between the outside and inside was at least 15 degrees (during the VIP testing this was fulfilled 99 % of the time, with an average temperature difference of 20.5 °C and a minimum temperature difference of 14.6 °C).
- The sensors were mounted at appropriate locations, investigated by thermography (Fig. 3c). The sensors were not under the direct influence of heating or cooling devices or under the draft of a fan.
- The Heat Flow Meter (HFM) was not installed near thermal bridges.
- The surface temperature sensor was mounted close to the HFM.
- The test time exceeded the minimum recommended test duration of 72 h.

By evaluating the average values of the heat flow rate and temperatures over several days and neglecting the hours where direct solar radiation impacts the results, an accurate approximation to steady-state was achieved. Calculations of R_T were done according to the average method in ISO 9869 (Eq. (1)).

$$R_T = \frac{\sum_{j=1}^{n}(T_{si,j} - T_{se,j})}{\sum_{j=1}^{n}(q_{si,j} + q_{se,j})/2} \tag{1}$$

where T_{si} is the interior surface temperature of the wall [K]

T_{se} is the exterior surface temperature of the wall [K]

q_{si} is the density of the heat flow rate measured at the interior surface [W/m^2]

q_{se} is the density of the heat flow rate measured at the exterior surface [W/m^2]

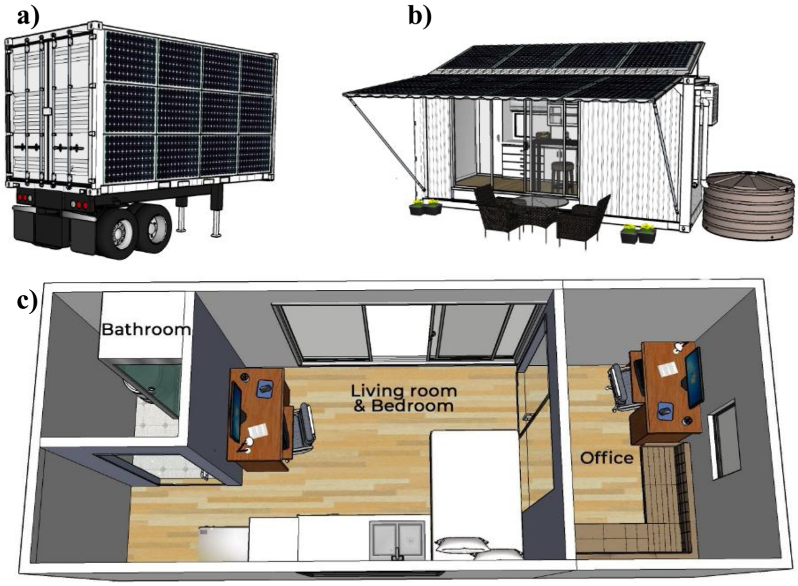


Fig. 1. Visualization of the case study building: a) during transportation, b) the south facade, c) top view.

j is the measurement number

n is the total number of measurements

It was assumed that there is a negligible lateral heat transfer. Consequently, a heat flow meter could be used to measure R_T. After the installation of VIP, the heat flow rate became low and the signal from the heat flow meter declined towards zero, making small disturbances having a large impact, which can be seen from the large fluctuations in Fig. 7. Consequently, better accuracy was obtained by using an average value of the outside and inside heat flow meter and removing the measurements between 7 AM and 5 PM that could be impacted by solar radiation. With additional measurements of the indoor and outdoor wall temperatures, the thermal transmittance of the building element (U-value) was calculated.

The thermal bridges before VIP installation were clear on the thermogram, as shown in Fig. 3c, thus it was determined that the installation of VIP could reduce the thermal bridges.

Fig. 4a shows the makeup of the wall. The sensors were mounted as illustrated in Fig. 4b. All sensor data were collected by the data collector Keithley 2700.

2.2.2. Validation of the simulation model

The energy model was verified based on monitoring data. Table 2 shows the specifications of the air-to-air heat pump that were used during the test. For the validation, a weather file made from measured weather data from an on-site weather station for the simulated period was used. In addition, the generic model of the air-to-air heat pump in IDA-ICE was adjusted according to performance data provided by the manufacturer. During the VIP experiment, the indoor temperature setpoint was set to 25 °C. It should be noted that this heating setpoint is higher than the ordinary heating setpoint in the building, which is 20 °C, since a 15 °C temperature difference between the outside and the inside had to be obtained.

Measurements were performed in Shanghai for seven days during the winter in January 2019 as well as for seven days during the summer in July 2019. The measured variables included indoor air temperature at three different heights, heat pump electricity consumption, ambient temperature, solar radiation, wind direction, and wind speed. The relevant parameters of the experimental sensors are shown in Table 3.

2.3. Model construction

Table 4 summarizes the design values that were used to simulate the energy need in IDA ICE. The passive house standard for the hot and humid climate (PHI, 2016) was used as a guideline establish stricter

Fig. 2. The prototype building as seen at Shanghai Jiao Tong University: a)the south facade, b) inside the living room.

Table 1
Container building characteristics.

External dimensions	Length: 9 m, Width: 3m, Height: 2.9 m
Heated floor area	21 m^2
Internal volume	54.6 m^3
Design occupancy	2 persons that are at home: Weekdays 5 pm-7 am and weekends 6 pm - 12 noon.
Window-to-wall ratio	19 %
Airtightness n_{50}	1/h
SCOP (heating) [Sarbu and Sebarchievici, 2016]	2.8
SEER (cooling) [Sarbu and Sebarchievici, 2016]	4.4
Electric appliances peak power	800 W

demand specifications than the Chinese Residential building energy efficiency standard DGJ 08-205-2015 DGJ 08-205-(2015) (2016).

By applying vacuum insulation panels, acceptable U-values were reached (Table 5), although the passive house standard was not achieved. Due to the limited budget, double glazing windows were used, although triple glazing, with a low g-value was assumed during the conceptual design phase. Fig. 5 shows the simulation of the U-value of the wall with symmetric boundary conditions at the short ends in THERM 7.7. The isotherms around the steel framing (black) show that these are thermal bridges. The U-value given in Table 5 includes the effect of the thermal bridges.

Table 5 summarizes the materials and total heat transfer coefficient for the constructed building envelop including floors, roof, and external walls.

A heat pump was used for heating and cooling. The appliance loads, in addition to the heat pump, can be found in Table A2. The peak power for electric appliances was set to 800 W.

The installed exhaust fan in the bathroom only has an on/off control with a constant airflow rate of 200 m^3/h, which equals 28 l/(s m^2) or 3.7 ACH. This airflow rate is 98 m^3/h higher than the design airflow rate for this building according to the EU standard EN 16798-1:2019 EN (1679)8-1:(2019) (2019), assuming two persons and a low polluting building. Fresh air is supplied by slightly opening the office window. The air overflows between the rooms through gaps in the doors.

The building was simulated with a heating setpoint of 20 °C and a cooling setpoint of 26 °C. A concentration below 1000 ppm is generally a sign of sufficient air change rate to dilute bioeffluents. Concentrations between 2000 and 5000 ppm are associated with headaches, sleepiness, and stuffy air.

Fig. 6 shows the building model from IDA ICE. Wind pressure coefficients based on AIVC recommendations for exposed suburban low-rise building locations. Pressure coefficients for openings were set to 0.75 for windows and 0.65 for internal doors (Heiselberg, Svidt, & Nielsen, 2001). The number of occupants was set to 2, with a clothing level equal to 1 ± 0.2clo and an activity level of 1.0 met (ISO (7730): (2005)(E) (2005)).

3. Results

In this section, the experimental results and model validation are first presented. Then simulation is used to evaluate alternative designs and schedules to provide a low energy need that is necessary to achieve off-grid ZEB in real operation but still maintain an acceptable indoor climate.

3.1. Experimental results

The thermal resistance of the building envelope (wall & roof) was increased from 1.0 m^2K/W to around 3.7 m^2K/W (Fig. 9a). Because the signal from the heat flow meter declined towards zero after installing the VIP, small disturbances caused large fluctuations, as seen in Fig. 7. In comparison, the measurements without VIP were much more stable, and from Fig. 8 it can be seen that the thermal resistance was around 1 m^2K/W, as expected.

Histograms (Fig. 9) were found to be more suitable than the average value in order to determine the trend, so as to avoid the impact of the measurement errors. Fig. 9(a) shows a peak between 3.6 and 3.8 m^2K/W, while Fig. 9(b) shows a peak between 1 and 1.05 m^2K/W.

The energy use for heating of the container was measured before and after the VIP installation. The relationship between the daily energy use of the heat pump and the average ambient temperature is shown in Fig. 10. It should be noted that environmental factors like solar radiation and wind speed also affect the energy use of the heat pump, but the ambient temperature is the main influencing factor. Fig. 10 only considers the effect of ambient air temperature. The energy use before VIP installation is 11.4–16.0 kW h/day, and the average energy use is 13.2 kW h/day. After the installation of VIP, the energy use of the heat pump was 7.0–8.7 kW h/day, and the average energy use was 7.9 kW h/day. Consequently, the average energy use after VIP installation was reduced by about 40 %. It can be clearly seen that the temperature dependence of the heating need is much less with VIP.

3.2. Model validation

Fig. 11b presents the differences between simulated indoor

Fig. 3. a) Standard container building, b) Test of Vacuum Insulation Panels (VIP) with thermocouples and heat flow meters, c) Thermogram of the walls before the installation of VIP.

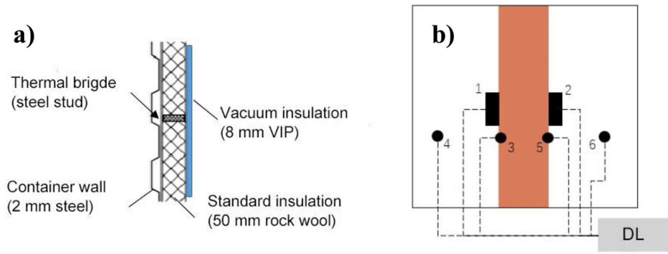


Fig. 4. a) Cross section of the wall and placement of sensors, b) The heat flow meters (1 and 2), the surface temperature sensors (3 and 5), and the air temperature sensors (4 and 6).

Table 2
Air-to-air heat pump specifications for GREE KFR-35W/FNhD02-A1 outdoor unit (corresponding to indoor unit model KFR-35GW/(35592)FNhAa-A1).

Cooling power (rated/min./max.)	3500/200/4200W
Heating power (rated/min./max.)	4900/500/5600 W + 1000 W (Additional electrical heating)
Cooling input power (rated/min./max.)	840/90/1300 W
Heating input power (rated/min./max.)	1450/120/1700 W
SEER	5.33
SCOP	3.53
Yearly COP	4.53

Table 3
Sensor parameters.

Sensor	Measurement	Type	Accuracy
Thermocouple	Wall temperatures and air temperatures in VIP testing in Section 5.1	T type	± 0.5 °C
Heat flow meter	Heat flow through the wall	HF-1A	± 3%
Electric meter	Heat pump electricity use	DDSD1352-C	0.01 kWh
Resistance thermometer	Indoor air temperature for validation of simulation	Pt 100	± 0.35 °C

Table 4
Demand specifications.

	Passive house standard for hot climate (PHI, 2016)	Chinese standard (DGJ 08-205-2015, 2016DGJ 08-205-2015, 2016)	Chosen design value
U-value External walls	< = 0.50 W/m²·K	< = 0.8 W/m²·K	0.26 W/m²·K
U-value for Roof	< = 0.50 W/m²·K	< = 0.70 W/m²·K	0.26 W/m²·K
U-value for Floor towards ambient air	< = 0.50 W/m²·K	< = 2.0 W/m²·K	0.99 W/m²·K
U-values for Doors and windows, including the frame	< = 1.25 W/m²·K	1.8 – 2.2 W/m²·K	2.8 W/m²·K
Solar Heat Gain Coefficient (SHGC) of windows	–	–	0.76
Normalized thermal bridge value	< = 0.03 W/m²·K	–	0.1 W/m²·K
Air leakage number at 50 Pa	< 0.60/h	< 1/h	1/h
Yearly average temperature efficiency of the heat exchanger *	> = 80 %	–	–
Minimum ventilation humidity recovery rate *	60 % in a humid climate	–	–
SFP	< =0.5 kW/(m³/s)	–	–

* Defined in the Appendix.

Table 5
Building partitions with their total heat transfer coefficient U [W/m^{2}K].

	U [W/m^{2}K]	Building materials from outside to inside
Floor	0.99	2 mm steel, 20 mm polyurethane insulation, 20 mm wood, 2 mm PVC
Roof	0.26	2 mm steel, 50 mm mineral wool, 8 mm VIP, 3 mm bamboo
External wall	0.26	2 mm steel, 50 mm mineral wool, 8 mm VIP, 3 mm bamboo

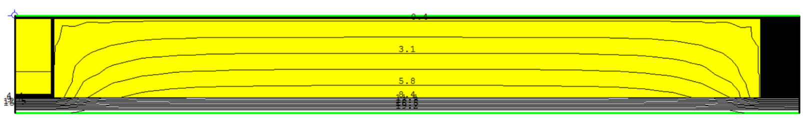


Fig. 5. Isoterms for the temperature in the wall between the outside at 0 °C and the inside at 20 °C. The green lines are the boundary conditions at the inside and outside, the yellow area is the mineral wool insulation, the black area is steel framing and the grey area is the VIP.

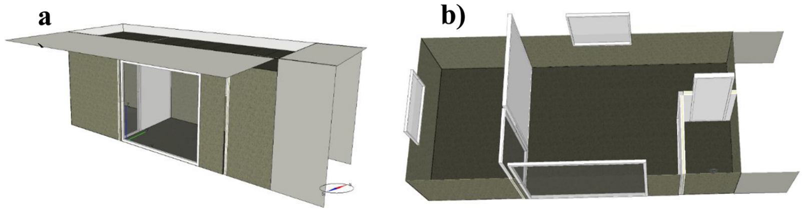


Fig. 6. Building model from IDA ICE. a) envelope with shading surfaces b) interior walls and openings.

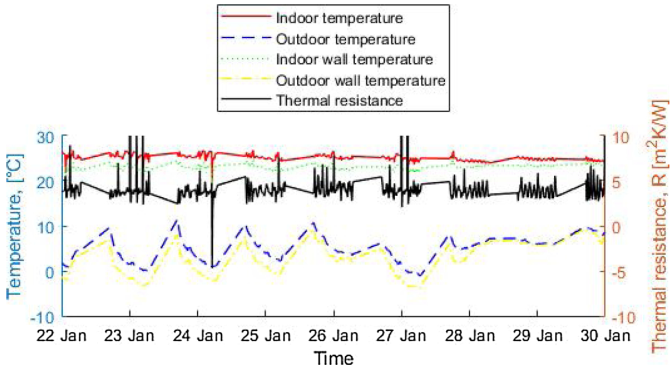


Fig. 7. Measured temperatures and calculated thermal resistance for the container wall with VIP, January 22-29, 2019.

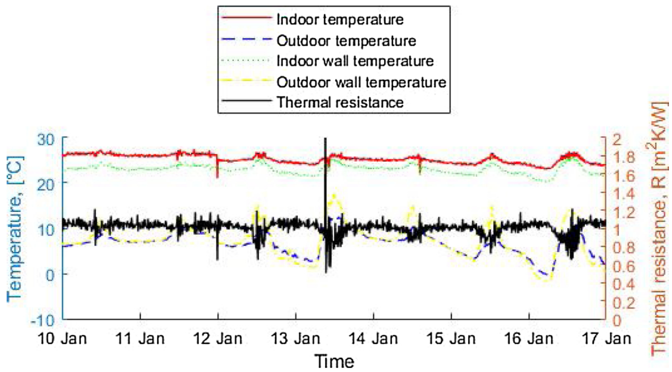


Fig. 8. Measured temperatures and calculated thermal resistance without VIP, January 10–17, 2019.

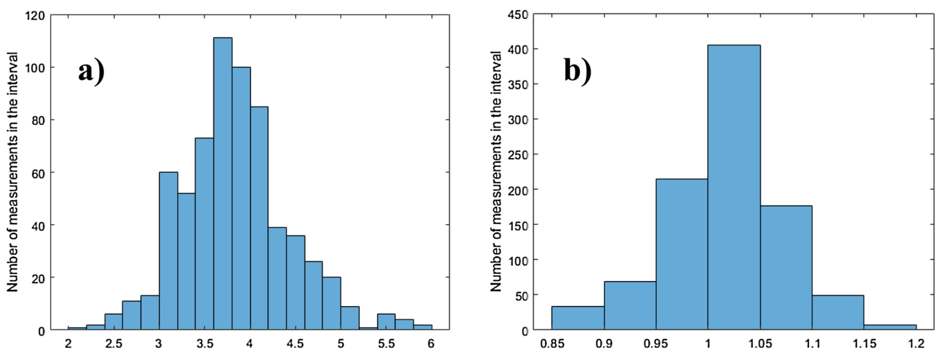


Fig. 9. Histograms for the measurements of thermal resistance: a) with VIP, b) without VIP.

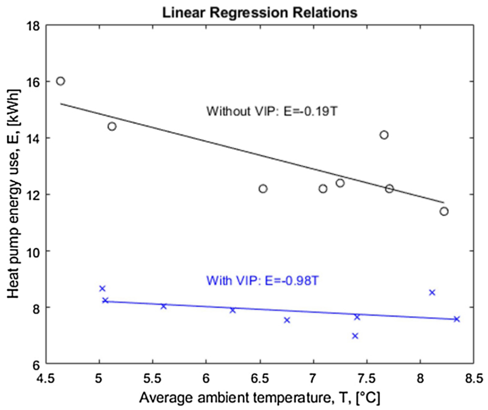


Fig. 10. Mean daily energy use with and without VIP as a function of ambient temperature.

temperature (T_s) and measured indoor temperature (T_m) during the space heating period 21.01–27.01 and the space cooling period 18.07 – 23.07. The time step of the data logging was one hour. The absolute error is below 0.5 °C for 85 % of the data during the week of measurements in January, while for 67 % of the data it is in the range of indoor temperature sensor accuracy of 0.35 °C (Fig. 11a). The Mean Bias Error (MBE) and Root Mean Square Error (RMSE), defined by Eqs. (3) and (4), for the same period was 0.13 °C and 0.36 °C, respectively.

$$MBE= \frac{1}{n}\sum_{i=1}^{n}(T_{s,i} - T_{m,i}) \tag{3}$$

$$R\ MSE= \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_{s,i} - T_{m,i})^2} \tag{4}$$

where

$T_{m,i}$ is the monitored temperature [°C]

$T_{s,i}$ is the simulated temperature [°C]

i is the measurement number

n is the total number of measurements

The measured electricity consumption of the heat pump in the heating mode (57.2 kW h) was 5% higher than the simulated one (55.5 kW h).

For the week in July, the differences between simulated and measured indoor air temperature were below 0.5 °C for 92 % of the data (Fig. 12a), while for 78 % of the absolute data error is in the range of indoor temperature sensor accuracy of 0.35 °C (Fig. 12b). For this validation period MBE and RMSE were 0.08 °C and 0.28 °C respectively. The measured electricity consumption of the heat pump in the cooling mode (31.3 kW h) was 2% higher than the simulated consumption (30.6 kW h).

3.3. Energy and indoor climate simulation

The simulation results are presented in the following subsections. Before Section 3.3.4, only exhaust ventilation is considered, as a base design scenario in the case building in Fig. 2. Firstly, in Section 3.3.1 the impact of different air change rates on the energy need, peak power, and indoor air quality in the form of the indoor CO_2 concentration are simulated. Secondly, the impact of four different heating and cooling setpoint schedules (Table 8) are analyzed in Section 3.3.2. Finally, several possible energy conservation measures, including different ventilation system types, are investigated in Sections 3.3.3 and 3.3.4.

3.3.1. The impact of different air change rates

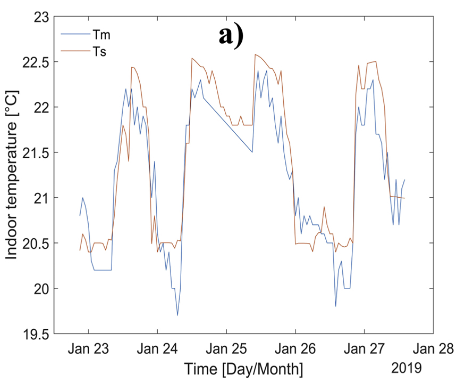
Table 6 presents the different simulated ventilation schedules.

The results in Table 7 show that the indoor air quality is clearly best when the extract fan is running whenever there is someone at home. There is little difference in electric energy need for the different schedules, except for heating, since no heat recovery is implemented. During the summer, the cooling need can be reduced mainly by operating the ventilation during the night, when the outdoor temperature is lowest.

For the “Present” schedule, Fig. 13 shows that the CO_2 concentration is kept below 800 ppm. The CO_2 level increases rapidly when the extract fan is turned off due to the limited room volume. The concentration is still far from reaching dangerous levels with any of these schedules. However, without an open window, there is likely to be problems with stuffy air, unless the extract fan is on whenever someone is at home. The “Present” schedule is therefore recommended unless power-saving measures during off-grid operation in the winter require the ventilation to be minimized.

Fig. 14 illustrates that reducing the ventilation rate significantly lowers the energy need as well, but other energy conservation measures that do not limit comfort are preferable.

Fig. 15 shows that it is possible to reduce the airflow rate of the extract fan to 68 m^3/h and still keep the CO_2 concentration below 1000 ppm over 7689 h a year. In comparison, the minimum requirement in the regulations would only provide a sufficient air change rate in less than 3000 h a year. An airflow rate of 68 m^3/h can be a reasonable compromise between indoor air quality and low energy need for this



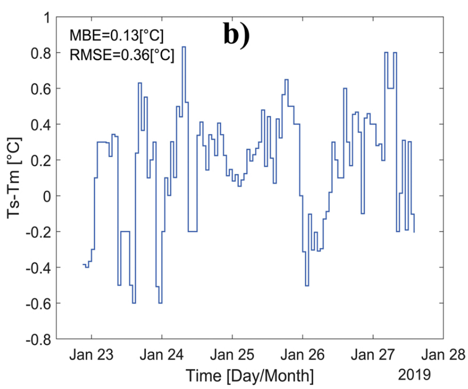


Fig. 11. a) Measured (T_m) and simulated (T_s) indoor temperature a week in January. b) Difference between simulated (T_s) and measured (T_m) indoor air temperature.

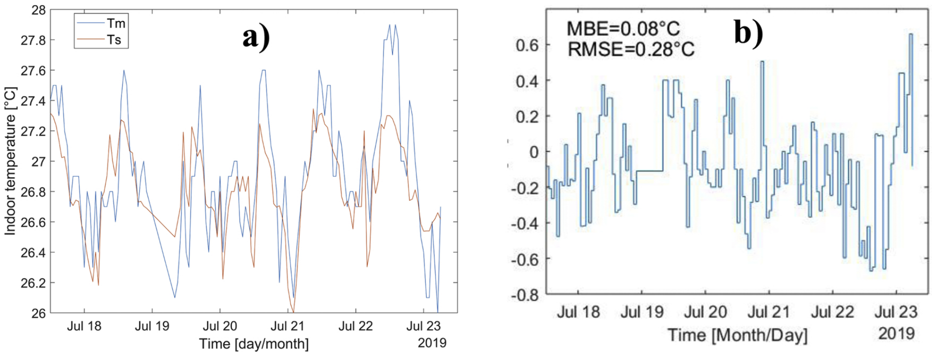


Fig. 12. a) Measured (Tm) and simulated (Ts) indoor temperature during a week in July.
b) Difference between simulated (Ts) and measured (Tm) indoor air temperature.

Table 6
Operation conditions and duration of extract fan simulation input.

Schedule	Operation condition	Time period	Duration [h]
Bathroom lights	The bathroom light is on	Sporadically	3
Bedroom	Occupants are sleeping	23:00 – 07:00	8
Present	Occupants are at home	17:00 – 07:00	14
Awake	Occupants are in the living room	17:00 – 23:00	6

Table 7
Simulation results for four different extract fan operation schedules.

	Extract fan operation schedules			
	Bathroom lights	Bedroom	Present	Awake
Indoor environment				
Duration CO_2 < 1000 ppm [h]	3543	3684	8760	5845
Electric energy need				
Heat pump, cooling [kWh]	698	704	797	760
Heat pump, cooling [kWh/m^{2}a]	33	33	37	35
Heat pump, heating [kWh]	594	891 (+50 %)	1167 (+96 %)	776 (+31 %)
Heat pump, heating [kWh/m^{2}a]	28	41	54	36
DHW [kWh]	941	941	941	941
DHW [kWh/m2a]	44	44	44	44
Appliances [kWh]	1032	1032	1032	1032
Appliances [kWh/m^{2}a]	48	48	48	48
Total [kWh]	3265	3568 (+9%)	3937 (+21 %)	3509 (+7%)
Total [kWh/m^{2}a]	153	166	183	163
Peak power				
Cooling (C) [kW]	1.02	1.03	1.03	1.03
Heating (H) [kW]	0.99	0.99	1	1
DHW [kW]	0.5	0.5	0.5	0.5
Appliances (A) [kW]	0.35	0.35	0.35	0.35
Total (C + H + DHW + A) [kW]	2.86	2.87	2.88	2.88

building, which is needed in order to reach ZEB.

3.3.2. *The impact of different indoor temperature setpoint schedules*

To investigate the impact of the alternative heating and cooling setpoint schedules in Table 8, simulations were done with an air change rate of 68 m^3/h for the "Present" schedule in Table 6. Intermittent heating or cooling is the most typically used operation pattern in China, but a drawback of this operation strategy is that it leads to a higher peak power demand. Intermittent heating or cooling in the case building resulted in temperatures as low as 10 °C and as high as 50 °C during non-occupancy hours.

From Table 9 it can be seen that the main effect of the energy conservation scenarios would be the over 40 % reduction in energy need for heating in scenarios 2 and 3. This is illustrated in Fig. 16. This is reasonable since the average temperature difference between the outdoor temperature and the heating setpoint in winter is much higher than the average difference between the cooling setpoint and the outdoor temperature in summer. Turning off the heat pump outside operation hours does not have a significant effect on the energy need, but strongly decreases the comfort, because it takes time to readjust the indoor temperature to the setpoint. Therefore, it is recommended to increase the temperature range outside operation hours, as in Scenario 2, unless energy shortage due to low forecasted PV generation is expected. All three scenarios increase the total peak power by 14–18 %. This may require an inverter with higher capacity, but that does not significantly impact the cost of the energy system, which is mainly decided by the PV and battery capacity.

Table 9 indicates that the indoor temperature falls outside the comfort range for part of the year. This probably occurs primarily when the occupants are sleeping during the winter, when they will have an insulation level higher than the standard indoor winter clothing that is assumed for the comfort simulation. Therefore, the occupants will likely not feel uncomfortable. Comfort category IV in Table 9 is based on EN-15,251 reference values and occurs when the indoor operative temperature is lower than 18 °C during the heating season or higher than 26 °C during the cooling season.

3.3.3. *Suggested energy conservation measures*

Table 10 presents various energy conservation measures that can reduce energy requirements. Particularly for off-grid buildings, these energy conservation measures can be cost effective because they reduce the need for investment in energy generation and storage capacity. Unless another reference is mentioned in the table, the impact of each energy conservation measure is provided, with reference to the built container building in Fig. 2, with constant temperature setpoints according to Table 8 and an air change rate of 68 m^3/h for the "Present" schedule in Table 6. The peak power remains unchanged at 3.01 kW due to the fact that the heat pump's maximum heating and cooling power is reached in all cases.

Lowering the U-values of the facade to 0.1 W/m^{2}K, for instance by tripling the VIP thickness to 24 mm, reduces the energy need for heating by 36 % without reducing the floor area significantly. Reduction of the door width does not significantly contribute to

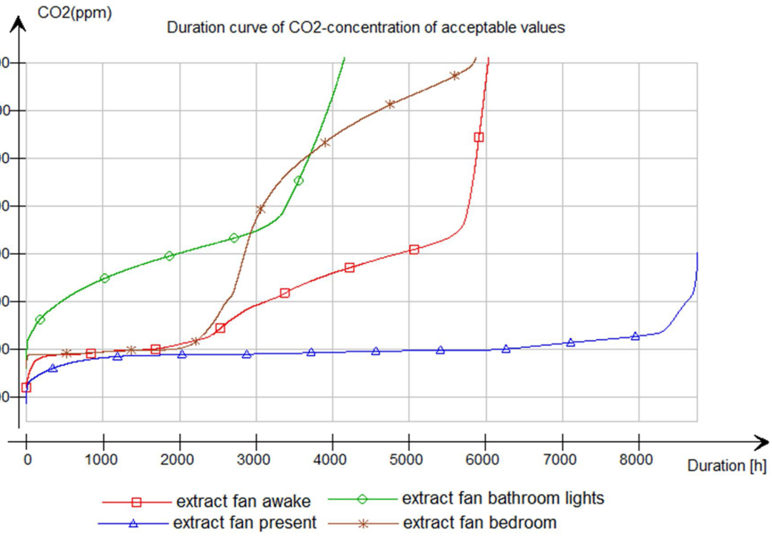


Fig. 13. Duration curve of CO2 concentration for four different ventilation schedules.

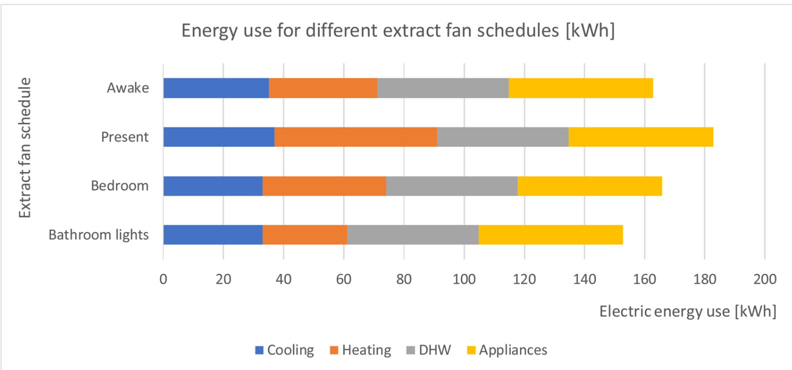


Fig. 14. Energy use for four different ventilation schedules.

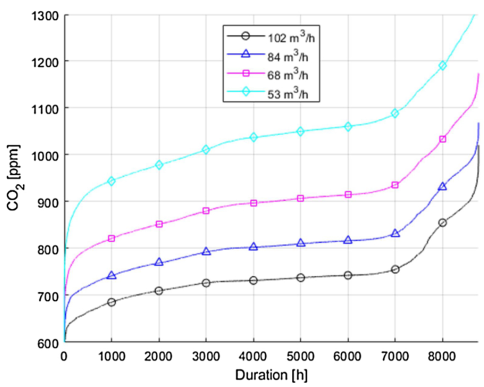


Fig. 15. Duration curve for different extract fan airflow rates for the "Present" schedule in Table 8.

reducing the heating requirement, since the windows also provide passive heating during the winter. However, reducing the width of the door makes it possible to place the door at the short end of the container. Thus the construction process might be simpler, since the container doors on the short end often must be replaced if a container is to be modified into a building. The energy and work required for strengthening the walls of the container to maintain its structural strength after cutting an opening will thereby be saved. A smaller window area towards the south that maintains good daylight conditions, while reducing the heat loss, is recommended in climates with cold winters. By upgrading to triple glazing with argon filling the U-value of the windows can be reduced to 0.7 W/m^{2}K. The price for such windows is around 4000 ¥/m^2 and they are around 25 % more expensive than traditional double layer glazing windows with air in the glazing gap. This energy conservation measure has a high impact on reducing both heating and cooling. Lastly, the reduction of the air change rate down to the Chinese standard can help to reduce the heating need and may, therefore, be an option during the coldest seasons.

Table 8
Heating and cooling setpoints.

Temperature schedule	Cooling setpoint	Heating setpoint
Constant	26 (00:00-24:00)	20 (00:00-24:00)
Energy conservation scenario 1	**Weekdays**	**Weekdays**
Wider range of heating and cooling setpoints outside operation hours	26 (16:00-07:00)	20 (16:00-07:00)
	28 (07:00-16:00)	15 (07:00-16:00)
	Weekends	**Weekends**
	20 (00:00-24:00	26 (00:00-24:00)
Energy conservation scenario 2	**Weekdays**	**Weekdays**
Wider range of heating and cooling setpoints outside operation hours and lower heating setpoint at night	26 (16:00-07:00)	20 (16:00-22:00)
	28 (07:00-16:00)	15 (22:00-16:00)
	Weekends	**Weekends**
	26 (00:00-24:00)	20 (06:00-22:00)
		15 (22:00-06:00)
Energy conservation scenario 3	**Weekdays**	**Weekdays**
Heat pump off outside operation hours and lower heating setpoint at night	26 (16:00-07:00)	20 (16:00-22:00)
	Off (07:00-16:00)	15 (22:00-07:00)
		Off (07:00-16:00)
	Weekends	**Weekends**
	26 (00:00-24:00)	20 (06:00-22:00)
		15 (22:00-06:00)

Table 9
Simulation results for alternative heating and cooling setpoint schedules with relative changes compared to constant setpoint in percentage.

	Constant setpoint	Scenario 1	Scenario 2	Scenario 3
Electric energy need				
Heat pump, cooling [kWh]	735	693 (-6%)	693 (-6%)	661 (-10 %)
Heat pump, cooling [kWh/m^{2}a]	35	33	33	31
Heat pump, heating [kWh]	755	671 (-11 %)	446 (-41 %)	440 (-42 %)
Heat pump, heating [kWh/m^{2}a]	36	32	21	21
DHW [kWh]	941	941	941	941
DHW [kWh/m^{2}a]	44	44	44	44
Appliances [kWh]	1032	1032	1032	1032
Appliances [kWh/m^{2}a]	48	48	48	48
Total [kWh]	3463	3337 (-4%)	3112 (-10 %)	3074 (-11 %)
Total [kWh/m2a]	163	157	146	144
Peak power				
Cooling (C) [kW]	0.83	1.01 (+22 %)	1.01 (+22 %)	1.06 (+28)
Heating (H) [kW]	0.88	1.05 (+19 %)	1.10 (+25 %)	1.10 (+25 %)
DHW [kW]	0.5	0.5	0.5	0.5
Appliances (A) [kW]	0.35	0.35	0.35	0.35
Total (C + H + DHW + A) [kW]	2.56	2.91 (+14 %)	2.96 (+16 %)	3.01 (+18 %)
Comfort category	No. of occupancy hours			
(EN-15251, with cooling)				
I (best)	408	408 (+0%)	399 (-2%)	349 (-14 %)
II (good)	827	827 (+0%)	825 (+0%)	742 (-10 %)
III (acceptable)	2364	2364 (+0%)	2646 (+12 %)	2488 (+5%)
IV (unacceptable)	136	136 (+0%)	124 (-9%)	282 (+107 %)

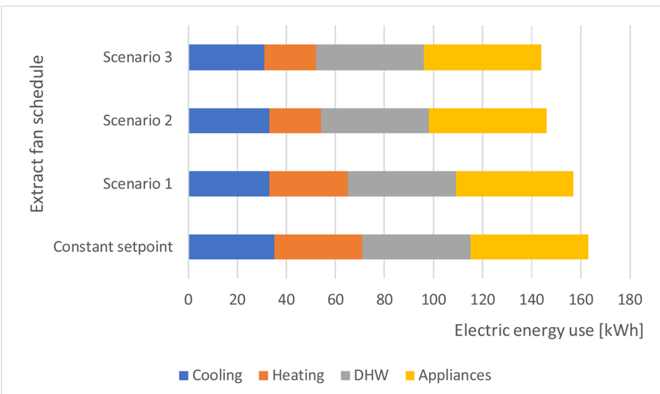


Fig. 16. Energy use for different heating and cooling setpoint schedules.

Table 10
Proposed energy conservation measures and impacts compared to the built reference case building.

Description	Electric energy need for heating		Electric energy need for cooling	
	[kWh/m²a]	Impact	[kW]	Impact
Improved insulation				
Base case (ref.)	21.2		31.5	
All surfaces U = 0.2 W/m²K	16.4	−23%	29.6	−6%
All surfaces U = 0.15 W/m²K	15.1	−29%	29.4	−7%
All surfaces U = 0.1 W/m²K	13.6	−36%	29.4	−7%
Reduced door width				
2.5m	20.4	−4%	31.5	−4%
2m	19.9	−6%	31.7	−5%
1.5m	19.4	−8%	29.8	−10%
Better windows				
U = 1.9 W/m²K g = 0.68	16.8	−21%	32.8	−1%
U = 1.1 W/m²K g = 0.56	14.6	−31%	31.7	−4%
U = 0.7 W/m²K g = 0.36	15.3	−28%	28.8	−13%
Reduced extract air flow rate				
53 m³/h (CN)	19.9	−10%	31.8	−4%

3.3.4. Evaluation of energy need for natural, hybrid and mechanical ventilation scenarios

To investigate whether a different ventilation strategy could further reduce the energy requirement, three different systems were simulated: Natural ventilation (NV), mechanical ventilation with heat recovery (MV), and hybrid ventilation (HV). Hourly load profiles were evaluated. The evaluation of the indoor air quality was limited to monitoring the CO_2 concentration in the office and living room. To meet the requirements of China's Indoor Air Quality standards, the upper limit was set to 1000 ppm (GB/T18883-2002, 2002GB/T3-, 2002GB/T18883-2002, 2002). In addition, the outdoor concentration was set to 400 ppm, and each person was assumed to generate 18 l/h of CO_2 (Persily & de Jonge, 2017).

3.3.4.1. Natural ventilation (NV). In the NV scenario, windows in the living room and office were opened to one-quarter of their maximum openable range when the indoor concentration of CO_2 in the occupied zone exceeded a value of 1000 ppm. The windows were shut when the indoor in-zone temperature fell below 16 °C during space heating periods or when temperatures exceeded 28 °C during space cooling periods. The hysteresis value of opening and closing windows was set at 300 ppm of indoor CO_2 concentration. If windows were closed, infiltration airflow was based on leak sizes, wind pressure and thermal buoyancy effects. The annual average infiltration rate was approximately 0.4 air changes per hour (ACH) when all windows were shut. Wind pressure coefficients were based on data recommended for low-rise buildings with exposed, suburban location and a length-to-width dimension ratio of 3:1 (Liddament, 1999).

3.3.4.2. Mechanical ventilation with heat recovery (MV). In the MV ventilation scenario, no windows were opened in spite of free-cooling conditions. The system was characterized as constant and balanced with a total airflow of 60 m³/h and supply air rates of 40 m³/h in the living room and 20 m³/h in the office. The exhaust air outlets were placed in the bathroom (40 m³/h) and office (20 m³/h). The utilized MV contained a heat recovery system with a rated thermal efficiency of 75 %. Power consumption for fans was estimated at 0.5 W/(m³/h) according to standard Chinese ventilation system data. Note that MV was only operational during building occupancy.

3.3.4.3. Hybrid ventilation (HV). The HV system was based on infiltration flow when indoor CO_2 concentration was below the zonal threshold of 1000 ppm. Otherwise, the system switched to MV mode.

A summary of the simulation results is presented in Table 11. The heat exchanger particularly reduces the energy need for heating for mechanical and hybrid ventilation. However, the recovered energy is outweighed by the increase in energy need for fans for mechanical ventilation.

Hybrid ventilation has the lowest total final electricity consumption, 11 % lower than for natural ventilation. The minor annual differences among the total final electricity consumption for all scenarios call into question the economic viability of implementing mechanical or hybrid systems with heat recovery based on the NPV calculation in Table 12. Maintenance and installation costs would further reduce this. Natural ventilation is therefore suggested from an economic point of view. The opening of windows can also provide the proper indoor CO_2 concentration in occupied rooms during the entire year, despite twenty hours with no wind conditions (Daniel Satola et al., 2019).

3.3.5. Economic consideration

To evaluate some of the suggested energy conservation measures, the Net Present Value (NPV) of the investments are calculated according to Eq. (5) with a discount rate of 4 % and an electricity price of 2.7 ¥/kWh. The high electricity price is due to the high cost for batteries and PV and is calculated in HOMER Pro (Energy, 2020) based on the market price for the current PV-battery system used in the demonstration building.

$$NPV = S\frac{1-(1+i)^{-n}}{i} - I \quad (5)$$

Table 11
Energy need and change compared to the base case for alternative ventilation strategies.

Ventilation scenario	Base case Exhaust 68 m³/h	NV	MV	HV
Electric energy need				
Heating (H) [kWh]	440	516 (+17 %)	332 (-25 %)	319 (-28 %)
Heating (H) [kWh/m²a]	21.2	24.0	15.4	14.8
Cooling (C) [kWh]	693	694 (+0%)	638 (-8%)	645 (-7%)
Cooling (C) [kWh/m²a]	33.0	32.6	29.7	30
Fan (F) [kWh]	41.7	0 (-100 %)	159.8 (+283 %)	112.2 (+169 %)
Total (H + C+F) [kWh]	1175	1210 (+3%)	1130 (-4%)	1076 (-8%)
Peak power				
Heating [kW]	1.1	1.07 (-3%)	1.07 (-3%)	1.07 (-3%)
Cooling [kW]	1.06	1.06	1.06	1.06

Table 12
Net Present Value of three suggested energy-saving measures.

Description of measure	Yearly energy cost before the measure [¥]	Yearly energy cost after the measure [¥]	Annual energy cost savings [¥]	Investment [¥]	Economic lifetime [years]	NPV [¥]
Add ventilation system	3,267	2,905	362	16,784 *	20	−11,867
Add 16 mm VIP	2,906	2,371	535	26,750 **	25 (Kim, Boafo, Kim, & Kim, 2017)	−18,394
Windows U = 0.7 W/m^{2}K	2,906	2,432	474	9,876 ***	25	−2,468

* Flexit C2 REL air handling unit. Mean annual temperature efficiency of 80 % in Shanghai at 150 m^3/h. ** 250 ¥/m2 *** 4000 ¥/m2.

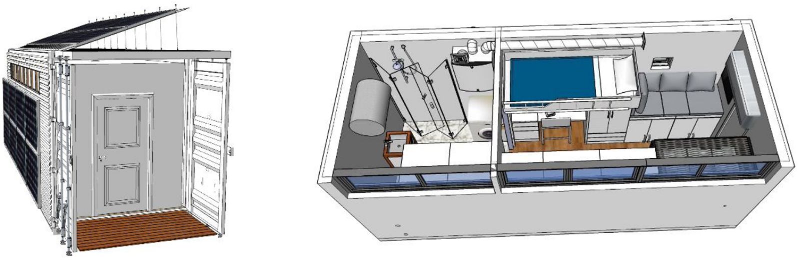


Fig. 17. Alternative design with daylight windows at the south facade.

where$S$is the annual energy cost savings
$i$is the discount rate
$n$is the economic lifetime
$I$is the additional initial investment

Table 12 presents the potential savings from three of the evaluated energy-saving measures. Because the initial energy use is already low, the annual energy cost savings due to the energy saving measures are also low. Consequently, the investments are unprofitable, unless the installed battery and PV capacity can be reduced. Improved windows are the most profitable option, but is still not cost effective since the investment is higher than the NPV of the annual savings. Here all 9.9 m^2 with windows and glass doors are replaced.

Based on these results, another solution would be to reduce the window area in order to reduce the investment cost. Even the best windows we have suggested have far higher U-value than the wall, so this will contribute to significant savings. An alternative design is sketched in Fig. 17.

3.4. Potential for rainwater harvesting

Lastly, to investigate the possibility of water self-sufficiency, the potential for water harvesting is briefly evaluated. Zhou and Tol Zhou and Tol (2005) found that the mean annual water consumption per capita varies from about 26 m^3/person in Shanxi province to 107 m^3/person in Shanghai. Water consumption is influenced by the characteristics of an individual as well as the efficiency of showerheads and tap fittings (Silva, Sousa, & Carvalho, 2015). In homes, around 25 % of the water is used for toilet flushing (Şahin & Manioğlu, 2019). By assuming a restrictive use of water, equal to that of Shanxi and withdrawing 25 % since a composting toilet does not use water, we can estimate a yearly consumption of 20 m^3/person, which equals 55 L per day.

Shanghai has a high mean annual precipitation of 1200 mm. Filter efficiency is specified by the manufacturer, commonly 90 %. For the container building in Figs. 1 and 2, if both roof surfaces are used for water harvesting and the drainage coefficient is 85 % for a metal roof with PV panels, there is a potential to harvest 25 m^3/year for the 27 m^3 roof or 50 m^3/year if the shading roof is used as well. A study by Zhang, et al. (Zhang, Zhang, Yue, & Jing, 2019) projects that the mean annual rainfall in China is going to increase by 2.7 %–62.0 % in the period 2020–2050, due to climate changes, leading to an increased potential.

4. Conclusions

This article has evaluated alternative solutions to improve energy efficiency in order to prepare a solar-powered shipping container building for off-grid operation. VIP is proven to have an excellent insulation performance, although the fragile design and the high price is currently a concern.

Key results include:

- A full-scale experiment showed that the thermal resistance of a container building envelope increased from 1.1 m^{2}K/W to 3.7 m^{2}K/W by applying 8 mm VIP insulation.
- Natural ventilation can provide comparable indoor air quality as mechanical ventilation with heat recovery for the described case study, with only 7% higher annual energy need for heating, cooling, and ventilation.
- Hybrid ventilation has the lowest energy need, but for a single container building in a subtropical climate, the 11 % difference compared to natural ventilation is not large enough to justify the investment based on a Net Present Value evaluation of the annual savings.
- Upgrading from double to triple glazing windows or reducing the window area was the most economical way of improving the energy performance of the case study building.
- Roof rainwater harvesting may be able to cover the entire need for water for the container home in Shanghai, although it is recommended to purchase drinking water.

Based on these results, further research should investigate control strategies and the inclusion of thermal storage to optimize the utilization of the PV generation. Subsequently, off-grid operation should be simulated and tested. How micro-grids with other energy sources can reduce the investment in the off-grid energy system should also be investigated. Improved strategies for dehumidification would also be important to secure a healthy indoor climate. In future research on ventilation of container buildings, the impact of outdoor Particular Matter (PM) should be included, together with possible filtration methods. A Life Cycle Assessment (LCA) should also be performed in order to compare the emissions for construction and building materials from this design compared to a conventional building. Finally, an LCA study of modular, container buildings in China, particularly with the off-grid energy-system design scenario, seems to be missing in the literature.

Declaration of Competing Interest

None.

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Appendix A

"Yearly average temperature efficiency of the heat exchanger" of 80 % means that 80 % of the energy is recovered from the exhaust air over the year, which reduces the need for heating and sensible cooling through the heat pump in our case.

$$\eta_T = \frac{t_{rec} - t_o}{t_e - t_o}$$

where t_{rec} is the supply air temperature after the heat exchanger [ºC]

t_e is the exhaust temperature [ºC]

t_o is the outdoor air temperature before the heat exchanger [ºC]

For application in warm and humid climates, the use of heat exchangers with moisture recovery is recommended in order to reduce the entry of moisture into the home from outside and related energy related to latent cooling and dehumidification needs.

Minimum ventilation humidity recovery rate of 60 % means that the heat exchanger be able to remove a minimum of 60 % of the moisture from the supply air by transferring it to the extract air to reduce the need for dehumidification (from the heat pump in our case).

$$\eta_x = \frac{x_o - x_{rec}}{x_o - x_{ext}}$$

where x_{rec} is the absolute humidity of supply air after the heat exchanger

x_{ext} is the absolute humidity of the extract air

x_o is the absolute humidity of outdoor air before the heat exchanger

Table A1 presents the most relevant related studies found in the literature, which focus on low energy need, passive solutions for heating or cooling, indoor climate or life cycle assessment. All these factors are important in order to achieve a sustainable ZEB building.

Table A1
Case studies of residential buildings related to container buildings (* Simulations (S), Experiments (E), Life cycle assessment (LCA)).

Author and year	Building type and climate according to Köppen-Geiger classification (Beck et al., 2018)	Location	Assessment method *	Learning outcomes and comments related to the project
Tavares, et al. (Tavares et al., 2019) 2019	One-story house. Dry-summer subtropical climate (Csb).	Aveiro, Portugal and 7 simulated locations	S (simulation), E (experiment), LCA	Evaluation of alternative structure materials. Focus on the embodied emissions (EE). The results are impacted by the 100 years estimated lifetime, significantly longer than most studies. Light steel or timber framing has the lowest GHG and EE emissions, compared with traditional concrete or steel-based structures. Operational energy, ventilation or thermal comfort is not considered.
Dara and Hachem-Vermette (Dara & Hachem-Vermette, 2019) 2019	Single-family house made from upcycled shipping containers. Continental Subarctic Climate (Dfc).	Calgary, Canada	S, LCA	The operational phase contributed to 85 – 95 % of the life cycle impacts. Over a 50 years lifespan upcycling steel-based shipping containers and reusing them for housing caused lower environmental impact than a wood-based housing. Upcycling a 12.2 m shipping container could save 8000 kW h that would be needed to melt and re-manufacture the steel. In 2018 there were enough leftover containers in Canada to cover 18% of the need for single-detatched houses.
Taleb, et al. (Taleb et al., 2019), 2019	Container home in a subtropical desert climate (BWh)	Aswan, Egypt	S, E	Green roofs and green walls were used to act as an insulation layer for the container envelope. Triple glazing windows with low-emissivity film played a key role in reducing the cooling load.
Bohm Bohm (2018), 2018	Container building in a warm, humid climate (Dfb).	Buffalo, USA	S, E	Thick walls, modest windows, structurally insulated panels with little thermal bridging, triple-panel windows with low-e coating. Natural ventilation with manually operated wooden hatches that are closed and filled with insulation during the winter. Good thermal comfort due to airtight and well-insulated envelope and separate thermal zones.
Tumminia, et al. (Tumminia et al., 2018) 2018	One-story NZEB office building with a container-like structure in warm summer and cold winter climate (Csa).	Sicilia, Italy	S, E, LCA	Low emissivity windows, lights controlled by illuminance dimming and presence sensor. Use natural ventilation, but it is found to be undesirable during the warm summer and limited during the cold winter due to thermal comfort. Materials use contributes to 72 % of the total environmental impacts and are recommended to be given more attention.

(*continued on next page*)

Table A1 (*continued*)

Author and year	Building type and climate according to Köppen-Geiger classification (Beck et al., 2018)	Location	Assessment method *	Learning outcomes and comments related to the project
Cornaro, et al. (Cornaro et al., 2017) 2017	Container building in a semi-arid, cold climate (BSk).	Irvine, USA	S, E	Patio with shading of the south façcade. Solar chimney for natural ventilation.
Elrayies Elrayies (2017) 2017	Single story building in a tropical and subtropical desert climate (Bwh)	Port Said, Egypt,	S	5 models with different insulation levels. Closed-cell spray polyurethane foam was found to provide the best thermal comfort, followed by straw. Crossflow natural ventilation. Thermal comfort studied according to EN 15251:2007. The thermal comfort was unacceptable 20 − 55 % of the time, depending on 7 simulated locations.
Wang, et al. (Wang, Shi et al., 2016) 2016	Zero Energy solar house in a semi-arid, cold climate (BSk).	Datong, China	S, E	Adjustable shading, natural ventilation, heat storage, atrium, double layer roof with south overhang, PCM, night cooling. Thermal comfort through controllable shading and ventilation with the atrium as a buffer zone.
Islam, et al. (Islam et al., 2016) 2016	Double-story home with container structure in a temperate climate (Cfb).	Mel-bourne, Australia	S, LCA	Doubles the building width to 4.9 m by connecting two standard 40-inch (12.2 m) containers horizontally. Use low emissivity windows. The study does not discuss ventilation and thermal comfort. More than 17 million used shipping containers are available globally and reusing them for buildings saves materials and reduce embodied emissions.
Irulegi, et al. (Irulegi et al., 2014) 2014	Solar house (54 m^2) with ventilation (90 % energy recovery in warm summer and cold winter climate (Csa).	Madrid, Spain	S, E	Prefabricated Cross Laminated Timber (CLT) structure. Highly insulated walls, shading and cross-ventilation during the summer, solar heat gain during the winter, thermal mass and PCM to flatten the temperature peaks. Hybrid ventilation, mainly cross-ventilation.
Vijayalaxmi Vijayalaxmi (2010) 2010	One-story home with container structure in hot and humid climate (Aw).	Chennai, India	E	Energy conservation from natural ventilation (comfort ventilation), building orientation and shading from trees. 59 % reduction in embodied energy due to the reuse of a shipping container, which was upgraded with an extra cement roof with overhang. The same average indoor temperature as in a traditional building.

Table A2 presents the load of the container building, in addition to the heat pump. Based on calculations that assume water-saving taps and an efficient use of hot water in order to live off-grid, the daily energy need for hot water for handwashing, showering and cleaning for two persons is estimated to be 3 kW h/day with a peak load of the electric water heater of 500 W and an efficiency of 0.96.

Table A2
Rated power and duration of the use for the technical equipment and lighting.

Internal loads	Power [W]	Duration per day [h]
Booster pump	100	1
Laptop	90	8
Fridge	13	24
Exhaust fan from composting toilet	3	24
Extract fan, bathroom	8	Not set
LED lights, living room	10	6
LED lights, bathroom	10	3
LED lights, office	10	3
Crock-pot (slow cooker)	100	8
Electric water heater	500	6
Other plug loads	73	24

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PAPER V

Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study. ***Published in Building and Environment (2020)***

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Comparative life cycle assessment of various energy efficiency designs of a container-based housing unit in China: A case study

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ABSTRACT

Providing sustainable and affordable housing in rapidly developing regions in East Asia is an essential need, which can be satisfied by the market implementation of prefabricated, modular units, with a high energy-efficient performance. This study presents a comparative analysis of a factory-made residential unit, produced and located in Shanghai, China. A combination of energy analyses and life-cycle assessments is performed to quantify the life-cycle impacts related to various energy efficiency designs (convectional, low-energy, net-zero energy and off-grid) of a building module, developed from a new shipping container. The life-cycle assessment results indicate that the net-zero energy design strategy has the lowest life-cycle impacts in all categories, with 26% reduction in water consumption and up to 86% reduction in terms of global warming potential with respect to the convectional, baseline design. The ambition of becoming independent from the local electricity grid in the off-grid design results in nearly two-fold larger PV system when compared to the net-zero energy design, resulting in average 59% increase of total life cycle impacts. The sensitivity analysis shows that projected climate change effects have a minor influence on the life-cycle impacts, whereas the potential reuse of the building structure provides significant environmental benefits. Comparison with existing literature studies demonstrates the significant GHG emissions mitigation potential related to the implementation of off-grid and zero energy buildings in rural, remote, or post-disaster areas with limited electricity access and energy facilities based on fossil fuels.

1. Introduction

China is the country that uses the most energy in the world. Moreover, it is the emitter of nearly 30% of all worldwide greenhouses gases (GHGs) [1]. The construction sector is responsible for 40% of the national carbon emissions [2] and for nearly 40% of municipal solid wastes, of which only 5% is recycled [3,4]. Indeed, nowadays, China accounts for around 50% of all new construction globally, and together with India is expected to contribute to 48% of the increase in the global primary energy demand and related carbon emissions between 2020 and 2040 [5].

To mitigate the environmental impacts related to the building life-cycle, the central government of China has enforced a wide range of policies related to energy efficiency. Despite achieving promising outcomes, most policies and initiatives have taken place in the megacities, whereas they do not take into consideration the reduction of environmental impacts of residential buildings located in rural and remote areas. Housing in these areas is characterised by weak thermal resistance and inefficient stoves based on coal or local biomass [6]. Consequently, occupants lack thermal comfort and significantly contribute to harmful environmental impacts related to the incomplete combustion of non-sustainable fuels [7]. With 43% (600 million) of the Chinese population living in rural areas, developing a decent housing solution with access to clean energy is a crucial need for dealing with challenges interrelated to energy poverty, GHG emissions, outdoor air pollution, energy efficiency, and renewable energy. Additionally, because China plans to build a lot of infrastructure in the coming years through the Belt-and-Road initiatives [8] there is a need for research and market development of transportable, decent temporary houses which can also operate in remote areas without or with limited connection to the

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conventional electricity grid.

To address these environmental problems and to speed up building construction, the Chinese government is actively promoting building prefabrication technology, and mandated that 15% of the nation's annual new constructions should be built in a prefabricated manner by 2020, with the target rising to 30% by 2025 [9]. In 2016, less than 1% of new construction was built in an industrialised approach [10]. Chinese state media reported that by 2019 there has been an increase in prefabricated construction, but still, less than 5% is built using prefabricated components. However, the target of 30% is still being pursued.

According to four different studies, prefabrication presents the potential to reduce construction waste by 50% on average [11–14], and energy consumption by about 20% [15]. A review presented a decade after the Chinese government released the *China Act on the Energy Efficient of Civil Buildings* in 2008 showed that the building demolition phase is a major area with huge improvement potential. Design for recyclability and reuse of materials were pointed out as areas that had to be prioritised in the construction sector [16].

A review by Kristiansen, Ma & Wang, 2019 [17] presents how photovoltaic (PV) powered homes based on a steel-container structure can provide affordable, decent housing solutions and contribute to an increase of prefabricated construction in China. An LCA approach is crucial for identifying and assessing environmental trade-offs between operational and embodied emissions, for instance, from photovoltaic panels and energy storage. Several researchers have investigated the life-cycle impacts associated with energy-efficient and prefabricated housing solutions. Dong, Wang & Li, 2018 [18] performed a cradle-to-grave life-cycle GHG emissions assessment of a temporary house (30 m^2) with a renewable energy PV system, located in a warm and humid climate in China. The net-zero-energy design based on a steel structure with estimated building lifespan of 20 years resulted in 54.5 $kgCO_{2eq}/m^2a$ life cycle emissions. The life cycle impact of a net-zero energy building fabricated with extensive use of PV systems (5.8 kW) operating in Sicily, Italy, was investigated by Tumminia et al., 2018 [19]. The total life cycle GHG emissions related to a 45 m^2 building module production characterised by 25-year building lifespan was estimated to be 57.9 $kgCO_{2eq}/m^2a$. The potential of reusing the steel containers for housing purposes was considered in the research performed by Dara, Hachem-Vermette & Assefa, 2019 [20]. A case study based on Canadian modular, grid-connected single-family building with an estimated life span of 50 years, energy-efficient insulation, and a building structure based on a reused shipping container resulted in a figure of 111 $kgCO_{2eq}/m^2a$ for total GHG emissions, with the dominant share (95%) of emissions originating from the building operation and use phase. Here, on account of significant annual energy consumption, life cycle GHG emissions are nearly two-fold higher than in the two previously mentioned studies and indicate the high potential of the zero-energy design approach to mitigate life-cycle environmental impacts of residential buildings. Another research conducted by Islam and Zhang, 2016 [21] shows that reusing a container as a building structure leads to the lowest embodied energy and GHG emissions per m^2 compared to 13 other prefabrication alternatives.

Based on the analysis of results of existing literature (Table A1 in the Appendix), there seems to be a limited number of studies about the life-cycle assessment of modular buildings in China, particularly which are characterised by low-energy and net-zero energy efficiency performance levels. Additionally, there seems to be a research gap regarding life cycle assessments of energy-self-sufficient (off-grid) residential buildings. To fill this gap and increase the number of studies on modular buildings in China, the authors explore the environmental impacts related to the life cycle of various energy efficiency designs of a transportable, modular housing unit.

2. Description of case building designs

The case building is designed as a prefabricated, affordable, and transportable housing unit intended for developing areas in China and East Asia. The city of Shanghai is the building study location, as well as, of the building manufacturing location. The pilot construction was built in Shanghai. The building superstructure is based on a new shipping container, which is mainly constructed from weathered (Corten) steel. The residence is on a single level and features a living room/bedroom, office space, and a bathroom (Fig. 1). The entire building is 9 m long, 3 m wide and 2.9 m high. The total gross floor area is 27 m^2, and the total net floor area is 21 m^2, with an internal volume of 54.6 m^3. The building is designed for two occupants.

This study aims to compare the life-cycle environmental impacts related to different designs of the case-study building, presenting a transition from the conventional (base design) to designs with upgraded energy efficiency and with local renewable harvesting technologies considered. The key differences between the building designs lie in the thermal properties of the building envelope and in technical systems which are described in detail in Table A2 in the Appendix.

The building designs are characterised as follows:

1) Design 1, base design (Fig. 2):

Serving as a reference model, this design corresponds to the already constructed, cost-effective building module which constitutes a living laboratory located in Shanghai Jiao Tong University. A transportable building module is practical because it can be placed anywhere that can be accessed by a truck or a cargo ship. It can later be removed without leaving waste or permanent harm to nature. The insulation of the external building partitions is made of a mineral wool wall and an 8 mm thick layer of vacuum insulation panels (VIP). The use of VIP makes it possible to achieve high thermal resistance without significantly reducing the already limited width of the container and enabling transportation on a truck. The implementation of an aluminium frame roof awning from the south side protects the facade from extensive solar heat gains.

2) Design 2, low-energy design (Fig. 3):

In this design, more attention was given to improving the thermal comfort and considering that for remote locations, there might not be access to public water supply or sewer. As the insulation needs to be added on the inside to limit the module width for transportation on a truck, VIP is suitable because it increases the floor area by 6 m^2 compared to if only mineral wool had been used. Several measures were implemented to improve the energy efficiency and reducing the water use in the building by:

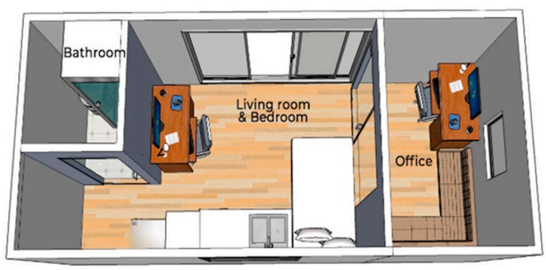

Fig. 1. Floor plan of the building module.

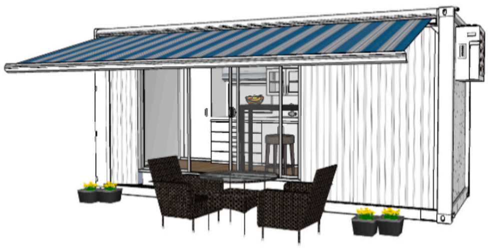

Fig. 2. Design 1, baseline.

Fig. 3. Design 2, low energy.

- Reducing the thermal conductivity of external walls, floor, and roof from 0.26 W/m^{2}K, 0.99 W/m^{2}K, and 0.26 W/m^{2}K, respectively, to 0.1 W/m^{2}K,
- Decreasing the south-oriented glazing from 5.7 m^2 to 2.85 m^2,
- Reducing the thermal transmittance of the windows from 2.8 W/m^{2}K to 0.71 W/m^{2}K, and decreasing the solar heat gain coefficient of the windows from 0.76 to 0.36,
- Reducing the exhaust flow rate (bathroom fan) from 200 m^3/h to 53 m^3/h,
- Installing a composting toilet and rainwater harvesting system.

3) Design 3, net-zero energy design (Fig. 4):

This design incorporates design 2, with the additional implementation of a 4.68 kW, multi-SI photovoltaic system, composed of 17 modules with a total area of 27.8 m^2. Although the PV modules could have been placed directly on the flat roof, mounting the PV on an additional tilted shading roof makes it easier to collect rainwater and reduces solar heat gain through the roof. The additional low-alloyed steel mounting structure is used for the installation of PV modules on the building roof, which is tilted 31 °C and faces south. The PV system is connected to the electricity grid and balances the operational energy consumed by the building on an annual basis. The sizing of the PV system is based on the TRNSYS model described in section 3. 2.3.

4) Design 4, off-grid energy design (Fig. 5):

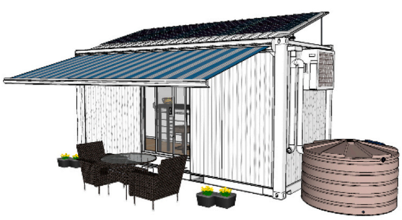

Fig. 4. Design 3, net-zero energy.

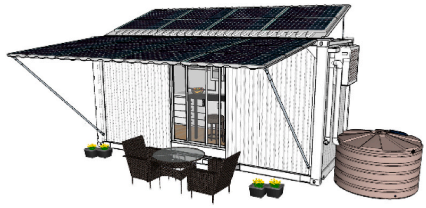

Fig. 5. Design 4, off-grid.

This design integrates Design 2 with a PV energy production and storage system, the operation of which enables the energy self-sufficiency of the building for more than 99% of the annual time, without a connection to the conventional electricity grid. For remote locations, it may be more practical and economic to be self-sufficient with electricity instead of extending the grid or rely on a diesel generator. In contrast to designs 2 and 3, the aluminium awning is replaced by a low-alloyed steel overhang (27 m^2), which in addition to solar shading also increases the available roof area for PV installation and rainwater collection. The ambition of becoming independent from electricity grid leads to nearly two-fold more extensive PV system requirements than in net-zero energy design. The higher power requirements are affected by the fact that generation of electricity from PV system needs to satisfy the increased energy demand during the winter season (with low PV energy generation), without access to convectional energy need.

Consequently, the 9.9 kW Multi-Si PV system consists of 36 modules with a total area of 58.9 m^2. Additionally, the system is equipped with two 5.0 kW solar inverters. The 24-kWh energy storage system is built with Lithium-nickel-manganese-cobalt-oxide (NCM) batteries with a Depth of Discharge of 20%. The sizing of the PV and energy storage model system is based upon a comparison of Net Present Values of possible system configurations in HOMER Pro with the TRNSYS building load as input, as described in section 3.2.3.

The estimated purchasing (investment) cost of each building design is presented in Table 1. The cost is excluding furniture, fittings, transportation and land acquisition. In design 1 the main cost is related to the shipping container structure and the VIP insulation. The cost increase by adding more VIP and upgrading to 3-layer glazing in design 2. In design 3–4, the additional cost is related to the energy system. Detailed information related to the net-present costs of investment, maintenance, replacement and energy, as well as energy payback time, are presented in Table A3-A3.2 in the Appendix section.

3. Methodology: life-cycle assessment

The process-based attributional life cycle assessment following the International Organization of Standardization (ISO) 14044:2016 [21] is used in this study. The assessment follows the recommendations and guides presented in ISO 21931–1:2010 [22] and EN15978:2011 [23].

The sections below provide detailed information about the LCA phases implemented under this study.

Table 1
Estimated purchasing cost of a housing unit in relation to energy efficiency design.

Case design:	Cost [RMB]	Cost [USD]	Cost [USD/ m^{2}Gfa]
Design 1 – Base design	47,400	7.584	281
Design 2 – Low-energy design	65,000	10,400	385
Design 3 – Net Zero Energy Building	94,870	15,180	562
Design 4 – Off grid	144,740	23,158	858

3.1. Goal and scope definition

3.1.1. Goal and functional unit

The main goal of this study is to identify, quantify, and assess the environmental impacts and the trade-offs that emerge from the development of the baseline design into low-energy, net-zero energy, and off-grid energy designs. The functional unit of this study, which enables comparisons across the design variants as well as with existing literature studies is the “total gross building area (GFA) over a building life span of 25 years”. The reason for choosing the service life of 25 years is strictly correlated with the primary market target focus, being for temporary and social housing, for which building life span, based on existing literature is in the range 10–25 years (Table A1).

3.1.2. System boundary

The cradle-to-cradle system boundary is used for this study, as presented in Fig. 6. The study takes into consideration three main life-cycle stages: pre-use, use and end-of-life, which are described in Section 3.2. Recycling and reuse processes with associated environmental benefits are included in the scope of the end-of-life phase, and consequently in the system boundaries.

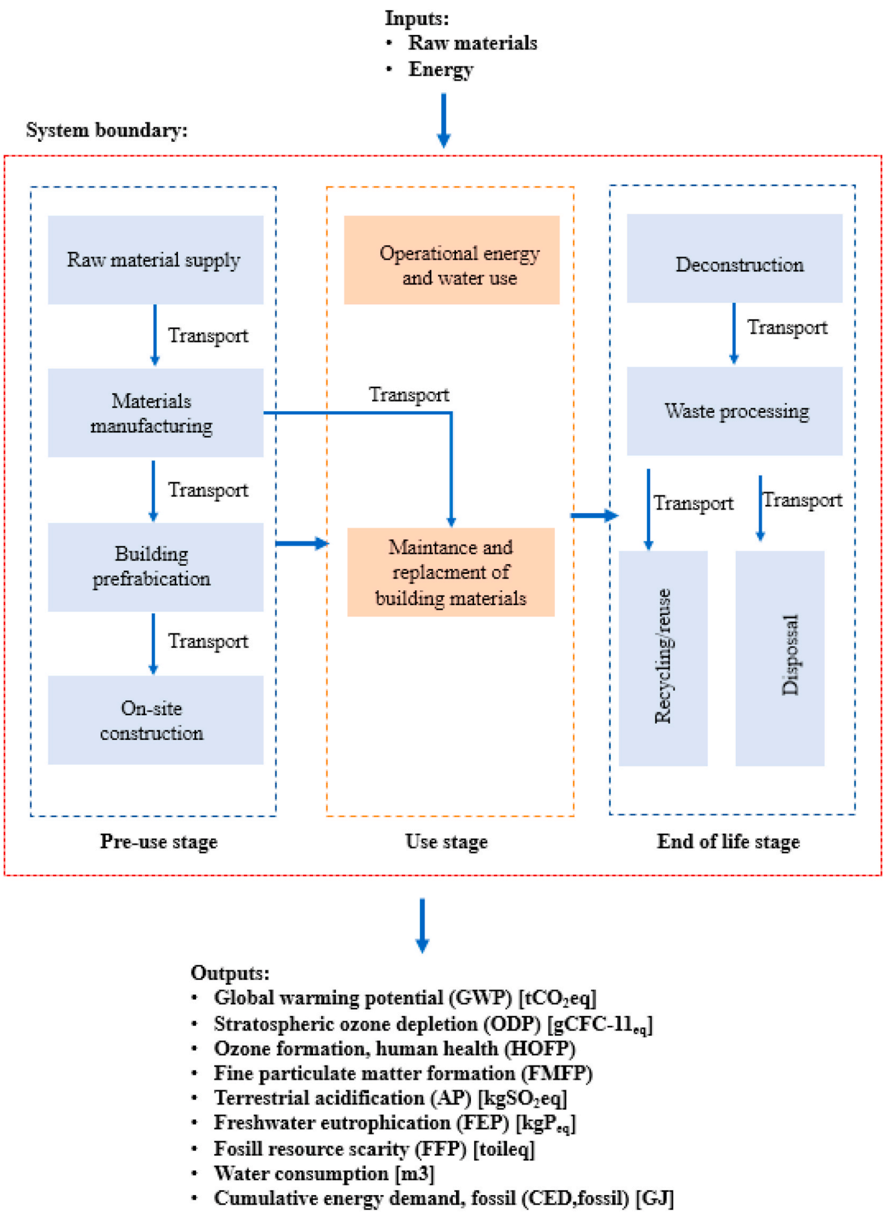

Fig. 6. System boundaries of LCA assessment.

3.2. Life cycle inventory (LCI)

The inventory analysis was carried out to quantify the significant environmental inputs of examined designs of the case building. Bill of materials, for each of the design, is presented in Table 2, while detailed data regarding LCI database and life cycle stages (pre-use, use, end-of-life) are described in followings sub-sections.

3.2.1. Life-cycle inventory database

The majority of life-cycle assessments of buildings in China are based on global inventory databases or refer to specific material impact values from previous literature studies owing to the fragmented national databases which are poorly updated and maintained [24]. Therefore, in the current study, Ecoinvent 3.6 is chosen as the main life-cycle inventory database with the global (GLO) dataset [25] representing activities which are, on average, valid for all countries in the world is. The use of a generic LCI database may limit the representativeness and accuracy of LCA, since around the world activities related to the production of construction materials and energy generation varies in terms of quantity of used raw materials, electricity mix, production efficiency [26].

Table 2
Bills of material quantities in relation to the considered energy efficiency designs of the case building.

Material	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero energy	Design 4 Off-grid	Unit
Total quantity					
Aluminium	102	88	31	31	kg
Weathering steel	3335	3335	3335	3335	kg
Low alloyed steel	12	12	854	1652	kg
Stainless, chromium steel	42.3	42.3	42.3	42.3	kg
Concrete, 25 MPa	3.3	3.3	3.3	3.3	m^3
Glue laminated timber	2.43	5.69	5.69	5.69	m^3
Softwood, plywood board	1.17	1.17	1.17	1.17	m^3
Softwood, timber cladding	0.51	0.51	0.51	0.51	m^3
Air and vapour barrier tape	53.74	53.74	53.74	53.74	m^2
Mineral wool	80.08	123.92	123.92	123.92	kg
Vacuum insulation panel (8 mm)	29.38	–	–	–	m^2
Vacuum insulation panel (24 mm)	–	112.63	112.63	112.63	m^2
Polyurethane foam	28.61	28.61	28.61	28.61	kg
Double glazed hard-coated argon	5.7	–	–	–	m^2
Triple glazed hard-coated argon	–	3.62	3.62	3.62	m^2
Flat glass, coated	132	132	132	132	kg
Polyethylene	8.2	8.2	8.2	8.2	kg
Polyvinyl chloride (PVC)	61.6	91.6	91.6	91.6	kg
Air-air heat pump	1	1	1	1	unit
Domestic hot water tank (40 l)	1	1	1	1	unit
Multi-Si PV module	–	–	27.8	58.9	m^2
Solar inverter – 5.0 kW	–	–	1	2	unit
Solar charging controller MPPT	–	–	–	1	unit
Lithium-nickel-manganese-cobalt-oxide (NCM) battery	–	–	–	221.53	kg
Internal wall paint	7.35	7.35	7.35	7.35	l
External wall and roof paint	9.2	9.2	9.2	9.2	l
Total building weight	**14558**	**17241**	**18198**	**18666**	**kg**
Total building weight	**539**	**639**	**674**	**691**	**kg/ m^2GFA**

In order to increase the accuracy of the current assessment, all LCI data inputs from Ecoinvent 3.6 database have been adjusted to better approximate the production processes in Shanghai province by substituting the generic, global grid mix with the specific data representing electricity mix in Shanghai Municipality. The NCM Li-ion batteries and vacuum insulation panels, whose life-cycle inventory data are not described in the Ecoinvent 3.6 database, were modelled separately in SimaPro [27] and were built upon available data from the literature [28,29].

Due to the lack of detailed industry data related to specific transportation distances and modes between locations of raw material extraction and manufacturing of the construction materials, the current study uses the transportation data modelled as the global average [30], which can increase the uncertainty of results.

3.2.2. Pre-use phase

Existing literature presents several LCA studies where the building structural frame, based on a steel container, was repurposed from its primary transportable purpose to be transformed into a structure component with zero environmental impacts [21,31]. These studies were located in Australia and Europe, where according to the national policies, transportation of goods in shipping containers needs to be fully registered and documented. However, in China, such regulations are not fully implemented nor required, often making the reuse of shipping containers for housing purposes particularly hazardous and unregulated. Due to this fact, the case study building employs a new weathered Corten steel container as the building frame, following the current market situation. Based on the data from the producer of the shipping container, the total mass of the container structure is approximately 4150 kg and consist of 3335 kg of weathering (Corten steel), 205 kg of unalloyed steel, 600 kg of plywood and 10 kg of rubber. Additionally, based on an expert's estimation the welding process of connecting the steel sheets into the container shape lead to consumption of approx. 1435 kWh of electricity from the local grid.

According to data from the producer of residential units the prefabrication process of transforming container module to a fully equipped housing unit consumed around 430 kWh of delivered electricity from the local grid. This energy consumption is close to the value mentioned by Islam et al., 2016 [20], who reported that repurposing a 3.63 t shipping container into a home required approximately 400 kWh of final energy.

Shanghai province is a leading manufacturer of construction materials in China, therefore average transportation distance between materials supplier and housing unit manufacture, which are both located within Shanghai Municipality borders is low, and by average estimated as 50 km (based on Google Maps). Transportation of construction materials, including the shipping container, was done by diesel-fuelled trucks with size class 7.5–16t, which needs to fulfil the emission requirements based on China IV class, which follows the European (Euro) 4 class model [32]. The environmental impacts from the transportation is within the system boundaries.

The building module is fully prefabricated; therefore, the transportation to the building site and on-site construction work consist of transporting the building module from the fabrication site to the building site (35 km), preparation of the four concrete foundation blocks (20 MPa), and placement of the prefabricated module by a crane. The final installation of the energy, water, and sewage system is done manually, not influencing the environmental impacts significantly, and it is outside the scope of the assessment.

3.2.3. Use phase

The use phase incorporates the environmental impacts related to life-cycle operational electricity consumption, water use, building maintenance, and replacement of materials during the building life span. The TRNSYS software [33] was used in this research to evaluate the annual energy consumption and energy loads related to space heating, cooling, ventilation, production of domestic hot water, lighting, and household appliances in all building designs. The performance models of energy efficiency design 2–4 are built on the model of the base design, in which electricity loads related to space heating and cooling were validated by utilising the on-site measurements of the temperature and heat pump energy consumption. The validation was performed during the space heating period 21.01–27.01 and the space cooling period 18.07–23.07. Additionally, the TRNSYS software was used for dimensioning the PV system in Design 3, enabling to achieve net-zero energy operation. To design an optimal off-grid energy system with sufficient energy storage capacity in Design 4, the building energy and PV system model from TRNSYS software was coupled with the HOMER Pro software [34], which enables the proper sizing of the off-grid system. The PV system in both designs 3 and 4 was modelled taking into consideration a dynamic approach, by including the loss of power output due to aging, which is 0.8%/year relating to the rated power.

In the case of design 3 (net-zero energy design) and design 4 (off-grid energy design), the total annual building energy demand is subtracted from the entire renewable energy production from each of the energy system design. The environmental impacts of the low voltage electricity from the local grid is based on Ecoinvent data, being representative for Shanghai's energy mix and considered as static, with no change during the building's life-span. Additionally, the same values of impacts are used for both the import and export of electricity from the case building, meaning that in the net-zero energy design (Design 3), the environmental impacts related to electricity consumption are equal to zero.

The mean annual water consumption in Shanghai province is estimated to be 107 m^3/person [35]with around 25% of the total domestic water consumption being used for toilet flushing [36]. In the design 2 (low-energy) and design 3 (net-zero energy design), implementation of the composting toilet and rainwater leads to reduction of water consumption to 68m^3/person. By assuming a more restrictive use of water, and the implantation of additional steel roof overhang which enlarges the rainwater harvesting surface in design 4 (off-grid design), the water-self-sufficiency ambition is achieved.

The annual results of energy consumption, generation, and water consumption for the designs are presented in Table 3. They were used as inputs into the LCA model to evaluate the life-cycle environmental impacts related to energy and water consumptions. Additional information about the energy simulation assumptions and detailed results of the energy performance of each case are presented in Tables A.4–A.4.3 and Fig. A.1-A.4 in the Appendix.

The timing for building maintenance, which is limited to internal and external re-painting as well as number of needed replacements of building elements during the building lifespan is presented in Table A5 in the Appendix.

3.2.4. End-of-life phase

The building module is planned to be dissembled and transported back from the building site to the modular construction factory in Shanghai at the end of the building service life. The process and related environmental impacts of the on-site disassembly of the building is estimated to be the same as in the assembly process. Based on current practice in China [37]it is assumed that the all building materials are disposed to landfill at the end of their life except metals from the building structure, roof, and in case of design 4 (off-grid), Li-ion NCM batteries, which are being recycled. The end-of-life phase includes impacts related to the transportation of wastes (50 km) from the factory to the landfill, done by diesel fuelled lorry with size class 7.5–16t (China IV).

All metal-based products from the residence are assumed to be recyclable in a closed-loop scheme. The process impacts from producing secondary materials are included in the scope of end of life impacts. Recycling rates of metals are based on current China market benchmarks and assumed to be 90% for steel and aluminium products [38,39]. The NCM Li-ion batteries, which are part of the energy system in design 4 (off-grid design), are assumed to be treated in pyrometallurgical processes; the associated credits from recycling copper, nickel, steel, and aluminium are included in the end-of life stage impacts. Recovery rates for steel and aluminium, coming from the batteries casing, are 90%, whereas the rates for recycling of copper and nickel from batteries cell are estimated to be 70% [40]. All environmental benefits (100%) from the reuse, recycling, or recovery of building materials are given for the present product system.

3.3. Impact assessment

The life-cycle impact assessment for this study follows the ReCiPe Midpoint methodology with Hierarchist (H) cultural perspective [41]. This method, in comparison with other assessment methods allows to include in the analysis the environmental impact categories like: fine particulate matter formation (FMFP) or water consumption [42], which contribute significantly to local, harmful impacts (Shanghai) in the form of health respiratory problems and water scarcity [43]. Additionally, to increase the comparability of results with other studies, the single indicator of non-renewable fossil energy demand, based on cumulative energy demand method [44] is included in the assessment scope. Finally, nine impact categories are assessed: global warming potential (GWP), stratospheric ozone depletion (ODP), ozone formation, human health (HOFP), fine particulate matter formation (FMFP), terrestrial acidification (AP), freshwater eutrophication (FEP), fossil resource scarcity (FFP), water consumption, and non-renewable, non-renewable, fossil energy demand (CED).

3.4. Sensitivity analysis

The sensitivity analysis performed under this research aims to increase the robustness of the total life-cycle impact results and investigate the significance of the study assumptions on the results. The sensitivity analysis was conducted for the factors related to:

- Climate change effects

The possible effects of climate change during the building lifespan can be considered as a significant uncertainty factor in the building life-cycle assessment [45]. Under this section, the possible influence of climate change effects in 2020 and 2050 to the total life-cycle impact of

Table 3
Results of annual energy consumption, PV energy generation, and water use according to the building designs.

	Space heating (kWh)	Space cooling (kWh)	Domestic hot water (kWh)	Lighting and appliances (kWh)	Total energy consumption (kWh)	PV generation (kWh)	Energy intensity (kWh/m^2)	Water use (m^3)
Design 1: Base design	2069	1002	1128	1779	5977	0	285	214
Design 2: Low-energy design	428	643	1128	1779	3978	0	189	136
Design 3: Net-zero energy design	428	643	1128	1779	3978	4077	0	136
Design 4: Off-grid design	428	643	1128	1779	3978	10254	0	0

the building design variants results is assessed. The climate data, representative of predicted climate conditions in 2020 and 2050, which take into consideration possible climate change effects, were generated by the transformation of the baseline weather file (IWEC2 Shanghai) in the CCWorldWeatherGen software developed by the University of Southampton [46]. The underlying weather file transformation methodology is based on the IPCC Report AR3 (2001) [47], AR4 (2007) [48] emission scenario A2 [49] which assume regionally oriented economic development, continuously increasing population, and global warming gases emissions with 2.0–5.4 °C temperature increase by 2100.

- End-of-life scenario and corresponding benefits and loads outside the system boundary

To assess the sensitivity of the end-of-life scenario choice, the authors performed the life-cycle assessment calculation by including additional assumption, in which:

The steel container structure, after the end of the building lifetime, is reused in the factory for the prefabrication of the next building module. The material losses of weathering and low-alloyed steel during this process are estimated at 15%.

4. Results and discussion

The following sections present and discuss the results of the life-cycle assessments for each of the nine impact categories, followed by the sensitivity analysis results.

4.1. Life-cycle assessment results

Table 4 presents the absolute values of the total life-cycle impact assessments of the impact categories for the four design versions of the case building. The following chapters includes graphical representations of the results and discuss these in more detail. The values are based on the functional study unit “gross building area over a building life span of 25 years”. The results present a breakdown of the environmental impacts related to each of the life-cycle phases, which enables a comparison across building designs. Additionally, the change of total environmental impact (Impact Change) in each of energy efficiency design and impact category in relation to baseline design is presented and calculated according to (equation (1))

$$Impact\ change^{scenario\ x}_{category\ y} = \frac{Total\ LCA^{scenario\ x}_{y} - Total\ LCA^{scenario\ 1}_{y}}{TotalLCA^{scenario\ 1}_{y}} * 100\% \quad (1)$$

where: Total LCA-life cycle impact including pre-use, use and end-of-life stages.

x – case design of the building [low energy (2), net-zero (3), off-grid (4)]

y – considered environmental impact category [GWP, ODP, HOFP, FMFP, AP, FEP, FFP, water consumption, CED fossil]

4.1.1. Total life-cycle impacts

The results of the total life-cycle assessment of the studied impact categories are summarised in Table 4. The use phase is responsible for most of the total life-cycle environmental impacts across all categories in designs 1 and 2. The dominant share of the use phase can be explained by a combination of significant electricity consumption and high environmental impacts of electricity generation, which is mostly based on hard coal combustion. Implementation of energy efficiency measures in design 2 decreased the annual total electricity consumption by 34% (Table 3) and resulted in total life-cycle impact reductions ranging between 21% (Freshwater eutrophication, FEP) and 29% (Global Warming Potential, GWP) relative to design 1. In contrast to the first two designs,

Table 4
Results of the life-cycle assessments by life-cycle phases.

Global Warming Potential, GWP (tCO_{2eq})				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	20.8 (9.9%)	24.3 (16.0%)	28.5 (94.1%)	44.4 (86.7%)
Use	192.0 (91.6%)	130.5 (86.0%)	5.9 (19.3%)	10.4 (20.3%)
End-of-life	−3.1 (−1.5%)	−3.1 (−2.0%)	−4.1 (−13.4%)	−3.6 (−7.0%)
Total LCA	209.5 (100%)	151.6 (100%)	30.3 (100%)	51.2 (100%)
Impact change %		**−29%**	**−86%**	**−76%**
Stratospheric ozone depletion, ODP ($gCFC\text{-}11_{eq}$)				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	9.4 (18.3%)	9.9 (25.9%)	12.1 (65.9%)	17.6 (75.5%)
Use	42.2 (82.4%)	28.7 (75.0%)	6.8 (36.7%)	7.2 (30.9%)
End-of-life	−0.4 (−0.7%)	−0.4 (−0.9%)	−0.5 (−2.6%)	−1.5 (−6.4%)
Total LCA (with no benefits)	51.2 (100%)	38.3 (100%)	18.4 (100%)	23.4 (100%)
Impact change %		**−25%**	**−64%**	**−54%**
Ozone formation, Human health, HOFP ($kgNO_{xeq}$)				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	47.4 (9.9%)	51.4 (14.9%)	61.8 (88.9%)	100.5 (85.3%)
Use	438.2 (91.3%)	297.8 (86.7%)	15.5 (22.2%)	27.02 (23.0%)
End-of-life	−5.8 (−1.2%)	−5.7 (−1.6%)	−7.7 (−11.1%)	−9.7 (−8.3%)
Total LCA	479.9 (100%)	343.4 (100%)	69.7 (100%)	117.8 (100%)
Impact change %		**−28%**	**−86%**	**−75%**
Fine particulate matter formation, FMFP ($kgPM_{2.5eq}$)				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	41.5 (12.1%)	43.6 (17.7%)	52.3 (90.7%)	89.7 (88.7%)
Use	308.4 (89.8%)	209.8 (84.9%)	13.6 (23.5%)	30.7 (30.3%)
End-of-life	−6.4 (−1.9%)	−6.3 (−2.6%)	−8.2 (−14.2%)	−19.2 (−19%)
Total LCA	343.5 (100%)	247.0 (100%)	57.7 (100%)	101.2 (100%)
Impact change %		**−28%**	**−83%**	**−71%**
Terrestrial acidification, AP ($kgSO_{2eq}$)				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	79.7 (9.7%)	92.2 (15.5%)	109.1 (83.8%)	186.2 (84.5%)
Use	753.0 (91.5%)	511.9 (86.1%)	33.8 (26.0%)	78.1 (35.4%)
End-of- life	−9.8 (−1.2%)	−9.7 (−1.6%)	−12.8 (−9.8%)	−44.0 (−20%)
Total LCA	823.1 (100%)	594.4 (100%)	130.3 (100%)	220.3 (100%)
Impact change %		**−28%**	**−84%**	**−73%**
Freshwater eutrophication, FEP (kgP_{eq})				
Life cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	12.5 (26.0%)	13.8 (37.8%)	17.0 (76.5%)	31.8 (86.0%)
Use	35.3 (73.8%)	24.0 (65.5%)	6.8 (30.4%)	16.6 (44.8%)
End-of-life	−1.2 (−2.6%)	−1.2 (−3.3%)	−1.5 (−6.9%)	−11.4 (−30.9%)
Total LCA	46.5 (100%)	36.6 (100%)	22.3 (100%)	37.0 (100%)
Impact change %		**−21%**	**−52%**	**−21%**
Fossil resource scarcity, FFP ($toil_{eq}$)				
Life cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	4.0 (10.7%)	4.2 (15.7%)	5.4 (94.9%)	9.0 (86.0%)

(continued on next page)

Table 4 (*continued*)

Global Warming Potential, GWP (tCO_{2eq})				
Life-cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Use	34.2 (91.1%)	23.2 (86.7%)	1.2 (20.5%)	2.3 (22.2%)
End-of-life	−0.7 (−1.8%)	−0.7 (−2.5%)	−0.9 (−15.4%)	−0.9 (−8.1%)
Total LCA	37.5 (100%)	26.8 (100%)	5.6 (100%)	10.5 (100%)
Impact change %		**−29%**	**−85%**	**−72%**
Water consumption (m^3)				
Life cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	121.6 (12.3%)	123.7 (18.0%)	345.7 (47.1%)	679.5 (88.0%)
Use	873.0 (88.2%)	569.5 (82.7%)	394.5 (53.8%)	109.7 (14.2%)
End-of-life	−4.4 (−0.5%)	−4.2 (−0.7%)	−6.4 (−0.9%)	−16.8 (−2.2%)
Total LCA	990.3 (100%)	689.0 (100%)	733.9 (100%)	722.5 (100%)
Impact change %		**−31%**	**−26%**	**−22%**
Cumulative energy demand, fossil CED (GJ)				
Life cycle phases	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Pre-use	234.3 (13.1%)	273.4 (20.7%)	345.2 (91.1%)	495.5 (87.8%)
Use	1581.2 (86.6%)	1075.2 (81.5%)	50.1 (14.3%)	106.8 (18.9%)
End-of-life	−30.2 (−1.7%)	−29.9 (−2.2%)	−39.8 (−11.4%)	−38.1 (-6.8%)
Total LCA (with no benefits)	1785.3 (100%)	1318.7 (100%)	350.5 (100%)	564.2 (100%)
Impact change %		**−26%**	**−80%**	**−68%**

the life-cycle impacts of design (net-zero) are dominated by the pre-use phase in all impact categories, except for the water consumption, which is dominated by the use phase. Similarly, the life cycle impacts of design 4 (off-grid) are governed by the pre-use phase in all the impact categories. The consequence of this shift is a combination of zero environmental loads from electricity consumption and increased embodied impacts related to the production of the photovoltaic system in designs 3 and 4, with the additional energy storage system in design 4. Design 3 (net-zero energy) is characterised by the lowest life-cycle impacts among all case-building designs. The reduction of total life-cycle impacts in relation to design 1 is in the range of 26% (for water consumption) to 86% (for GWP). Design s 4, with the off-grid energy system, presents significantly higher life-cycle environmental loads in all impact categories in comparison with design 3 (net-zero), with the average 59% impact increase among all categories. The relative increase of 86% is highest for fossil fuel scarcity category, followed by 76% increase for fine particulate matter formation and 69% for GWP The life-cycle increase is mainly connected to increase of environmental loads in pre-use stage by need of designing nearly two-fold larger PV system (off-grid design) in order to becoming self-sufficient and independent from electricity grid.

However, despite the significant rise of embodied impacts related to the off-grid energy system, life-cycle impact reductions from the baseline design all of impact categories are observed.

In all designs, the end-of life stage impacts are characterised by negative values, which are related to the environmental benefits coming from recycling process of construction materials, being higher than environmental impacts from end-of life processes of building demolition, waste transport and treatment and landfill.

In the first two designs (1 and 2), the negative impacts from end of life stage do not have a significant potential (less than 3%) for reducing the total life-cycle impacts. In contrast, in design 3 and 4 there is a more significant reduction potential, especially with respect to fossil resource scarcity (15.4%) in design 3, and freshwater eutrophication (30.9%) in design 4.

4.1.2. Pre-use impacts

The distribution of the pre-use impacts for the various building designs is presented in Fig. 7, while Fig. A5 in the Appendix presents relative increase of pre-use impacts in relation to additional building materials/systems in each of energy efficiency designs.

Designs 2–4 show increasing impacts in all the environmental categories in comparison with the baseline design, which results from the increased quantities and embodied life-cycle loads of the additional implemented materials. The lowest increase of pre-use impacts values is observed in design 2 (Fig. 8), where the implementation of the additional layers of vacuum insulation panels is responsible for most of the increase being in the range between 56% for ODP and 84% for GWP (Fig. A5 in the Appendix). Replacement of energy-intensive VIP (2.4 cm), to mineral wool insulation (32 cm) in design 2 can provide, reduction of pre-use impacts being in the range 6% for ODP and 23% for CED. However, this measure will lead to significant reduction: of useable floor area.

In design 3 (net-zero energy), the increase in the pre-use impact is larger, with e.g. 26% for fine particulate matter formation (FMFP) and 45% for CED, and with a significant 184% impact increase in water use consumption (Fig. 8) which in 94% is attributed to the high water-consuming processes of cooling, chemical processing, and toxin removal during the production of silicon in the manufacturing of PV modules (Fig. A5 in the Appendix).

Design 4 (off-grid) leads to the highest overall total pre-use impact values, among all case study designs, e.g. with an increasing impact of 89% for ODP to 155% for FEP, and with nearly 460% increase in water consumption (Fig. 8). The highest increase of the impacts, being in the range 41% for AP and 87% for water consumption (Fig. A5) is related to extensive PV system, working in off-grid mode without connection to electricity grid. The implementation of energy storage in the form of NCM Li-ion batteries, contributes the most: 32% to increase in the freshwater eutrophication (FEP) category (Fig. A5) and is mainly attributable to the process of copper mining, which is the primary material of the battery cells, and produces a significant volume of toxic waste.

In all design's variants, the environmental loads related to the production stage (raw material supply, transport, and materials manufacturing) occupy a dominant share in the pre-use life-cycle phase. This study employs the transportation distances and modes of raw materials to product manufactures based on averaged Global (GLO) dataset from Ecoinvent database. If the more specific, local data will be available, the expected loads from production stage should be slightly lower due to shorter transportation distances of most dominant raw-materials (iron ore, cement, sand) occurring in East China than modelled in global database.

The accumulated loads from building module production, on-site construction activities, as well as, transportation to the building site, is less than 3% of the total impact in each impact category and design variant. This can be explained by the low energy consumption related to building prefabrication and the short transportation distance from the factory to the building site.

4.1.3. Use impacts

The distribution of the use/operational impacts of the building designs is presented in Fig. 8. The implementation of energy efficiency and water use reduction measures in design 2 (low-energy) resulted in an average 32% impact reduction among all categories with respect to the baseline design.

In design 3 (net-zero) a decrease in operational impact between 55% for water use and 97% for GWP is achieved. This high reduction potential can be attributed to a combination of two factors: total compensation of impacts related to electricity use from the environmentally burdened electricity grid due to the use of the renewable PV

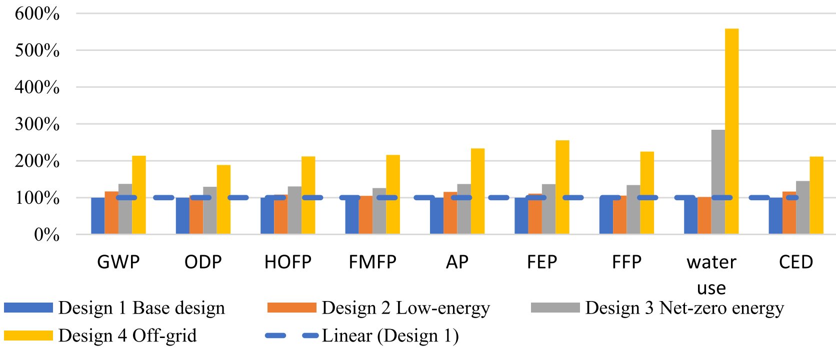

Fig. 7. Pre-use impact results relative to the baseline design.

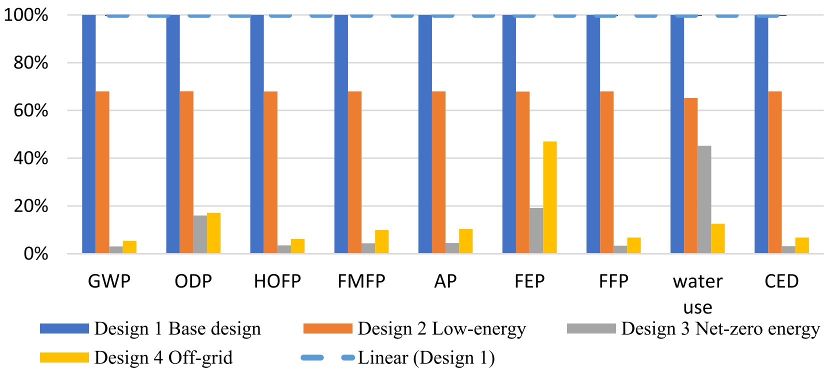

Fig. 8. Use impact results relative to the baseline design.

system, and low impacts associated with the replacement phase.

The increase of environmental embodied loads mainly related to the one-time replacement of energy storage system in design 4 (off-grid), during the 25-years building life-span explains the higher impacts in all categories in comparison with design 3 (net-zero). Consequently, the reduction potential in design 4 relative to the baseline design ranges between 53% for FEP and 95% for GWP.

4.1.4. End-of-life impacts

The distribution of the end-of-life impacts, being an aggregate value coming from processes of building demolition, waste transport, waste processing, landfill and recycling is presented in Fig. 9. The

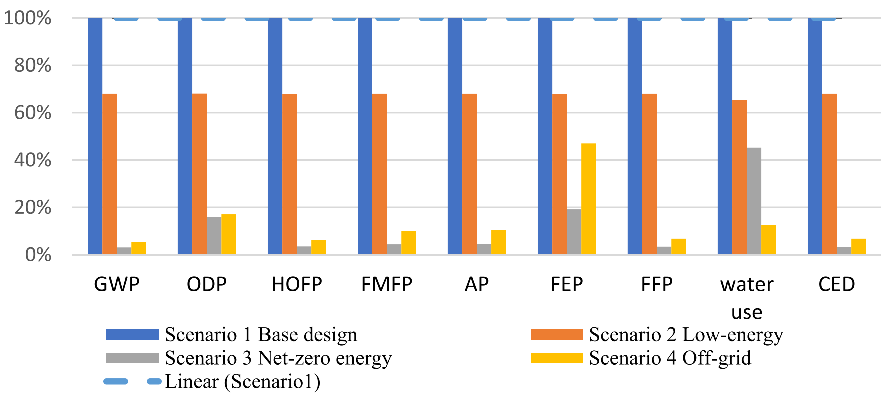

Fig. 9. End-of-life impact results relative to the baseline design.

environmental benefits coming from recycling process occurring in the end-of-life phase scope is presented separately in Fig. A6 and Table A6 in the Appendix.

The variation between end-of life impact's in each of design variant is driven by differences in environmental benefits coming from recycling process. The increase of environmental impacts related to building waste transportation and landfill, which can be attributed to increasing mass of building waste in designs 2–4 present minor influence on the results. It can be seen in design 2 (low-energy), which features the same quantity of materials being recycled as those in the baseline design. As a result, the values of environmental benefits form recycling process are the same (Fig. A6). Consequently, the increase of end-of-life impacts due to the increased mass of building wastes is less than 2% (Fig. 9).

The decrease of end-of-life impacts in design 3, from 20% for FEP to 32% for water consumption in design 3 can be attributed to the additional benefits coming from recycling of the additional low alloyed construction, which serves as the PV mounting roof system.

The pyro-metallurgical process used for recycling copper and nickel from Li-ion battery cells is the main contributor to the significant increase of environmental benefits in design 4 (off-grid) (Fig. A6 in the Appendix) and resulting in decrease of end-of-life impacts in all categories, except GWP and CED, relative to design 3 (Fig. 9). In this category, the impacts related to the intensive energy consumption during the pyro-metallurgical process exceed the environmental benefits associated with the recycling of metal-based products.

4.2. Sensitive analysis results

4.2.1. Climate change effects

The results in terms of mean annual temperature, horizontal radiation, space heating, cooling electricity consumption, as well as the specifications for PV and energy systems related to possible climate change effects in 2020 and 2050 are summarised in Table 5 below. These data serve as an input for assessing the sensitivity of life-cycle impacts due to possible climate change effects, which results are presented in Fig. 10.

An increase of mean annual temperature is considered from 16.2 °C (baseline) to 18.4 °C (2050), with a slight decrease in mean horizontal radiation from 142 Wh/m^2 (baseline) to 138 Wh/m^2 (2050). Generally, a decline in space heating electricity consumption is observed for all designs, with a simultaneous increase in space cooling. However, there is not a significant change in the overall space heating and cooling electricity demand.

Life-cycle impacts in all categories in design 1 (baseline design) are slightly lower, on average, by 0.4% and 0.6% for the climate predictions in 2020 and 2050, respectively, in comparison with the baseline conditions. This can be attributed to the higher annual mean temperatures

Table 5
Sensitivity analysis results: Weather data, electricity consumption, PV power, and energy storage capacity according to the simulated climate change effects in 2020 and 2050.

	Baseline	2020	2050
Mean annual temp [°C]	16.2	17.2	18.4
Mean global horizontal radiation [Wh/m^2]	142	139	138
Design 1: Heating consumption [kWh/m^2a]	98.5	90.2	78.1
Design 1: Cooling consumption [kWh/m^2a]	47.7	54.8	65.6
Design 1: Total heating and cooling [kWh/m^2a]	146.2	145	143.7
Design 1: Total electricity consumption [kWh/m^2a]	285	283.8	282.5
Design 2–4: Heating consumption [kWh/m^2a]	24.3	20.8	16.1
Design 2–4: Cooling consumption [kWh/m^2a]	30.6	34.7	40.5
Design 2–4: Total heating and cooling [kWh/m^2a]	54.9	55.5	56.6
Design 2–4: Total electricity consumption [kWh/m^2a]	189	190.6	191.7
Design 3: PV system power [kW]	4.7	4.95	4.95
Design 4: PV system power, energy storage capacity [kW, kWh]	9.9 kW, 24 kWh		

in 2020 and 2050, and results from the energy savings owing to space heating needs that exceed the additional energy consumption for space cooling. In contrast, in design 2 (low-energy), with the well-insulated building envelope, a minor increase of the total life-cycle impacts in all categories can be seen, which relates to the dominant share of space cooling electricity consumption in the total thermal energy loads of the building.

The higher electricity loads because of cooling needs, as well as the decreased values of horizontal radiation in design 3 (net-zero), lead to the increased PV power need (from 4.7 to 4.95 kW), which contributes 1–2% to the overall life-cycle impact increase among all categories. There is no change in life-cycle impacts in design 4, in which the PV energy system coupled with energy storage provides can reduce the climate change effects.

4.2.2. End-of-life scenario

The results of the sensitivity analysis for the total life-cycle impacts in relation to the change in the end-of-life scenario is presented in Fig. 11.

Reusing the building superstructure in the form of steel container decreases the total life-cycle impact in all designs among all environmental categories, compared to baseline assumptions. Reusing of steel container, presents the higher environmental benefits than recycling, since there are less environmental impacts associated with product reprocessing. Additionally, there is an additional savings coming from reduction of energy used in the prefabrication (welding) process of new weathering container.

The reduction of total life-cycle impacts is most significant in design 3 and 4, which life-cycle impacts are dominated by pre-use stage. The highest reduction, from 8.0% for (water consumption) to 27.1% for (FEP) – that come from the reuse of the building superstructure can be observed in design 3 (net-zero).

4.3. Comparison with existing studies

To better evaluate the environmental performance of the building designs in this case study, a comparison with other studies from the literature, featuring residential functionality, warm climate conditions, and cradle-to-grave life-cycle boundaries was performed (see Table 6 below). The comparison is based on functional unit: life cycle GHG emissions of 1 m^2 of gross area over one year of building life span: $kgCO_2eq/m^2$year, supported by unit presenting life cycle GHG emissions of 1 occupant during over one year of building life span: $kgCO_2eq$/occupant year. Single indicator in form of GHG emissions is used, since it is included in the most of literature studies.

The life cycle GHG emissions of the baseline design as well as the low-energy design (design 2) in this study are similar to those of prefabricated, well insulated, air-conditioned post-disaster buildings in Turkey with a steel structure [50]. In comparison with other low-energy studies [51–53], design 2 presents significantly higher life-cycle GHG emissions. However, these studies are characterised by life-span of 50 years and several fold larger gross flor areas, making a straight comparison by using functional unit of $kgCO_2eq/m^2$year, deceptive. The comparison by using occupant-based unit: $kgCO_2eq/m^2$year provides more reliable comparison between case studies, indicating decreasing distinction of final emissions.

The difference of life-cycle GHG emissions between the net-zero energy design in this study and net-zero energy designs in Ref. [18,19,54] is in the range between 18 and 29%. The lower life cycle GHG emissions of net-zero energy design assessed under current study can be attributed to higher environmental benefits coming from the recycling process as well as lower impacts occurring in the use stage, due to no need of replacing PV system during building-lifespan.

A comparison with the results provided by Atmaca, 2017 [50] shows that both the net-zero energy and off-grid modular building designs provide a more than threefold decrease in life-cycle GHG emissions. This

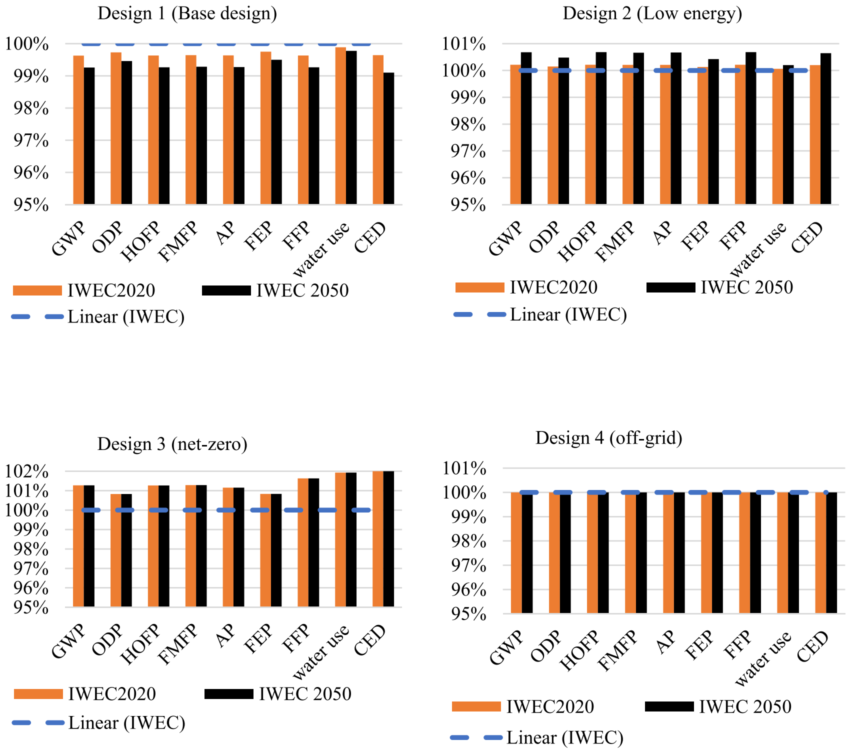

Fig. 10. Sensitivity analysis to climate change of the total LCA impacts relative to the baseline (IWEC) climate data.

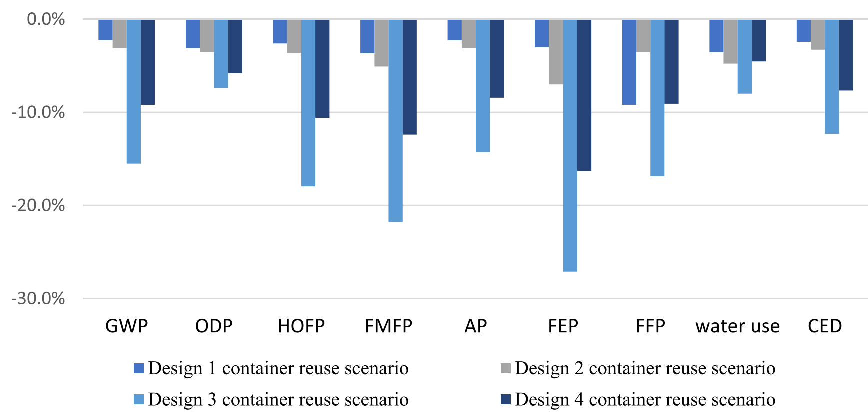

Fig. 11. Sensitivity analysis of end-of life, container reuse scenario on total LCA impacts relative to baseline assumption (90% recycling).

result demonstrates the significant GHG emissions mitigation potential related to the implementation of off-grid and zero energy buildings in rural, remote, or post-disaster areas with limited electricity access and energy facilities based on fossil fuels.

5. Conclusions

The life-cycle environmental impacts of four energy-efficiency design variants for an industrial, modular housing unit produced and located in Shanghai were analysed in this study. The life-cycle impacts in all environmental categories in the baseline design (design 1) and in the low-energy design (design 2) are strongly dominated by the use phase

Table 6
Comparison between the case study designs and literature case studies, GWP indicator.

Reference	Case study description	Energy efficiency design	Location/Climate	Life-span [years]	GFA [m^2]	Life-cycle GHG emissions	
						[$kgCO_{2eq}$/ m^2year]	[$kgCO_{2eq}$/ occupant year]
Kahhat,et.al 2009 [51]	Single story residential building with a steel -stud based structure	Low energy	Phoenix, USA/Tropical and subtropical desert	50	200	89.5	4475
Bukowski et al., 2017 [52]	Single family building with steel-reinforced structure	Low energy	Bankog, Thailand/ Tropical	50	148	57.6	2131
Yang et al., 2018 [55]	Single family building with concrete -brick structure	Low energy	Baiguoba, China/Humid subtropical	50	423	59.6	3151
Atmaca, 2017 [50]	Modular post-disaster, housing unit based on steel container structure	Convectional	Turkey/Mediterranean	15	21	491	5155
	Prefabricated, steel-based post-disaster housing unit	Low energy	Turkey/Mediterranean	25	70	255	3570
Dong et al., 2018 [18]	Prefabricated, PV powered, steel-based temporary housing unit	Net-zero energy	Nanjing/Humid subtropical	20	30	54.5	818
Tumminia et al., 2018 [19]	Prefabricated, PV powered housing unit with a structure based on pultruded fibre reinforced material,	Net-zero energy	Messina, Italy/ Mediterranean	25	45	57.9	867
Schiavoni et al., 2017 [54]	PV powered, housing unit based on end-of-life steel container with wooden cladding	Net-zero energy	Perugia, Italy/ Mediterranean	10	16	63.1	1010
Satola et al., 2020 (current study)	Housing unit based on the new weathering steel container characterised with different energy efficiency design variants	Convectional Low energy Net-zero energy Off-grid	Shanghai, China/Humid subtropical	25	27	310.3 224.7 44.9 75.9	4190 3030 606 1024

(88% and 82% on average, respectively), for which the impacts are mainly attributed to the consumption of electricity which derives from the hard coal-based electricity grid. The implementation of energy and water reduction measures in design 2 leads, on average, to a 27% reduction of total life-cycle impacts, with the highest reduction observed in the GWP (28%) and water use (30%) impact categories. Improving the thermal properties of the building envelope by adding additional insulation materials can significantly contribute to life-cycle impact reductions. In contrast to the first two designs, the life-cycle impacts of the net-zero energy design and the off-grid design are dominated in most of the categories by the pre-use phase. The net-zero energy design presents the lowest life-cycle impacts in all categories, with a 86% lower GWP impact compared to the baseline design. The results of this study show that the design of a net-zero energy building with on-site renewable energy sources can offer great life-cycle impact reduction potential, especially in locations with highly carbonised electricity production.

The off-grid design (design 4), presents 59% higher life-cycle impacts, on average, compared to the grid-connected net-zero energy design (design 3). The highest increase (86%) is observed in the fossil resource scarcity category. The ambition of going off the convectional electricity grid leads to a two-fold higher power requirement for the PV system as well as a need for energy storage, which together are responsible, by average for more than 70% of the impacts in the pre-use phase. Based on this, further research should explore additional design strategies to decrease the building electricity load and the resulting off-grid system size and embodied life-cycle impacts.

The results of the sensitivity analysis indicate that the implementation of a circular approach to building products, with the reuse of the building structure in the form of a weathering container, can significantly increase the potential life-cycle environmental benefits, particularly, in designs characterised by dominant share of pre-use stage in total life cycle impacts.

The life-cycle assessment conducted under this study has several limitations and suggests the scope for future research. For instance, the life-cycle inventory data is mostly based on the Ecoinvent database adjusted to local production conditions in Shanghai. The more active collaboration between industry and research is needed in China to develop reliable, open-access national LCI databases and environmental product declarations to increase the accuracy of performed life cycle assessments. Additionally, the energy model for case studies designs was validated by using on-site measurements for a single baseline design. The additional measurements for net-zero energy and off-grid operation should be performed in the next research to increase the accuracy of results. Finally, there is a great potential for extending the object of assessment from single building to the interconnected group of buildings. The research on optimising the energy generation, consumption and storage between buildings can develop measures, which will have the potential for reducing environmental impacts, particularly coming from pre-use phase of buildings characterised by net-zero and off-grid energy operation.

Declaration of competing interest

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

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Appendix A. Supplementary data

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Appendix

Table A1 Case studies related to LCA of residential, modular buildings

Author and year	Location and climate according to Köppen-Geiger classification	Building type	Energy efficiency performance	System boundaries	Life-span [years]	Life cycle assessment indicators	Learning outcomes and key findings
Tavares et al. 2019	Aveiro, Portugal (baseline location). Mediterranean climate (Csb)	One-story, prefabricated house with the container-based structure	Not specified	"Cradle to side."	100	Embodied energy and embodied GHGs emissions.	Light steel or timber framing has the lowest GHG and EE emissions, compared with traditional concrete or steel-based structures. The impacts of transportation vary significantly for the final case study location
Dara and Hachem-Vermette 2019	Calgary, Canada Continental Subarctic Climate (Dfc).	Single-family house made from upcycled shipping containers	Convectional (baseline scenario) and low-energy (alternative scenario)	"Cradle to grave"	50	GWP, SP, PEU, FFC, AP, HHP, ODP, EP, SWG	The operational phase contributed to 85-95 % of the life cycle impacts. Implementation of energy efficiency measures leads to a significant reduction (up to 35% of the environmental effects) The life-cycle operation of the steel-based building caused lower environmental impact than a wood-based housing. In 2018 there were enough leftover containers in Canada to cover 18% of the need for single-detached houses.
Islam et al. 2016	Melbourne, Australia temperate climate (Cfb).	Double-story home, constructed from upcycled shipping containers	Low energy	"Cradle to grave."	60	GWP, AP, EP, CED, water use, solid waste	Operation phase had the most dominating impact for all the indicators expect water use and solid generation. More than 17 million used shipping containers are available globally and reusing them for buildings saves materials and reduce embodied emissions.
Schiavoni et al. 2017	Perugia, Italy Mediterranean climate (Csb)	Housing module based on end-of-life shipping container	Net-zero energy	"Cradle to grave."	10	Primary energy and GWP	The contribution of product stage to life-cycle impacts is the highest in the each of considered scenario. Recycling of steel cladding led to significant environmental benefits.

Atmaca, 2017	Turkey, Mediterranean climate (Csb)	Post-disaster temporary house with a stell based structure	Convectional	“Cradle to grave	15	Life cycle energy and CO_2 emissions	Operation phase has the most significant impact on life-cycle primary energy demand and CO_2 emissions. Reducing the requirements for operational energy by implementing energy efficiency measures is crucial for reducing environmental impacts.
Dong et al .2018	Nanjing, China Humid subtropical climate (Cfa)	Prefabricated temporary housing with aluminium-based structure	Net-zero energy	“Cradle to grave”	20	GHG emissions	The material embodied emissions comprise the most significant proportions of total emissions (82%), with operation emissions, contribute only 12%. Application of passive-energy technologies decreases the area of solar photovoltaic cells as the results embodied emissions decrease by approx. 18%
Chastas et al. 2016 (literature review)	Worldwide locations	90 case building studies	Various: convectional, low energy, passive, net-zero energy	“Cradle to grave”	50 years (normalised value)	Life cycle energy	In the review data sample, there is a lack of case studies from China. European locations dominate case studies. Operating energy appeared to dominate in life cycle energy analysis of residential buildings in the past. Through time as the energy efficiency regulations conform towards the nZEB, the embodied energy leads with a dominating role in LCEA of residential buildings.
Chastas et al. 2018 (literature review)	Worldwide locations	95 case building studies	Various: convectional, low energy, passive, net-zero energy	“Cradle to grave”	50 years (normalised value)	GHG emissions	In the review data sample, there is a lack of case studies from China. European/Australia locations dominate case studies. The analysis on different building’s energy efficiency definitions by considering carbon balances indicates a share for embodied emissions between 9% and 22% for conventional, between 32% and 38% for passive and between 21% and 57% for low energy buildings. For an nZEB of the initial sample, the share of embodied emissions is 71%
Rock et al. 2020 (literature review)	Worldwide locations	238 case-building studies	Various: Existing standard, new standard, new advanced	“Cradle to grave.”	50 years (normalised value)	GHG emissions	The data sample in the review is dominated by Europe locations (175 case studies) with 35 case studies from Asia, and 19 from China. The average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases.

Table A2. Properties of the building envelope and technical systems according to the building design variants.

Partition	Design 1 Base design	Design 2 Low energy	Design 3 Net-zero	Design 4 Off-grid
Superstructure	New, 30 feet, high cube shipping container based on weathering (Corten) steel (wall thickness 2 mm) with 18 mm plywood floor			
Foundation	100 mm concrete slab (20 MPa mix), four stainless steel footings			
External walls	2 mm weathering steel (superstructure), 50 mm mineral wool, 8 mm VIP, 3 mm bamboo. **U=0.26 W/m^{2}K.** Total partition area: 53.1 m^2.	2 mm weathering steel (superstructure), 60 mm mineral wool, 24 mm VIP, 3 mm bamboo. **U=0.1 W/ m^{2}K.** Total partition area: 53.1 m^2.		
Windows	Double-paned glazing filled with argon gas. Aluminium window frame. Total area: 9.9 m^2 U=**2.8 W/m^{2}K, SHGC= 0.76.**	Low emissivity, triple-paned glazing filled with argon gas. Aluminium window frame. Total area: 6.3 m^2, U=**0.71 W/m^{2}K, SHGC=0.36.**		
Internal wall	8.8 m^2 flat glass internal wall, 8.2 m^2 light internal wall with timber frame, 20 mm polyurethane insulation and 3 mm bamboo cladding. **U=0.48 W/m^{2}K**			
Floor	2 mm weathering steel (superstructure), 20 mm polyurethane insulation, 9 mm laminated timber floor, 2 mm PVC (tiles only on the bathroom floor). **U=0.99 W/m^{2}K** Total area: 21.0 m^2	2 mm weathering steel, 24 mm VIP, 60 mm mineral wool, 20 mm polyurethane insulation, 24 mm timber laminated floor, 2 mm PVC (tiles only on the bathroom floor). **U=0.1 W/m^{2}K**. Total area: 21.0 m^2		
Roof	Flat roof (27 m^2) with aluminium-frame awning (3 m) from the south side, 2 mm weathering steel (superstructure), 50 mm mineral wool, 8 mm VIP, 3 mm bamboo finish. **U=0.26 W/m^{2}K**.	Flat roof (27 m^2) with an aluminium-frame awning from the south side (3 m), 2 mm weathering steel 60 mm mineral wool, 24 mm VIP, 3 mm bamboo finish. **U=0.1 W/m^{2}K**	Flat roof (27 m^2) with a **low alloyed steel PV mounting system and** aluminium-frame awning from the south side (3 m), 2 mm weathering steel 60 mm mineral wool, 24 mm VIP, 3 mm bamboo finish. **U=0.1 W/m^{2}K**	Flat roof (27 m^2) with low alloyed steel PV mounting system. **Low alloyed steel overhang (27 m^2)** from the south side. 2 mm weathering steel. 60 mm mineral wool, 24 mm VIP, 3 mm bamboo finish. **U=0.1 W/m2K**
Furniture	Large dining table in wood with four chairs mainly made of steel and bamboo. Bed and desk mostly made from particleboard and fibre board.			
Technical system	**Scenario 1** **Base design**	**Scenario 2** **Low energy**	**Scenario 3** **Net-zero**	**Scenario 4** **Off-grid**

Space heating and cooling	Air-to-air, inverter and reversible heat pump with rated heating and cooling power of 4.9 and 3.5 kW, respectively. SCOP=2.4, SEER=3.8.			
Domestic hot water	Hot water tank (40 l) integrated with the electric coil (thermal efficiency=98%)			
Ventilation	Natural cross ventilation with bathroom exhaust fan with on/off control ($\dot{V}$=200 m^3/h)	Natural cross ventilation with bathroom exhaust fan with on/off control ($\dot{V}$=53 m^3/h)		
Energy supply	Low voltage electrical power from the local grid		Grid-connected, 4.68 kW, Multi-Si PV modules. Rated module* efficiency: 16.8%. 1×5 kW solar inverter.	Stand alone, off-grid system. 9.9 kW Multi-Si PV modules Rated module* efficiency: 16.8%. 2× 5.0 kW solar inverters.
Energy storage	n/a			Lithium-nickel-manganese-cobalt-oxide (NCM) batteries with a total energy storage system capacity of 24 kWh. Deep of discharge: 20%
	Building characteristics			
Envelope tightness (air infiltration rate)	1.0 ACH per hour @ 50 Pa pressure			
Above ground window-floor area ratio [%]	36%	23%		
Building orientation	South orientation. The long side of the building aligned along the east-west axis			

Table A3 Net-present investment cost of case building scenarios

	Design 1 (baseline)	Design 2 (low energy)	Design 3 (net-zero)	Design 4 (off-grid)

Building element/system	Investment cost [¥]			
Shipping container[1]	**16,300**			
Additional low-alloyed steel	n/a	n/a	2,445	4,890
Thermal insulation[2]	7,100	30,800		
Windows and door[3]	20,400	14,300		
HVAC system	3,600			
PV system[4]	n/a	n/a	27,425	50,850
Energy storage[5]	n/a			24,000
Total cost [¥]	47,400	65,000	94,870	144,740
Total cost [USD]	7,584	10,400	15,180	23,158
Total cost [USD/m²Gfa]	**281**	**385**	**562**	**858**

Gfa – gross floor area

[1] Based on market price of weathering 30 ft steel container from Alibaba service

[2] Average price in Chinese market VIP: 125 ¥/m², mineral wool: 8 ¥/m²

[3] Based on price of certified windows exported from UK, double glazing: 3200 ¥/m2, triple glazing: 4000 ¥/m2. The price is higher for Design 1 due to larger door area.

[4] Average price in Chinese market including installation 5000 ¥/kW PV

[5] Average price in Chinese market 1000 ¥/kWh

Table A3.1 Net-present replacement cost of the case building scenarios

	Design 1 (baseline)	Design 2 (low energy)	Design 3 (net-zero)	Design 4 (off-grid)
Building element/system	**Replacement cost [¥]**			
HVAC system	2,016	2,016	2,016	2,016
PV system	n/a	n/a	5,299	1,893
Energy storage	n/a	n/a	n/a	16,949
Total cost [¥]	2,016	2,016	7,315	20,858
Total cost [USD]	322	322	1,170	3,337
Total cost [USD/m²Gfa]	**12**	**12**	**43**	**124**

Table A3.2 Net present: investment, replacement, energy cost and energy payback time of case building scenarios

Net-present cost calculation assumptions:
Project lifetime: 25 years, discount rate:5%, inflation rate:2%, average price of electricity in Shanghai province: 0.54 ¥/kWh

	Design 1 (baseline)	Design 2 (low energy)	Design 3 (net-zero)	Design 4 (off-grid)
Net present, lifetime cost [¥]				
Investment cost	47,400	65,000	94,870	144,740
Replacement cost	2,016	2,016	7,315	20,858
Energy cost	54,732	36,290	0	0
Total cost [¥]	104,148	103,306	99,740	160,708
Total cost [USD]	16,664	16,529	15,958	25,713
Total cost [USD/m²Gfa][2]	**617**	**612**	**605**	**982**
Energy payback time [years]	-	**23.8**	**22.3**	**>25**

Table A4. Building performance simulation inputs.

Climate data: ASHRAE IWEC2 Weather File for SHANGHAI
Normalised thermal bridge value: 1 W/m^2K
Airtightness (at 50 Pa): 1 ACH
Domestic hot water use: 53 l/day person, temp 45 °C
Heating and cooling setpoints: according to Table A3.1
Equipment and lighting power: according to Table A3.2, max. electric appliances peak power 800 W
Ventilation: natural, forced by windows opening
Wind pressure coefficients: based on AIVC recommendations for exposed suburban low-rise building location
Pressure coefficient windows openings: 0.75, internal doors: 0.65
Number of occupants: 2, CLO=1+/-0.2 and MET=1.0
Design occupancy: 2 occupants on weekdays from 5 pm to 7 am and on weekends from 6 pm to 12 noon

Table A4.1. Heating and cooling setpoint schedule.

Temperature schedule	Cooling setpoint	Heating setpoint
Heat pump off outside operation hours and lower heating setpoint at night	**Weekdays** 26 (16:00-07:00) Off (07:00-16:00) **Weekends** 26 (00:00-24:00)	**Weekdays** 20 (16:00-22:00) 15 (22:00-07:00) Off (07:00-16:00) **Weekends** 20 (06:00-22:00) 15 (22:00-06:00)

Table A4.2. Rated power and duration of use for the technical equipment and lighting.

Internal loads	Power [W]	Duration per day [h]
Booster pump	100	1
Laptop	90	8
Fridge	13	24
Exhaust fan from composting toilet	3	24
Extract fan, bathroom	8	On during occupancy
LED lights, living room	10	6
LED lights, bathroom	10	3
LED lights, office	10	3
Crock-pot (slow cooker)	100	8
Electric water heater	500	6
Other plug loads	73	24

Table A4.3. Specifications of the air-air heat pump used in building energy modelling.

Cooling power (rated/min./max.)	3500/200/4200 W
Heating power (rated/min./max.)	4900/500/5600 W
Cooling input power (rated/min./max.)	840/90/1300 W
Heating input power (rated/min./max.)	1450/120/1700 W
SEER	3.8
SCOP	2.4

Table A4.4. Specifications of the PV modules TSM-275PD05.

PMPP - Rated output at STC	275 W
ISC – Short circuit current	9.32 A
VOC – Open circuit voltage	38.1 V
IMPP – Rated current	8.84 A
VMPP – Rated voltage	31.1 V
Loss of power output relating to initial guaranteed power	0.8%/year

Table A5. The excepted service life of building elements and their replacements during the building life-span

Building element	Expected service life (years)	Source of data	Number of replacements during building lifespan of 25years
Superstructure (weathering container)	50-120[1]	Literature [1,2]	0
Foundations	>50	SIA 2032 [3]	0
External walls	>50	SIA 2032	0
External insulation	25	Standard for Building Carbon Emission Calculation [4]	0
Internal walls	>30	SIA 2032	0
Windows	35	Standard for Building Carbon Emission Calculation	0
Doors	35	Standard for Building Carbon Emission Calculation	0
Floor	>50	SIA 2032	0
Roof	>50	SIA 2032	0
HVAC system	10-20	Standard for Building Carbon Emission Calculation	1
Fixed furniture	>30	SIA 2032	0
PV panels	25[2]	Specific product declaration [5]	0
Solar string inverter/ charging station	8-10	Specific product declaration [6]	2
NCM Li-ion batteries	12 (1000 cycles)[3]	Specific product declaration and performance simulation [7]	1
Internal paint	5	Market's average	4
External paint	10	Market's average	2

[1] The service life of superstructure based on weathering (Corteen steel) container is mainly influenced by climate conditions in the place of the final installation. In order to achieve the service life more than 50 years under urban conditions, the corrosion rate after the first 10 years of operation should not exceed 0.2mm/10years [1]. According to available data [2], the measured corrosion rate, occurring after 10 years in the case study climate location zone (humid subtropical climate of China) is in the range between 0.012-0.03mm/10years. Consequently, the long service life requirement is assumed to be achieved.

[2] Producent declares 25 years of product service life, taking into consideration loss of power output relating to initial rated power, which is 0.8%/year.

[3] The service life of NCM Li-ion batteries is depended on cycle durability guaranteed by producer (1000 cycles) and performance of off-grid scenario which determines the annual number of charging-recharging cycles (83 cycles in case off-grid study scenario)

References to data sources:

[1] Producent declaration, revived from https://www.apsaus.com.au/wp-content/uploads/2015/07/Rukki-Corten-Life-Expectancy.pdf. Access on 21.08.2020

[2] Dong, J., Han, E., & Ke, W. (2007). Introduction to atmospheric corrosion research in China. Science and Technology of Advanced Materials, 8(7-8), 559-565

[3] Merkblatt, S. I. A. (2010). 2032: Graue Energie von Gebäuden. Swiss Society of Engineers (SIA): Zurich, Switzerland.

[4] GB/T51366-2019 Construction Carbon Emission Calculation Standard (in Chinese)

[5] Product declaration, Trina solar, revived from https://static.trinasolar.com/sites/default/files/PS-M-0323%20Datasheet_Allmax_US_Apr2018_C.pdf Access on 21.08.2020

[6] Product declaration, ABB string inverters, revived from https://library.e.abb.com/public/056a93c2644e4f15b55475647c6e0156/PVI-5000-EN-Rev%20E.pdf Access on 21.08.2020

[7] Product declaration, Alpha ESS, revived from https://www.alphaess.com/Upload/Images/20191219051618_642397.pdf Access on 21.08.2020

Figure A1. Detailed energy consumption in the building baseline design, Shanghai location.

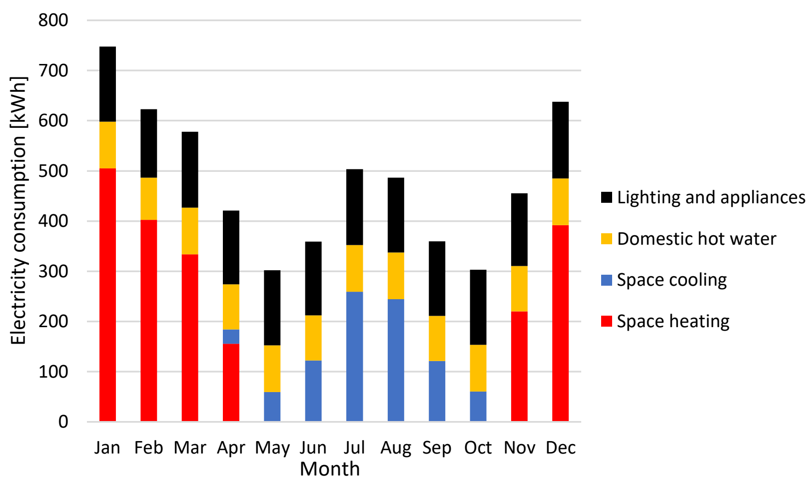


Figure A2. Detailed energy consumption in building designs: 2-4 , Shanghai location.

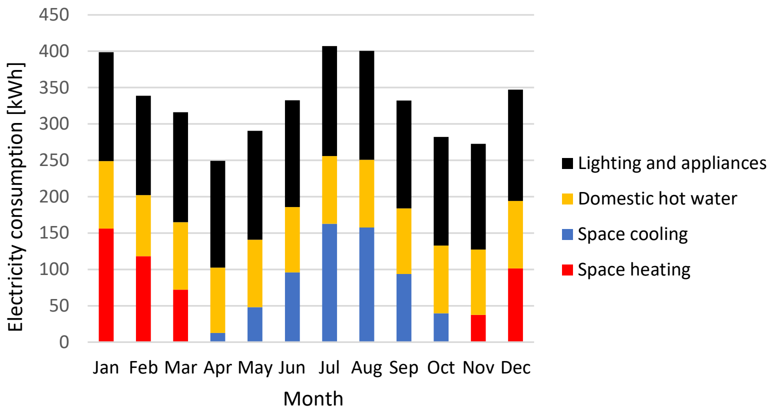
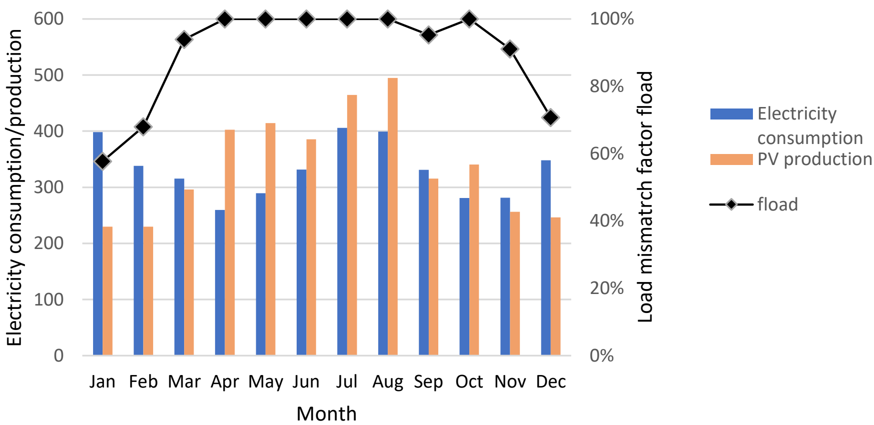
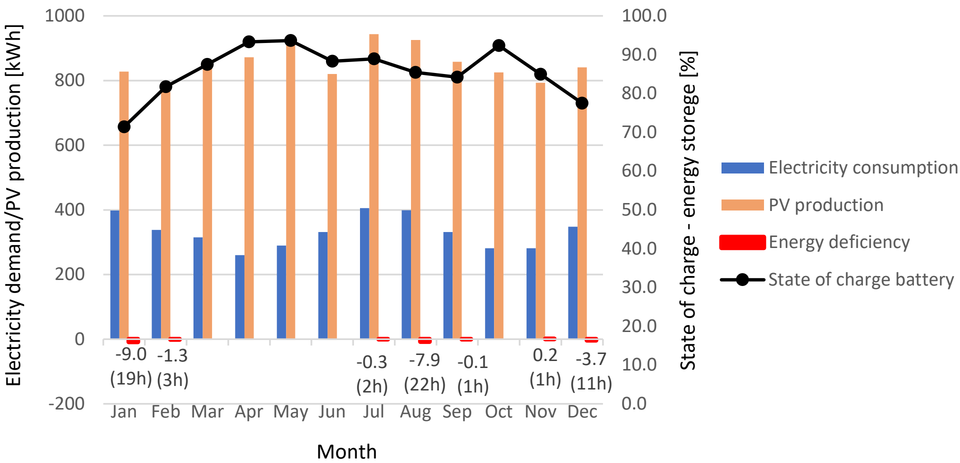


Figure A3. Monthly performance of the case building in design 3 (net-zero).



During six months between April–August and October, the PV production exceeds the building demand. In the rest of the year, a net import of electricity is required. Annually, 89% of the electric demand is met by PV production, while 11% needs to be imported from the grid. 87% of the PV production is used for self-consumption by building, while 13% is exported to the electricity grid.

Fig A4 – Monthly performance of the case building in design 4 (off-grid).



The energy self-sufficiency in the off-grid design is achieved for 99.3% of the annual time (8701 h). The energy self-sufficiency conditions are not met mostly in August (22 h), January (19 h), and December (11 h), during which electricity loads are the highest. The annual mean of the batteries' state of charge is 85.8%.

Fig A5 – Influence of specific building material/system to increase of total pre-use impacts, relative to the baseline design

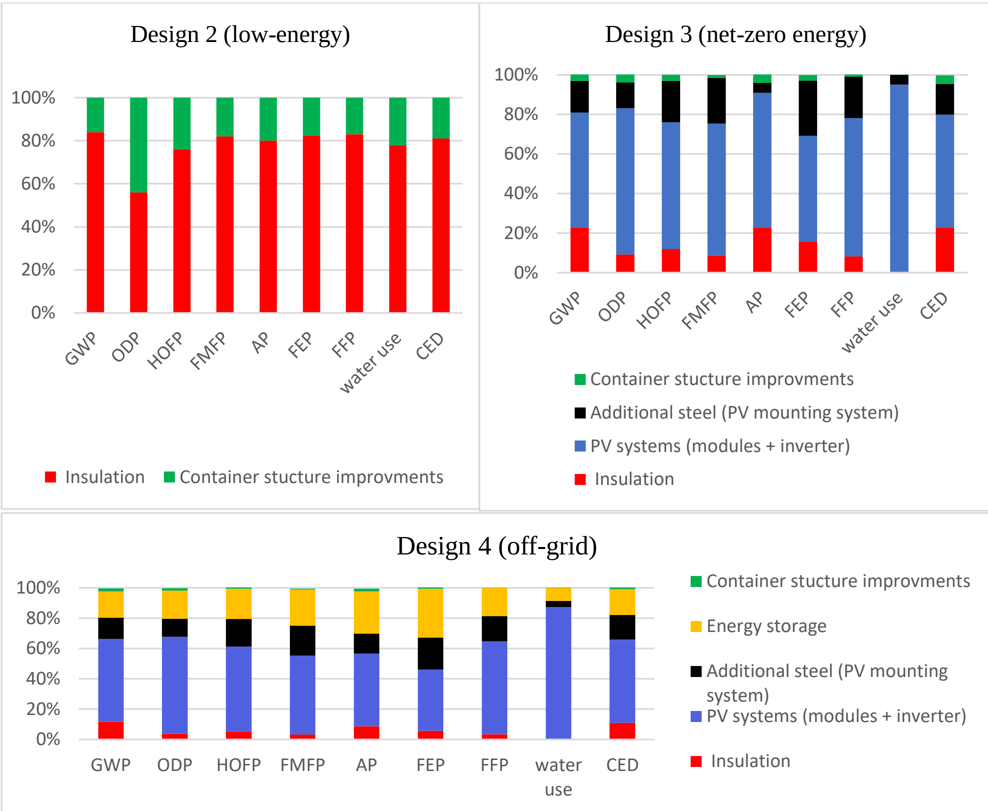


Fig A6 – Environmental loads and benefits coming from the recycling process, relative to the baseline design

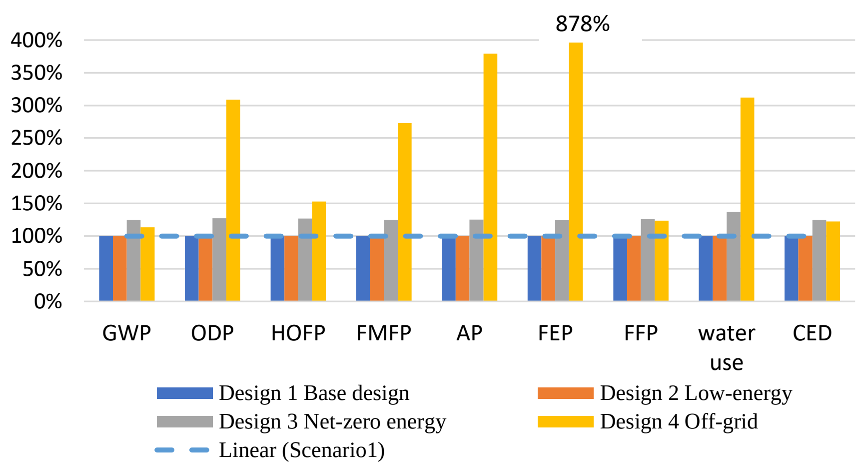


Table A6 Environmental benefits coming from recycling and reuse process

		Environmental benefits			
Environmental impact category	Unit	Design 1 Base design	Design 2 Low-energy	Design 3 Net-zero energy	Design 4 Off-grid
Global Warming Potential GWP	tCO2eq	-3.86	-3.86	-4.82	-4.38
Stratospheric ozone depletion ODP	gCFC-11eq	-0.54	-0.54	-0.69	-1.68
Ozone formation, Human health HOFP	kgNOxeq	-7.81	-7.81	-9.90	-11.96
Fine particulate matter formation PMFP	kgPM2.5eq	-7.45	-7.45	-9.30	-20.35
Terrestrial acidification AP	kgSO2eq	-12.33	-12.33	-15.44	-46.75
Freshwater eutrophication FEP	kgPeq	-1.31	-1.31	-1.63	-11.52
Fossil resource scarcity FFP	toileq	-0.83	-0.83	-1.05	-1.03
Water consumption	m3	-5.88	-5.88	-8.05	-18.34
Cumulative energy demand CED	GJ	-38.92	-38.92	-48.62	-47.57

PAPER VI

Global sensitivity analysis and optimisation of design parameters for low GHG emission life cycle of multifamily buildings in India. *Published in Energy and Buildings (2022).*

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Global sensitivity analysis and optimisation of design parameters for low GHG emission lifecycle of multifamily buildings in India

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ABSTRACT

In India, nearly 25% of citizens live in slums, unfit for a decent living. Replacing the existing residential building stock and the rapid development of the economy will significantly increase energy consumption and related greenhouse gases (GHG) emissions in the coming decades. Consequently, there is a high need of developing low lifecycle GHG emission, affordable and comfortable multifamily building designs, which can be widely implemented in the Indian construction market.

The objective of this article is first to explore the most influential design parameters of the multifamily building located in the in: warm and humid (Bhubaneswar), hot and dry (Jodhpur), and composite (New-Delhi) climate zones of India on life cycle GHG emissions and indoor thermal comfort, and secondly, to perform a multi-objective optimisation considering the life cycle GHG emissions, life cycle cost and initial material investment cost based on the set of the most sensitive design parameters. The study combines a two-step global sensitivity analysis based on the Morris and Fast method with a multi-objective genetic algorithm integrated into one framework based on the parametric multifamily building model with extensive building performance simulations.

The global sensitivity analysis results indicated that for all investigated locations: the apartment's floor area, equipment load, windows-to floor ratio, mechanical ventilation airflow, and cooling temperature setpoint were the most influential design parameters in relation to the lifecycle GHG emissions. Finally, based on the multi-objective optimization, significant reductions in the range of 62–75% in terms of life cycle GHG emissions and 40–54% in terms of life cycle cost were achieved compared to the baseline 7-storey multifamily design scenario based on the minimum requirements of the Indian energy conservation code. At the same time, the initial material investment cost was 25–34% higher. The optimal set of the design strategies, resulting in the lowest life cycle GHG emissions and life cycle cost was found to be minimisation of the apartment's floor area and windows to floor ratio, maximisation of the on-site renewable energy use, and design of a mechanical ventilation system combined with ceiling fans thus enabling the energy-efficient and thermally comfortable operation of the multifamily building with a high cooling temperature setpoint.

1. Introduction

1.1. Environmental impact of the construction sector in India

The construction sector is responsible for 36 % of global final energy consumption and 37 % of energy-related CO_2 emissions [1]. Additionally, when accounting for embodied GHG emissions, the construction sector accounts for more than 40 % of global life cycle GHG emissions [2]. These emissions could potentially triple by 2060 due to the extensive growth of the residential sector and improved access to electricity, air-conditioning and other facilities in developing economies in the Global South [3].

India is the world's third-largest energy-consuming country, contributing to nearly 6 % and 8 % of primary energy and greenhouse emissions globally [4,5]. India's largest emitter of GHG emissions is the energy sector, followed by agriculture and industrial processes. Buildings in residential and commercial sectors consume over 35 % of India's electricity energy [6]. However, on a per capita basis, India's energy use and GHG emissions are less than half of the world's average, mainly because of the limited access of nearly 35 % of the population to decent housing and appliances [7]. Based on future projections, the residential building

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sector development, rapid growth of the economy and standard of living may increase energy consumption and related GHG emissions by more than four times in the next 20 years [8]. Based on the fact that most areas in India are located in the cooling dominated climates, the increased use of air-conditioning systems for achieving thermal comfort in the buildings is widely recognised to become the major contributor to GHG emissions nationwide [9].

Consequently, there is an increased need to develop low GHG emissions and affordable residential buildings concepts with the wide use of energy efficiency measures, which can be successfully implemented in the construction market. The Government of India emphasises this need in annual energy efficiency reports [10], indicating that the broad implementation of building energy efficiency measures and minimum requirements can reduce>30 % of energy and GHG emissions in the national building stock. This example shows the importance of introducing the relevant building standards and other regulatory measures to enhance energy efficiency and decarbonisation of the construction stock, especially in rapidly developing economies like India. In recent years, the Indian Government, after a successful release of the Energy Conversation Code (ECBS) for the commercial buildings [11,12], had introduced the Energy Conversation Code for Residential Buildings [13]. This standard focuses on the building envelope properties and sets minimum performance requirements to limit heat gains (for cooling-dominated climates) and heat loss (for heating-dominated climates).

In this study, the design of the multifamily building used for global sensitivity analysis and multi-objective optimisation is aligned with Energy Conversation Code for Residential Buildings as described above (for more details, see Methodology section).

1.2. Influence of design parameters on the environmental performance of the buildings

In the sustainable building design process, a sensitive analysis identifies the most influential design parameters, contributing to developing alternative, more sustainable design solutions [14]. Additionally, a sensitivity analysis can serve as a basis for identifying and choosing the critical design parameters for frameworks, simplifying the optimisation problem and significantly reducing the computation time. [15,16]. Sensitivity analysis methods can be categorised into two main groups: local and global. The local sensitivity analysis assesses model response to only one local parameter, in contrast to a global sensitivity analysis based on the simultaneous variation of all input factors. The model response is evaluated over the entire range or for each input factor.

Consequently, global sensitivity analysis methods provide more accurate information about the effect of varying input factors; however, it needs more computational resources. The most commonly used global methods include the Morris elementary effect [17], Sobol [18] and Fourier Amplitude Sensitivity Test (Fast) [19]. The main advantage of the screening Morris method is a low computation cost compared to the other methods. The main drawback is that the screening method does not consider the effect of the complex interactions among variables found in variance-based Sobol or Fast methods [20].

Based on the global sensitivity analysis methodology, numerous researchers have investigated the most influential building design parameters impacting building performance for different locations and climate conditions worldwide (Table 1). Zeferina et al.,2020 [21] found that the ventilation rate, cooling temperature setpoint, and lighting power density were the most influential parameters on the total energy consumption in a large office building independent of the analysed climatic conditions. In the case study performed by Li et al.,2018 [16] based on a medium-size, nearly zero-energy office building in Hong Kong, the window to wall ratio, indoor temperature setpoint, and outdoor infiltration air rate were found to be the main parameters that contributed the most to annual energy consumption. Similarly, research conducted by Delgarm et al.,2017 [22] indicated that for a typical office room located in warm climate zones, the fenestration area, solar heat gain coefficient and building orientation are the most crucial design parameters contributing to total annual energy consumption. On the other hand, various sensitive analyses [23,24] per-

Table 1
Overview of sensitive analysis studies in the design of sustainable buildings.

Reference	Building type and gross floor area	Location and climate type	Method	Objectives	Most influential parameters
Zeferina et al.,2020 [21]	Office Building, 46 430 m^2	a) Singapore, tropical humid b) Cairo, hot desert c) Athens, Mediterranean d) d)Beijing, continental e) Lisbon, Mediterranean f) London, humid maritime climate	Morris and Sobol	Annual and peak energy consumption related to space cooling, HVAC, and total	Ventilation rate, cooling setpoint temperature equipment and lighting densities
Li et al.,2018 [16]	Multifunctional, educational building, 14 700 m^2	Hong Kong, humid subtropical	Regression method (local), Morris and FAST	Annual energy consumption	Skylight to roof ratio, window to wall ratio, windows solar heat gain coefficient, indoor temperature setpoint, infiltration air flowrate
Delgarm et al.,2017 [22]	Office room 160 m^2	Different climate zones in Iran (Cold, Temperate, Warm-dry, and Warm-humid)	OFAT (local) and Sobol	Cooling, Heating, Lighting, and total annual energy consumption	Windows size, building orientation and glazing solar transmittance
Song et al., 2014 [23]	Office building, 4000 m^2	London, humid maritime	Sobol	Cooling, Heating energy consumption and operational carbon emissions	Heat recovery unit (Heating), windows solar heat gain coefficient (Cooling), Peak lighting and equipment gains (operational carbon)
Mechri et.al,2010 [24]	The typical floor of the office building, 400 m^2	Different climate zones in Italy (Mediterranean, Temperate, Warm and Humid)	FAST	Cooling and heating load	Windows to floor ratio, compactness ratio, thermal insulation thickness

Table 2
Overview of the selected building design optimisation studies.

Reference	Building type and gross floor area	Location and climate type	Optimisation approach, algorithm	Objectives	Design variables
[16]	Multifunctional, educational building, 14 700 m2	Hong Kong, humid subtropical	Single objective, genetic algorithm (NSGA)	Annual energy consumption	Window solar heat gain coefficient, window to wall ratio, building orientation, solar absorbance, overhang ratio
[28]	Three-storey residential building 600 m2	Chongqing (China), humid subtropical	Multi-objective, genetic algorithm (NSGA)	Annual energy consumption and thermal comfort	Orientation, shape, window-wall ratio, heat inertia and transfer coefficients of walls, roof and window
[15]	Single-family house, 83 m2	Parana (Argentina) , humid subtropical	Single objective, genetic algorithm	The weighted sum of annual energy consumption and thermal discomfort	Thermal transmittance and capacity of building partitions
[29]	Single-family house,186 m2	Balton Rouge (USA), humid subtropical	Multi-objective harmony search algorithm (HS)	Life cycle cost and GHG emissions	Building envelope elements
[30]	Multifamily residential building, 740 m2	Budapest (Hungary), continental	Multi-objective, genetic algorithm (NSGA)	Environmental indicators: GWP[1], EP[2], POCP[3], ODP[4], CED[5], AP[6]	Number of storeys, building width, windows to wall ratio, glazing type, insulation type and thickness
[31]	Renovation of an apartment building, 2779 m2	Hvalso(Denmark) , temperate	Multi-objective, genetic algorithm (Omni-Optimizer)	Operational and embodied energy, GWP[1] and investment cost,	Insulation material and thickness of building partitions, glazing type, heating technology

[1] Global warming potential,
[2] Eutrophication potential,
[3] Photochemical ozone creation potential,
[4] Ozone depletion potential,
[5] Cumulative energy demand,
[6] Acidification potential.

formed on office buildings in dominant heating climates show that the ventilation heat recovery efficiency and thermal insulation thickness are the most critical design parameters influencing energy consumption.

When analysing existing literature (Table 1), there seems to be a research gap related to the lack of global sensitive studies based on the residential building typology in India. Secondly, objectives in existing studies are based mainly on energy indicators, excluding the building's life cycle impact and indoor environmental quality.

1.3. Building design optimisation

Optimisation can be defined as a set of applied mathematics equations that develop particular methods to find the maximum or minimum values of the objective function by changing the values of the input variables, which are characterised by bounds and constraints in most engineering problems [25]. The possible range of design parameter values in the building design optimisation frameworks usually depends on the building standard's technical and architectural quality requirements [26]. Optimisation frameworks can be categorised into two main groups: single objective and multi-objective, depending on the number of objective functions to be solved. The single-objective optimisation aims to find the best solution for a specific objective function, with usually only one optimum value. However, in most cases, the optimisation problem is more complex and based on two or more conflicting optimisation goals. The solutions of multi-objective optimisation are compromise solutions that can be different from the absolute minimum or maximum of each objective function. If no preference is expressed for a specific objective function, the obtained solutions of a multi-objective optimisation represent a set of equally optimal compromise solutions, called Pareto front [27].

The overview of existing research based on the optimisation of the residential buildings located in warm climates indicates that the building's optimisation objectives focus primarily on operational energy consumption and thermal comfort metrics (Table 2). This finding is also in line with the review study performed by Longo et al. 2019 [25], which analysis showed that the most common objective functions are the costs and the operating energy consumption, while the environmental aspects are often neglected.

However, in recent years, the number of optimisation studies that consider the lifecycle environmental indicators, including operational and embodied impacts, has grown, mainly in Europe, because of the vast interests in the full lifecycle decarbonisation of the construction sector. Among all optimisation algorithms, the genetic ones are the most favourable and used methods, considering the correlation and interaction between the design parameters [25].

Based on the literature analysis, only a few studies intercorporate lifecycle environmental impacts with indoor environmental quality and lifecycle cost. Additionally, there seems to be a research gap related to a lack of holistic optimisation building case studies in India. This research tries to fill this gap by exploring the influence of the design parameters and optimal design solutions for low GHG emission, comfortable and affordable multifamily residential building case study in India's various climate zones. The created framework integrates parametric modelling, building energy simulations, life cycle GHG emission, and cost assessment as a base for global sensitivity analysis and further multi-objective optimization.

2. Methodology

This research is based on the holistic modelling approach, which integrates a parametrical, architectural model of the multifamily building with a comprehensive building environmental performance assessment, linking building energy simulations, life cycle GHG emission and cost assessment, global sensitivity analysis, and genetic multi-objective design optimisation into one framework. The general structure of the framework is described in the sections below, while the most important data sources are summarised in Table 3.

Table 3
Source of the essential methodological data.

Data	Source and reference
Energy efficiency requirements (baseline/benchmark model)	Energy Conversation Code (ECCRB) for Residential Buildings [13]
Climate data	International Weather for Energy Calculation (IWEC2.0) [32]
Embodied GHG emissions of construction materials	India Construction Materials Database of Embodied Energy and Global Warming Potential [33] and Ecoinvent 3.5 [34]
The GHG emission factor of electricity	CO_2 Baseline Database for the Indian Power Sector [35]
Construction materials cost	Analysis of Rates for Delhi [36]

2.1. Parametrical building model and main design parameters

In this research, to assure the possible most broad implementation of the research outcomes, the base case study model is developed using the multifamily building design example presented in Energy Conversation Code (ECCRB) for Residential Buildings, developed by the Indian Government [13]. The building model was created in the Rhinoceros 3D software coupled with the Grasshopper plugin [37], enabling the parametric design model based on the 30 main parameters, grouped into seven categories: architectural layout, integrated shading, envelope/material properties, HVAC system, lighting and equipment, occupant behaviour and renewable energy systems (Table 4). The type and range of building design parameters are strictly related to mandatory requirements presented in ECCRB and local construction market conditions. Each floor in the multifamily building consists of 16 apartments, predicted for a living of a standard, average-income family with four members. The benchmark(base) design scenario is based on the market dominated construction approach (Fig. 1) (Table.4) being in line with requirements and guidelines presented in Energy Conversation Code (ECCRB) for Residential Buildings. The benchmark design scenario is based on the seven-floor multifamily building, with 4720 m^2 of the gross floor area (GFA).

2.2. Building locations and climate data

In this study, the performance of the multifamily building design is evaluated for three cities in India, located in different cooling-dominant climate zones: Bhubaneswar (hot and humid), New Delhi (composite), and Jodhpur (hot and dry) (Fig. 2). The climate data are based on the international weather measurements for energy calculations (IWEC2.0) maintained by National Climatic Data Centre [32]. The overview of climate conditions in each explored location is presented in Fig. 3. A significant difference can be observed in the number of heating degree days (base 15℃), which vary between 34 in Bhubaneswar to 397 in New Delhi. The maximum annual dry bulb temperature is highest for Jodhpur – 47 °C, and the lowest: 41.7 °C in Bhubaneswar.

2.3. Building performance simulations (BPS) – Quantification of annual operational energy use, renewable generation, and indoor thermal comfort

Evaluation of the annual energy consumption, renewable energy generation and the occupant's thermal comfort level was performed using the building energy models created in the Ladybug and Honeybee tools [38], strictly based on the parametric geometry models. The created multi-zone energy models were evaluated using the Openstudio platform [39] based on the EnergyPlus simulation engine [40]. The evaluation of the annual energy use was based on the IWEC 2.0 weather database and included heating and cooling (air-conditioning), domestic hot water production, lighting, and equipment energy use.

Each apartment in the analysed multifamily building is designed for the typical medium-class Indian family with four members. The profile of the occupancy, as well as operation schedules for lighting and equipment, were adapted from [41] and presented in Appendix (Fig. A1). The cooling and heating system are based on an ideal air-air heat pump model with infinite cooling/heating capacity. The seasonal coefficient of performance depends on the input design parameter (SEER) (Table 4), ranging between 250 and 350 %. The staircase and corridor spaces of the building are not conditioned. The maximum indoor relative humidity threshold is 70 % for space conditioning areas. The investigated building energy model includes the possibility of on-site renewable energy generation from the thermal solar collectors, photovoltaic modules, or a combination of these mounted on the building roof. The roof area coverage of solar and photovoltaic modules depends on input design parameters PV and SC (Table 4). The technology of thermal solar collectors and PV modules are based on the glazed plate collectors and the crystalline silicon (c-Si) PV modules. The total annual energy consumption of the building is determined as a result of total energy demand and possible compensation coming from annual renewable energy generation. A more detailed description of energy model assumptions, and technical systems, can be found in Appendix section: A1.

The evaluation of occupant thermal comfort is based on the Fanger PMV comfort model according to the ASHRAE-55 thermal comfort standard [42]. The occupants' human metabolic rate (MET) is set as 0.5, while the clothing insulation factor (CLO) varies from 0.5 in the cooling period to 1.0 in the heating period. In the building design scenarios, which exclude indoor ceiling fans operation, the indoor airspeed velocity is estimated as 0.1 m/s. While including the ceiling fans operation in the building design, this airspeed velocity is predicted as 0.7 m/s, as recommended in [43]. The minimum indoor temperature for turning on the ceiling fans is set as 27.0℃, based on the guidelines and the tool developed by the Center for the Build Environment, University of California, Berkley [44,45].

2.4. Building material's inventory, embodied GHG emissions and cost background data

The parametric design model of multifamily was integrated by a Python scripting language [46], firstly with the calculated building materials inventory quantities and secondly with the background data related to the construction material's embodied GHG emissions and cost. The building materials inventory covers the building systems and components as presented in Fig. 4.

The primary source of the material's embodied GHG emissions is an India Construction Materials Database of Embodied Energy and Global Warming Potential [33], developed by the World Bank with the European Union Partnership. The data has been developed using local knowledge and data, including stakeholder consultation. Consequently, the database provides generic data for construction products typically used in India(both manufactured locally and imported). The system boundary for each material used in the database represents the" cradle to gate", covering the product stage (A1-A3), including the raw materials supply, transport and manufacturing as defined in EN 15804 + A2,2019 [47]. The additional database used for the materials not included in the Indian database is Ecoinvent 3.5 [48]. " This data is a base for calculating the embodied GHG emissions related to the building materials production (A1-A3) and their replacement (B4) during the building lifespan" Evaluating investment and replacement materials cost is based on the Governmental database: Analysis of Rates for Delhi [36]. The calculations exclude the labour costs

Table 4
Range of building design parameters, and design specification of benchmark scenario.

Category	Parameter	Abbreviation	Range	Benchmark (base) design scenario	Unit
Architectural layout	Apartment floor area	AA	30–60	30	m^2
	Floor's height	FH	2.8–3.2	3.0	m
	Floors number	FN	4–12	7	[-]
	Windows to floor ratio	WFR	ECCRB [1]-50	17	%
	Orientation	O	0–360	0 (N/S)	°
Integrated Shading	Roof overhang/ balcony length	RO/BL	0–3	2	m
	Side-fin length	SFL	0–2	0	m
Envelope/material properties	Construction type (external walls)	CTW	Reinforced concrete, Clay brick, Autoclaved aerated concrete	Autoclaved aerated concrete	–
	Insulation type	IT	Extruded polystyrene, Glass wool, Stone wool, Wooden Fibre Insulation	n/a	–
	Insulation thickness walls	ITW	0–15	0	cm
	Solar reflectance	SA	0.4–0.8	0.4	–
	Insulation thickness roof	ITR	ECCRB [2]-15	5	cm
	Window U value	UW	1.2–4.0	4	W/m^2 K
	Window solar heat gain Coefficient	SHGC	0.25–0.7	0.6	–
	Infiltration rate	AT	1.0–5.0	3	1/h (50 Pa)
	Concrete type	CT	Standard, Low carbon	Standard	–
	Construction type (internal walls)	IWC	Concrete, Clay Brick, Autoclaved aerated concrete, Timber	Autoclaved aerated concrete	–
HVAC system	Airflow per person (mechanical ventilation)	MVA	0(natural)-36	0 (natural ventilation)	m3/h person
	Sensible heat recovery efficiency	HRS	0–85	n/a	%
	Latent heat recovery efficiency	HRL	0–70	n/a	%
	Energy efficiency ratio- air-conditioning	SEER	2.5–3.5	3	–
	Energy efficiency ratio domestic hot water	SCOP	0.9–3.0	0.9	–
	Ceiling fan air velocity	CF	0–0.7	0	m/s
Lighting and equipment	Lighting load	LL	2–10	3	W/m^2
	Equipment load	EQ	5–10	5	W/m^2
Occupant behaviour	Cooling temperature setpoint	TC	24to29	26	°C
	Heating temperature setpoint	TH	20to22	20	°C
	Domestic hot water use	DHW	35–75	35	l/person day
Renewable energy systems	Roof coverage with PV panels	PV	0–90	0	%
	Roof coverage with solar thermal panels	SC	0–90	0	%

[1] Minimum requirement of window-to-floor area ratio (WFR) is based on Energy Conversation Building Code for Residential buildings (ECBCR): Composite climate zone (New Delhi): 12.5%, Hot-Dry (Jodhpur): 10%, Warm-humid:(Bhubaneswar) 16.5%.
[2] Thermal resistance of the roof shall comply with the maximum value of 1.2 W/m^2K.

and the cost of the building plot. The detailed overview of the construction systems and materials' embodied GHG emissions, price and the background data sources are presented in the Table 5.

2.5. Global sensitive analysis framework and methods

The sensitive analysis applied in this study follows the two-steps approach. In the first step, the Morris Screening method [17] was adopted to assess the impact of the whole set of 30 design parameters' on life cycle GHG emissions and thermal comfort level (performance objectives). Consequently, the collection of key design parameters identified as the most influential on model outputs was used in the second step as the input for a more complex and detailed global sensitivity analysis, applying the Fourier amplitude sensitivity test (FAST) [19] method. The two-step global sensitivity analysis is coupled with the holistic parametric framework using the Salib library [49], based on the Python environment.

2.5.1. Performance objectives

The global sensitivity analysis is conducted to identify the design parameters contributing the most to lifecycle GHG emissions and annual thermal comfort level in the case of a multifamily

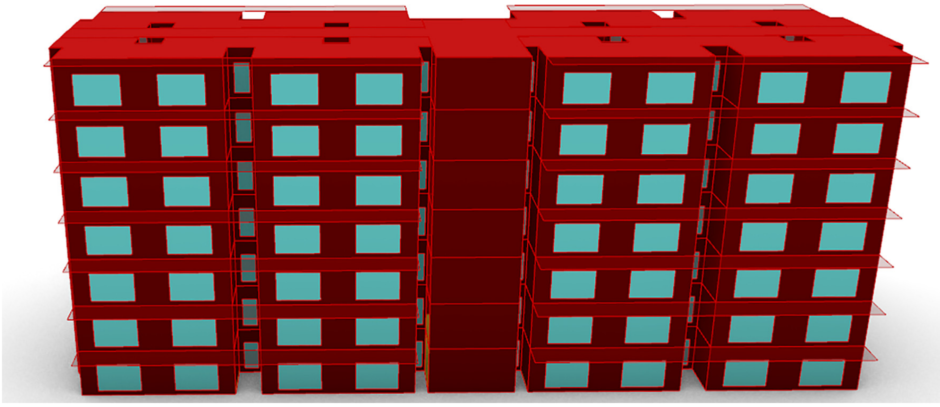

Fig. 1. Benchmark, multifamily (7storey) building model(design).

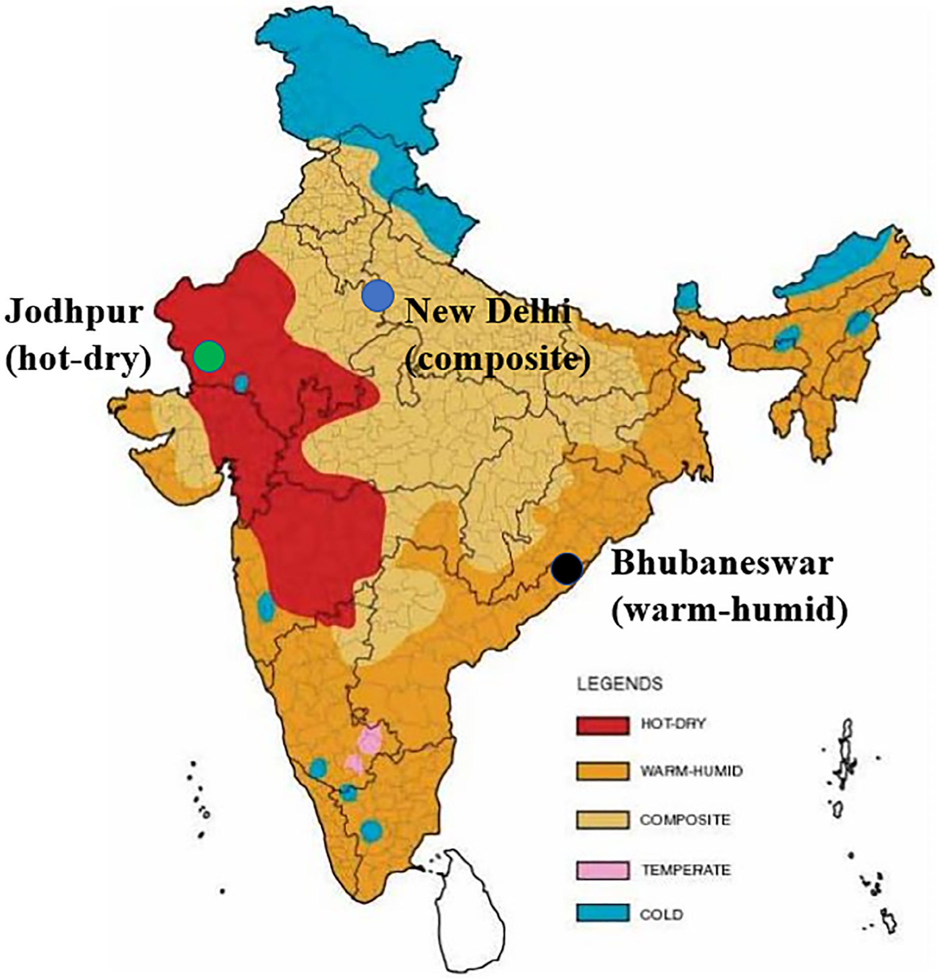

Fig. 2. Investigated building locations and climate zones of India. Adopted from Bureau of Energy Efficency (BEE),2018 [13].

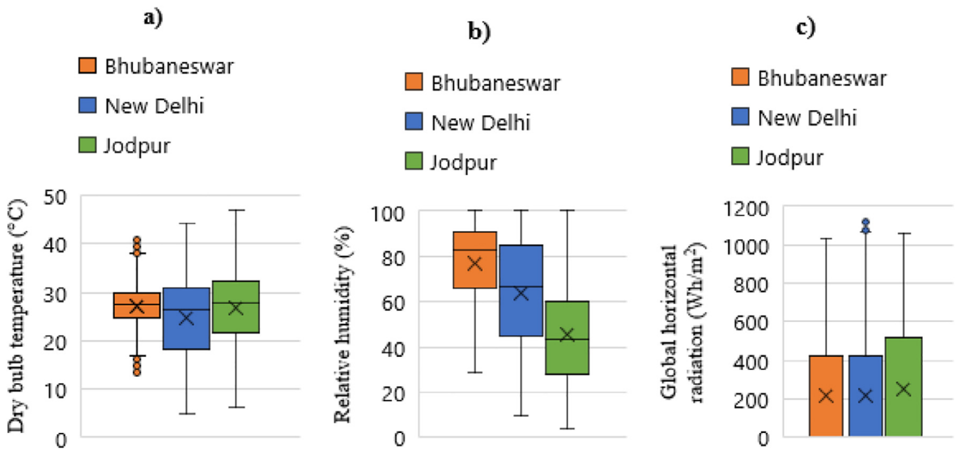

Fig. 3. Annual distribution of climate data: a) Dry bulb temperature, b) Relative humidity, c) Global horizontal radiation in investigated locations: Bhubaneswar, New Delhi, and Jodhpur.

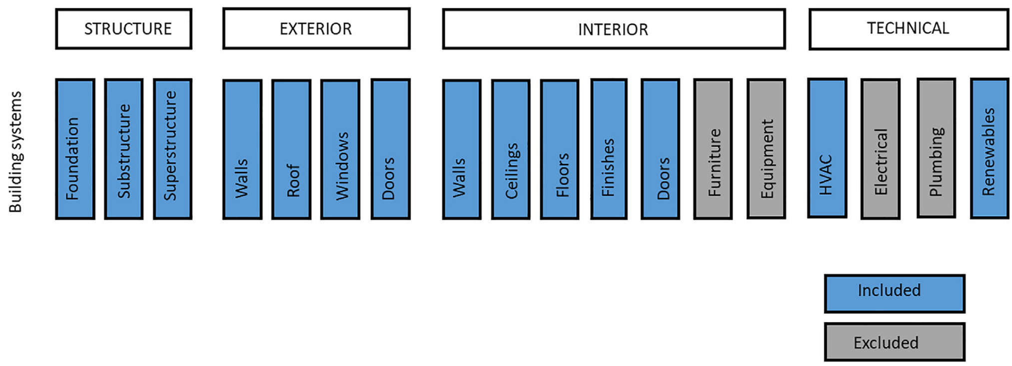

Fig. 4. Scope of the building systems included in the materials inventory.

building. The system boundaries for the lifecycle GH emissions include the production of the construction materials (A1-A3), their replacement (B4) and operational energy use (B6). Building reference service life (RSL) is estimated as 50 years, which is consistent with the other studies for India [43,44], and in agreement with the assumption of durable construction. Definitions for component service life are taken from the existing literature and construction materials declarations (Appendix, Table A3). Operational GHG emissions from energy use are calculated as the multiplication of the building's annual energy consumption and static, the average GHG emission factor of the Indian electricity grid: 0.91kgCO_{2eq}/kWh, which is based on the Indian Governmental data [35].

The choice of the functional unit used in the lifecycle assessment of the buildings significantly influences the life cycle impact results. The impact of building construction and operation stages, in absolute terms, tend to increase together with the amount of its area and volume. Still, the building impact value divided by its area, volume or occupants may change the results (Asdrubali et al., 2013). Norman et al. (2006) compared dwellings with variation in occupancy and found that the life cycle GHG emissions value using a functional unit based on m^2 per year were smaller in a single dwelling with larger occupancy compared with a multi-dwelling unit, Although the ranking of lifecycle GHG emission values was inverted when using a functional unit based on occupants per year.

In this study, the functional unit of the life cycle GHG emissions is defined as per capita(occupant) over a year [kgCO_2eq/capita year]. The selection of this unit over the most used floor-based indicator is recommended [50] when assessing the influence of the different space efficiency design parameters and strategies (in this study, the apartment's floor area (AA) design parameter).

The second performance objective used in the global sensitivity analysis is an annual thermal comfort level, defined as the percentage with thermally comfortable conditions. Precisely, it is calculated as the percentage of the total number of hours in the year, when predicted mean vote (PMV) in the analysed thermal zones is between −1.0(slightly cool) and + 1.0 (slightly warm).

2.5.2. Morris Elementary effect method

The first step of the global sensitivity analysis was based on the Morris Elementary Effect method, which determines two quantitative indicators: absolute mean (μ^*), which measures the overall influence of each input factor on the model outputs, and standard deviation (σ), which presents the effect of each input factor due to the interaction with other parameters. The Morris Elementary method's key idea is to initiate the model evaluations from various

Table 5
Properties and embodied GHG emissions and cost of building materials.

Material/system	Density	Thermal conductivity	Specific heat	GHG emissions	Unit	Source (GHG emissions)	Cost	Unit	Source (cost)
	kg/m3	W/mK	J/kgK	kgCO2eq/ unit			$/ unit		
1.Aggregate	410	2	1180	0.009	kg	India Construction Materials	18.4	m3	Government of India.
2. Ready mix concrete with ordinary Portland cement (OCP), standard concrete	2200	0.53	840	0.011	kg	Database of Embodied	32.6	m3	Analysis of rates for Delhi
3. Ready mix concrete with fly ash (30 % pozzolana), low-carbon concrete	2200	0.53	840	0.0084	kg	Energy and Global Environmental Indicators for Warming Potential Materials	37.5	m3	
4. Autoclaved aerated concrete	500	0.184	1240	0.5	kg		48.3	m3	
5.Bitumen felt (membrane)	1100	0.23	1000	0.24	kg		1.2	m2	
6.Steel reinforcement (rebar)	7850	50	450	2.6	kg		611.2	t	
7.Cement plaster	2200	1	1000	0.44	kg		79.1	m3	Government of India.
8. Cement mortar	2800	0.88	896	0.14	kg		74.2	m3	Analysis of rates for
9. Particleboard	710	0.21	1000	0.2[1]	kg		4.5	m2	Delhi
10.Timber (kiln-dried)	700	0.18	1600	1.07[1]	kg		611.6	m3	
11. Fired clay bricks (bulls trench kiln)	1920	0.81	1000	0.32	kg		82.4	m3	
12. Ceramic tiles	1780	1.2	1000	0.67	kg		12.4	t	
13. Wood laminate flooring	1200	0.046	2100	2	kg		25.3	m2	
14. Expanded polystyrene (EPS)	25	0.035	1400	2.9	kg		142.6	m3	
15.Glass wool thermal insulation	16	0.043	920	2.5	kg		39.2	m3	
16.Stone wool thermal insulation	25	0.033	700	1.2	kg		50.7	m3	
17.Wood fibre insulation	50	0.037	2100	0.21[1]	kg		73.5	m3	
18.Single pane glazing	–	–	–	12	m2	Ecoinvent database	54.3	m2	
19.Double pane glazing (uncoated)	–	–	–	39.3	m2		88.2	m2	
20.Double pane glazing (coated)	–	–	–	45.2	m2		98.8	m2	
21.Window frame (timber)	700	–	–	2.4	kg		–	–	
22. PV s-Ci module	–	–	–	270.4	m2		638.0	kW	
23. Flat glazed solar collector	–	–	–	172.8	m2		162.0	m2	
24. Ceiling fan	–	–	–	13.1	unit		27.1	unit	Market data
26.Mechanical ventilation system (Without recovery)	–	–	–	400	unit		300.0	unit	
27. Mechanical ventilation system (With heat or energy recovery)	–	–	–	420	unit		500.0	unit	
28. AC room unit	–	–	–	25.1	unit		400.0	unit	

nominal points randomly selected over the grid and gradually advance one grid jump between each model evaluation (one at a time) along a different dimension of the parameter space chosen randomly.

The minimum number of simulations (computation cost) needed for the Morris Method is determined by the equation (1):

$$n = r * (k + 1) \quad (1)$$

where:

n – minimum number of outputs needed for a Morris Elementary Effect Method.
r – number of trajectories (rmin = 10).
k – number of design parameters (for this study k = 30).

Consequently, 310 simulations were performed for this study for each analysed location. The real computing time was around 15 h for evaluating the Morris sensitive measures for each building location.

2.5.3. Fourier amplitude sensitivity test variance method (FAST)

In the second step, the set of the most influential design parameters to performance objectives based on the Morris Elementary Method was further evaluated using the Fourier amplitude sensitivity test (FAST) variance-based method. FAST is one of the most used global sensitivity analysis methods, which uses the periodic sampling approach and a Fourier transformation to decompose the model output variance into partial variances contributed by different model parameters. The two main sensitive measures of the FAST method are first-order effect (S_i) and total order effect (S_t). The first order of parameter (S_i) reflects its main effect, indicating how much the output variance can be reduced if the parameter (i) can be fixed, while the total order of parameter (S_t) is an addition of the main parameter effect and interaction effects with other parameters.

The minimum number of simulations (computation cost) needed for the Fourier amplitude sensitivity test (FAST) variance method is determined by the equation (2):

$$n = N * k \quad (2)$$

where:

n – minimum number of outputs for a Morris Elementary Effect Method.
N- minimum sample size to generate, (N > 64).
k – number of design parameters (for this study k = 14).

Consequently, 910 simulations were performed for this study for each analysed location. The real computing time was around 45 h for evaluating the FAST, sensitive measures for each investigated location.

2.6. Multiobjective optimisation

The two-step global sensitive analysis served as the base for identifying the most important design parameters, influencing life-cycle GHG emissions and thermal comfort level the most. Consequently, the key nine design parameters were chosen to be optimised further using a multi-objective optimisation framework based on the HypE genetic algorithm [51] provided by the Octopus tool [52]. The other design parameters follow the benchmark design scenario values (Table 4). The settings of the optimisation algorithm, including high mutation rate and relative population size, were set to avoid getting stuck in local optima and are presented in Table 6.

The three objective functions in the multi-objective framework were defined as:

i) Annual life cycle GHG emissions per capita ($GHG_{cappita}$), calculated based on equation (3).

$$GHG_{capita} = \frac{GHG_{embodied} + GHG_{operational}}{RSL * n_{occupants}} \quad (3)$$

where,

GHG_{capita} – annual life cycle GHG emissions per capita $[kgCO_{2eq}/capita\ year]$

$GHG_{embodied}$ – Embodied GHG emissions related to materials production $(A1 - A3)$ and replacement $(B4)$ $[kgCO_{2eq}]$

$GHG_{operational}$ – Operational GHG emissions related to the energy use $(B6)[kgCO_{2eq}]$

RSL – building service life [years] = 50 (based on references provided in Section 2.5.1)

$n_{occupants}$ – number of occupants living in the analysed multifamily building

ii) Life cycle cost per capita [$/capita] calculated based on equations ((4)–(6)).

$$LCC_{capita} = \frac{LCC_{embodied} + LCC_{operational}}{n_{occupants}}[/capita] \quad (4)$$

$$LCC_{embodied} = C_0 + \sum \frac{C_{comp}}{(1+i)^t}[/capita] \quad (5)$$

$$LCC_{operational} = \sum_t^{RSL} \frac{C_{el} * (1+r)^t}{(1+i)^t}[/capita] \quad (6)$$

where,

LCC_{capita} – life cycle cost per capita.[/capita]

$LCC_{embodied}$ – life cycle cost per capita including initial materials investment cost and replacement.[/capita]

$LCC_{operational}$ – life cycle cost related to energy use [/capita]

Table 6
Settings of the optimisation algorithm.

Parameter	Value
Population size	80
Maximum number of generations	20
Elitism	0.5
Mutation probability	0.2
Mutation rate	0.9
Crossover rate	0.8

C_0 – initial investment cost related to building materials []

C_{comp} – the cost of the replaced component [

C_{el} – the cost of electricity [

t – year of analysed building lifetime, $t = (0, 50)$

i – discount rate [%]

r – annual increase of electricity price [%]

The assumed electricity price, 0.08$/kWh and the increase rate of electricity cost – 3 %/year is based on the Indian central electricity regulatory commission report, 2019. [53] The discount rate – of 6 % is based on the avarage bank rate from the last 5 years (2017–2022) as presented by the Reserve Bank of India (RBI) [54].

iii) Initial material investment cost - $\boldsymbol{C}_0$ [$].

Additionally, to assure that all solutions of multi-objective optimisation framework comply with Indian building standards and acceptable indoor environmental quality levels, the two constraints were implemented into the model:

i) Residential envelope heat transmittance value (RETV) is less than 15 W/m^2. The details of the RETV calculation method can be found in Appendix, Section A3.
ii) Annual thermal comfort level is higher than 85 %.

3. Results and discussion

Performance of the benchmark(base) design scenario of the multifamily building.

The distribution of the annual energy consumption of the base case (benchmark) buildings related to the cooling, heating, production of domestic hot water, equipment and lighting in the investigated locations is presented in Fig. 5, together with the results of the annual thermal comfort level.

The highest annual energy consumption: 166 kWh/m^2a is observed in the warm and humid climate zone of Bhubaneswar city, followed by New Delhi (composite climate, 133kWh/m^2a) and Jodhpur (hot and dry climate, 127kWh/m^2a). It is clear that differences between locations are mainly related to the changes in the air-conditioning energy demand. In all locations cooling process is found to be a dominant source of annual energy consumption, contributing to 70 %,46 % and 45 % of total annual energy consumption in Bhubaneswar, Jodhpur and New Delhi locations accordingly. The nearly twofold higher cooling energy demand in Bhubaneswar than in other sites can be explained by significantly higher outdoor temperature and moisture content, increasing sensible and latent cooling (dehumidification) demand. The space heating demand was found to be negligible in Bhubaneswar, which does not present clear cut seasons, and the weather is humid and warm all year round. However, external temperature profiles in the Jodhpur and New Delhi locations lead to the situation where the space heating energy demand is becoming essential to the energy consumption balance, contributing to nearly 20 % of total building energy consumption.

It can be noted that the distribution and values of the annual energy consumption in the hot-dry (Jodhpur) and composite (New-Delhi) climate zone are nearly equivalent, despite differences in the climate conditions. The energy consumption related to domestic hot water production differs slightly between investigated locations from 22.2 kWh/m^2a in Bhubaneswar to 24.9kWh/m^2a in New Delhi, which is related to the difference in the soil temperature and consequently cold-water temperature. Domestic hot

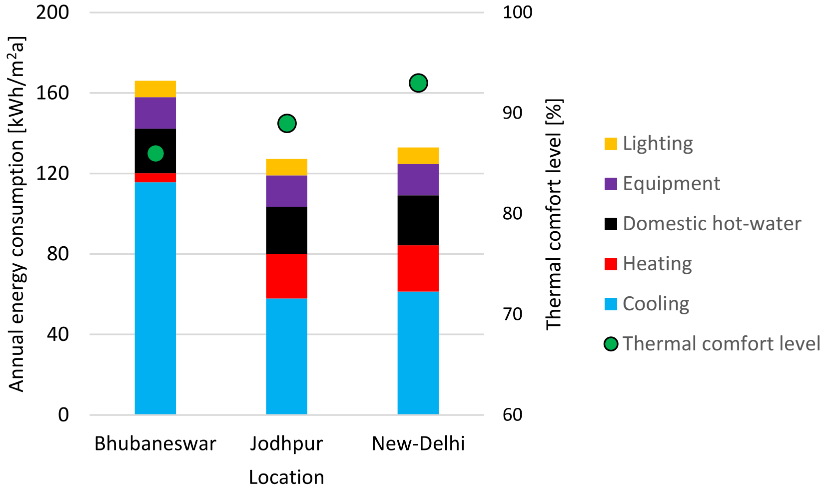

Fig. 5. Annual energy consumption and thermal comfort level of base case buildings in the investigated locations.

water production is responsible for 13 % of total annual energy consumption in Bhubaneswar and 19 % both in Jodhpur and New Delhi locations. The simulation results indicate that the thermal comfort level is higher than 85 % in each investigated location (Fig. 5).

The lifecycle GHG emission profile of the base case buildings in each investigated location is dominated by the operational type of GHG emissions related to energy consumption (Fig. 6). The share of embodied type of GHG emissions coming from material use and replacement to total life cycle GHG emissions was less than 5 % in each investigated location (Fig. 6). The value of the embodied GHG emission of baseline case study: 300kgCO2eq/m^2 is similar to the results- 240kgCO2eq/m^2 from life-cycle GHG emission assessment of the mansory, multi-residential building located in the warm-humid climate of India [55].

It can be explained by the combination of high energy consumption and the high GHG emission factor of India's local electricity grid, whose energy mix is dominated by coal. At the same time, the relatively small apartment floor area (30 m^2) contributes to reducing the quantities of construction materials and, consequently, the embodied GHG emissions.

It is worth highlighting that the lifecycle assessment performed in this study was based on the static approach to the GHG emission intensity of the electricity grid. The ambitious policy goals in India aim to achieve the net-zero emission balance by 2070, with the goal of a 45 % reduction of electricity carbon intensity by 2030 [5]. With the decarbonisation of the electricity grid, the share and influence of the embodied type of GHG emission on total lifecycle GHG emissions are increasing [56,57]. However, the long-term evolution of the electricity mix is highly uncertain.

3.1. Sensitive results from the Morris EE Method (first step of global sensitive analysis)

The ranking order of the 30 design factors (Table 4) influencing life cycle GHG emissions and annual thermal comfort level in each investigated location is presented in Fig. 7 and Fig. 8 accordingly. The ranking order is based on the mean sensitive indices (μ^*) from

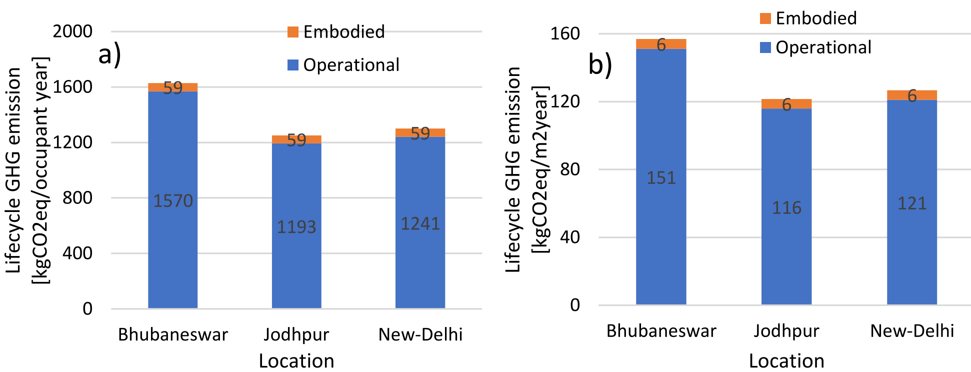

Fig. 6. Life cycle GHG emission profile of base case building in the investigated locations. a) functional unit: annual GHG emission per capita (occupant), b) functional unit: annual GHG emission per m^2 of gross floor area.

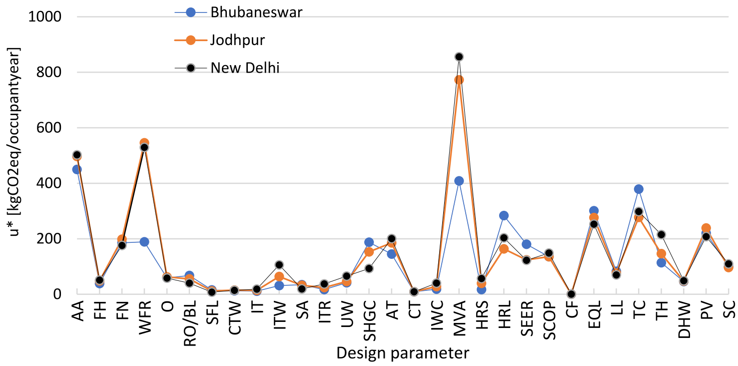

Fig. 7. Absolute Morris elementary effect of design parameters to life cycle GHG emissions in investigated locations.

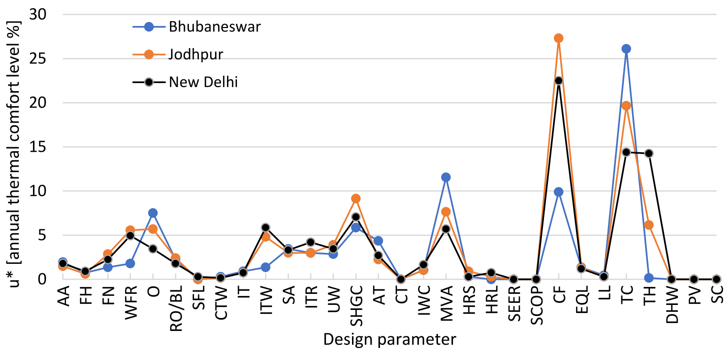

Fig. 8. Absolute Morris elementary effect of design parameters to the annual thermal comfort level in investigated locations.

the Morris elementary effect method. Additional information presenting the correlation (ratio) between standard deviation (σ) and mean elementary effect (μ^*) indices of the design parameters is shown in the Appendix, section A4, Fig.A3 - Fig.A8. This information allows the characterisation of the input model parameters in terms of linearity, monotony and interaction with other parameters based on the classification scheme proposed by Garcia Sanches et al.,2014 [58].

Considering the lifecycle GHG emissions (Fig. 7), it was found that the ranking order of the most influential design parameters varies among the investigated locations. However, the apartment's floor area (AA), mechanical ventilation airflow (MVA), cooling temperature setpoint (TC), equipment load (EQ), roof coverage with photovoltaic panels(PV) and windows to floor ratio(WFR) parameters were found to be in the group of the most influential parameters in the each of investigated locations (Fig. 7). Interestingly, the influence of the heating setpoint temperature (TH) and the insulation thickness of exterior walls and roof (ITW, ITR) on the lifecycle GHG emissions is getting higher in the New-Delhi location, which can be explained by the outdoor temperature profile, which increases space heating demand (Fig. 7). The results show that the indoor air velocity (CF) design parameter presents almost no influence on life cycle GHG emissions. This observation may be misleading since the installation of ceiling fan (CF) and consequent increase of the indoor air velocity directly influences the increase of cooling setpoint, which indirectly contributes to reducing operational energy use. The MVA, WFR, SC and TH parameters have non-linear behaviour with interaction with other parameters ($\sigma/\mu^*>1$). The other parameters seem to present monotonic or almost monotonic effects ($1 < \sigma/\mu^*$less than0.5) (Fig. A3, A5 and A7).

The indoor airspeed velocity (CF), together with the cooling temperature setpoint (TS), mechanical ventilation airflow (MVA) and solar heat gain coefficient of windows (SHGC), are among the most influential parameters influencing the thermal comfort level in each of the investigated locations (Fig. 8). Similarly, to the life cycle GHG emissions results, the influence of the heating setpoint temperature (TH) and the insulation thickness of exterior walls and roof (ITW, ITR) on the thermal comfort level are getting higher in the Jodhpur and New-Delhi location, where the space heating time is much higher than in cooling-dominated Bhubaneswar location. When analysing the σ/μ^* ratio (Fig.A4, A6, A8), it can be found that almost all input parameters seem to have non-linear behaviour with interaction with other parameters ($\sigma/\mu^*>1$). Overall, the ranking order presented in Fig. 7 and Fig. 8 is in good agreement with findings from the previous research, which commonly identified set points temperatures, ventilation airflow, windows-floor ratio and equipment/lighting load as influential for building performance (Table 1).

Based on the Morris Elementary Effect method results, the collection of the most influencing 14 design parameters in each investigated location (Table 7) was selected to be analysed further in the second step of the global sensitivity analysis based on the FAST method.

3.2. Sensitive results from the FAST method (second step of global sensitive analysis)

The results from the second step of the global sensitivity analysis based on the FAST method for investigated locations are shown in Figs. 9-11. The sensitivity measure: total order was used to analyse the influence of 14 design parameters on life cycle GHG emission and annual thermal comfort level, which reflect its main effect and correlated effect with other parameters.

The sensitivity order from the FAST method related to life cycle GHG emission is significantly different from that of the Morris method, particularly for the Bhubaneswar location. However, the apartment floor area (AA), equipment load (EQ), windows-to floor ratio (WFR), mechanical ventilation airflow (MVA), and cooling temperature setpoint (TC) are the common recognised highly influential parameters in both methods. The building orientation (O) is identified as a highly sensitive parameter to life cycle GHG emission by the FAST method, which is very different from the results of the Morris method. When analysing sensitive measures related to annual thermal comfort level, it can be seen that the ranking of the most influential parameters in the FAST method is similar to that presented in the Morris method. The mechanical ventilation airflow (MVA), cooling (TC), heating (TH) setpoints and indoor air velocity (CF) are the most sensitive parameters to the annual thermal comfort level in each investigated location.

The ranking order of the highly sensitive parameters, using two global sensitive analysis methods in each investigated location, is presented in Table 7. Based on the second step of the global sensitivity analysis, the AA, MVA, TC, EQL, PV, WFR, SHGC, AT and CF parameters were chosen as the most significant input for the multi-objective optimisation framework in the Bhubaneswar location. The AA, MVA, TC, EQL, PV, WFR, TH, HRL and CF parameters were selected for Jodhpur and New-Delhi locations.

3.3. Multi-objective optimisation results

The identified key, nine design parameters from the two-step global sensitivity analysis, were optimised using the genetic multi-objective optimisation framework. The improvement of the objective functions over the generations for each investigated location is presented in Figure 12. In all investigated locations and for all objectives, significant improvement (minimization) is observed from the first generation, with no improvement after the 15th generation. The multi-objective optimisation algorithm led to the 44–53 %, 24–32 %, and 6–11 % reduction related to the life cycle GHG emissions, life cycle cost, and initial materials investment cost accordingly.

The sets of Pareto-optimal (non-dominated solutions) obtained from the last optimisation generation in each investigated location are presented in Figure 13 . The three graphs show possible correlations between three objective functions. Based on the analysis of the results related to the correlation between life cycle GHG emissions and lifecycle cost, it can be indicated that these objectives are not conflicting. This means that it may be sufficient to include only one of the two performance indicators as an objective, reducing the computation time.

Simultaneously with the minimisation of the life cycle GHG emissions, the life cycle cost is reduced (Figure 13). This trend can be explained by the fact that the implementation of the energy reduction strategies leads to the significant reduction of operational GHG emissions, with only a slight increase of the embodied GHG emissions. The additional life cycle cost related to the energy efficiency strategies, mainly coming from the use of additional technical systems, is fully compensated, and outweighed by operational lifecycle cost reduction, associated with the minimisation of the annual energy use and related operational GHG emissions. Similarly, the reduction of the life cycle GHG emissions and life cycle cost in the Pareto solutions are strictly correlated with the increase of the initial investment cost, which scope covers the cost of the building materials and systems (Figure 13).

The performance indicators and design parameters values of the optimal (best) design scenarios, characterised by the lowest life cycle GHG emissions and cost, are presented in Table 8. The best performance design scenario obtained in the optimisation framework for the Bhubaneswar located in the warm and humid climate zone is characterised by the 75 % and 54 % lower life cycle GHG emissions and life cycle cost accordingly compared to the baseline (benchmark scenario) (Figure 13). At the same time, the initial material investment cost is 27 % higher. For the Jodhpur location (hot and dry climate), the 62 % reduction of the life cycle GHG emissions and 42 % of the life cycle cost was achieved, with the 34 % increase of the material investment cost compared to baseline (benchmark scenario). Finally, for the New Delhi (composite) location, the 65 % and 40 % reduction regarding life cycle GHG emissions and life cycle cost is observed, with the 25 % increase of the material investment cost, in reference to the baseline scenario. The obtained design solutions from the multi-objective optimisation framework lead to 10 %-30 % and 12 %-35 % (depending on location) lower life cycle GHG emissions when compared to the best design solutions based on the Morris and Sobol dataset, which are in line with the performance constraints: RETV < 15 W/m^2 and annual thermal comfort level > 85 %. The rising reduction effectiveness from more straight forward (Morris) to the complex (genetic optimization) methods indicates that the proposed methodology combining global sensitivity analysis and multi-objective optimisation is efficient.

Similar trends and values characterise the optimal design solutions in each investigated location (Table 8). Firstly, it can be indicated that the apartment's floor area (AA) in each solution is set as 30 m^2, being the minimum value in the range. The reduction of the floor area minimises the building envelope heat transfer and the mass of building materials, contributing directly to the decrease in operational and embodied GHG emissions. The design strategy related to increasing space efficiency based on the "build less and clever" principle is in line with the results and guidelines presented in the studies by Stephan and Crawford,2016 [59] and Ness, 2020 [60] and proven to provide significant environmental benefits.

The windows to floor area ratio values (WFR) in all locations are close to the minimum requirements set in the building energy code. It can be explained that all investigated cases are in the cooling dominated climate zones characterised by high solar radiation. Decreasing the windows surface leads directly to reducing solar heat gains and cooling energy consumption. This finding is consistent with the results from the studies [16,28] performed for the office building located in the humid subtropical climate zone.

Implementing the personal ceiling fans in the building design scenarios leads to increased airspeed (0.7 m/s) in the air-conditioned (AC) zones, enabling achieving the acceptable thermal comfort level according to the PMV model despite the high cooling temperature setpoint:29°C. This strategy significantly reduces the cooling-based energy consumption leading to the high lifecycle GHG emission reduction. The detailed analysis of results indicates that this strategy presents the AC energy reduction potential from 34 % in New Delhi to 40 % in Bhubaneswar. Consequently, it reduces the life cycle GHG emissions and lifecycle cost in the range

Table 7
Ranking orders of highly influential design parameters based on the Morris and Fast global sensitive analysis methods in investigated locations (orange coloured positions stand for the 14 design parameters identified as the most influential in the first step of the global sensitivity analysis (Morris method), green positions stand for the 9 key design parameters identified as the most significant in the second step of global sensitive analysis (Fast method).

DesignParameter (Table 4)	Bhubaneswar				Jodhpur				New Delhi			
	Life cycle GHG emissions ($kgCO_{2eq}$/ occupant year)		Thermal comfort (%)		Life cycle GHG emissions (kgCO2eq/ occupant year)		Thermal comfort (%)		Life cycle GHG emissions (kgCO2eq/ occupant year)		Thermal comfort (%)	
	Morris	Fast	Morris	Fast	Morris	Fast	Morris	Fast	Morris	Fast	Morris	Fast
AA	*1*	1	11	8	*3*	4	15	7	*3*	2	14	11
MVA	*2*	6	2	1	*1*	2	4	4	*1*	1	22	6
TC	*3*	8	1	3	*4*	3	2	1	*4*	3	2	3
EQL	*4*	2	15	6	*5*	1	16	5	*5*	4	17	4
HRL	*5*	12	25	–	*9*	7	21	–	*8*	7	20	5
PV	*6*	9	–	–	*6*	6	–	–	*7*	5	–	–
WFR	*7*	3	12	7	*2*	5	7	6	*2*	6	6	9
SHGC	*8*	4	5	5	*10*	11	3	9	*15*	13	*4*	7
FN	*9*	14	–	–	*7*	14	–	–	*10*	14	–	–
SEER	*10*	13	–	–	12	–	–	–	12	–	–	–
AT	*11*	5	6	11	*8*	10	14	8	*9*	12	12	8
SC	*12*	10	–	–	14	–	–	–	13	–	–	–
TH	13	–	22	–	*11*	12	5	3	*6*	10	3	1
SCOP	14	–	–	–	13	13	–	–	*11*	8	–	10
LL	15	–	19	–	15	–	22	–	16	–	23	–
RO/BL	16	–	10	–	18	–	13	–	23	–	15	–
O	17	7	*4*	4	17	9	*6*	10	*18*	9	*5*	–
DHW	18	–	–	–	20	–	–	–	21	–	–	12
UW	19	–	9	–	21	–	9	–	17	–	9	–
FH	20	–	18	–	19	–	20	–	20	–	18	–
SA	21		7	–	23	–	10	–	25	–	10	–
ITW	22	–	14	–	16	–	8	–	14	–	8	–
IWC	23	–	16	–	24	–	17	–	22	–	16	–
HRS	24	–	21	–	22	–	18	–	19	–	22	–
ITR	25	–	8	–	25	–	11	–	24	–	7	–
SFL	26	–	–	–	24	–	–	–	29	–	–	–
CTW	27	–	20	–	26	–	23	–	27	–	24	–
IT	28	–	17	–	27	–	19	–	26	–	19	–
CT	29	–	–	–	29	–	–	–	28	–	–	–
CF	30	11	*3*	2	30	8	*1*	2	30	11	*1*	2

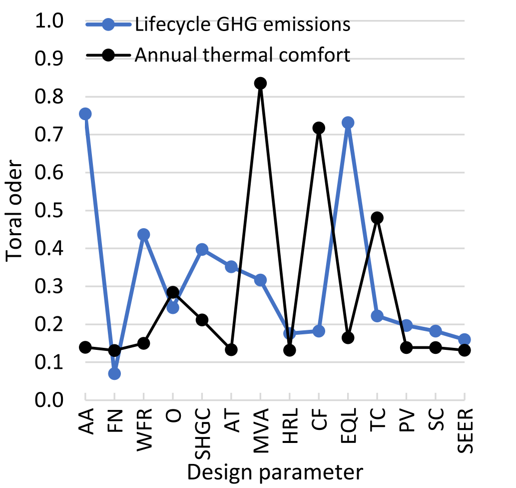

Fig. 9. Total order indices of key design parameters related to life cycle GHG emissions and annual thermal comfort level in Bhubaneswar (warm and humid climate).

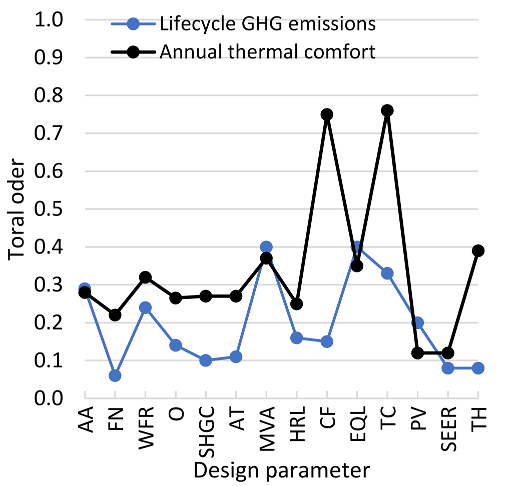

Fig. 10. Total order indices of key design parameters related to life cycle GHG emissions and annual thermal comfort level in Jodhpur (hot and dry climate).

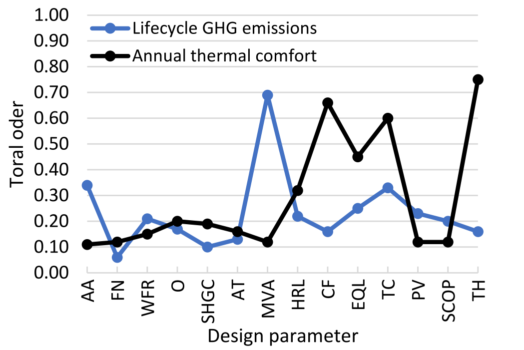

Fig. 11. Total order indices of key design parameters related to life cycle GHG emissions and annual thermal comfort level in New Delhi (composite climate).

21 %-30 %, and 12–14 % accordingly compared to the design scenario with no use of the ceiling fan and standard cooling temperature of 26℃. At the same time, the increase of the initial investment cost is less than 1 %. The higher reduction potential in Bhubaneswar than in other locations can be attributed to the solely cooling dominant climate, with the more prolonged ceiling fans time use. The range of the achieved energy reduction and high thermal comfort levels using a ceiling fan system is similar to those presented in the [43,61].

The use of the mechanical ventilation system with energy (both sensible and latent heat) recovery, with the airflow volume of 15 m^3/person, was achieved as the optimal solution regarding minimisation of the life cycle GHG emissions and cost in each of investigated locations. The operation of the mechanical ventilation system leads to the reduction of both sensible and latent heat gains coming from natural infiltration airflow based on the windows openings. The detailed analysis of best LCA/LCC solutions indicates that in comparison to the natural-based ventilation system, the mechanical system with energy recovery enables the reduction

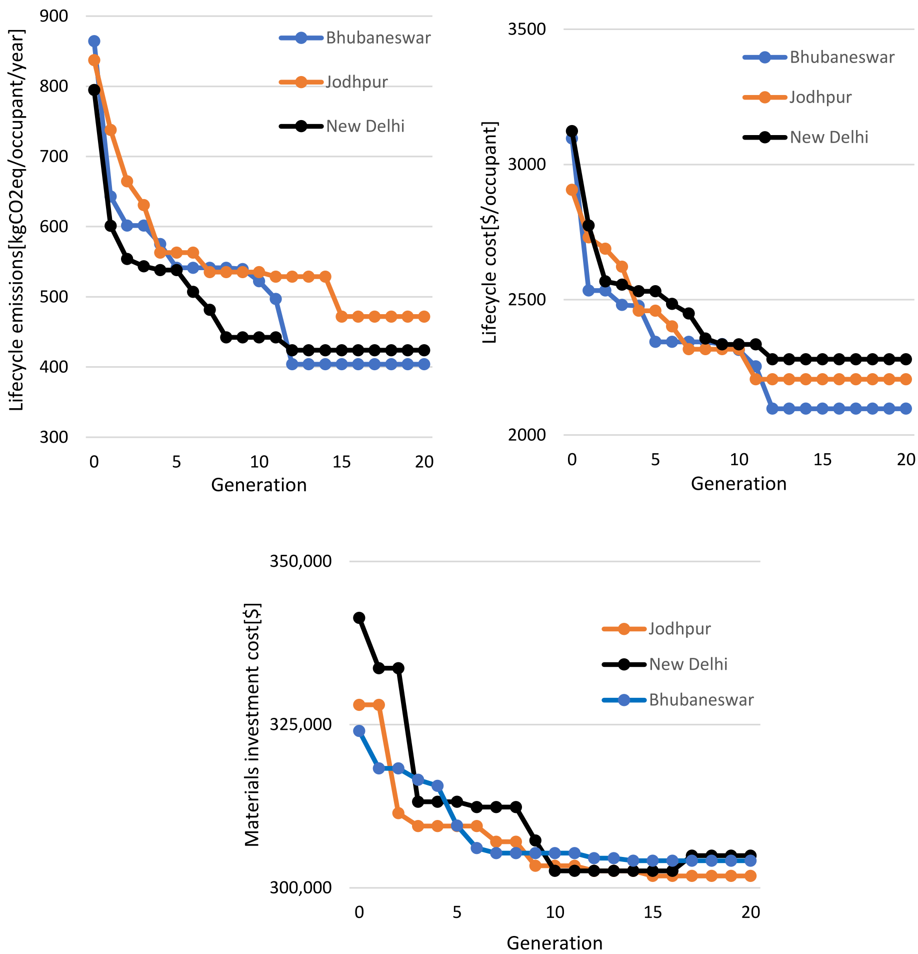

Fig. 12. Improvement of the objectives (minimum values) through the generations in the multi-objective optimisation in investigated locations.

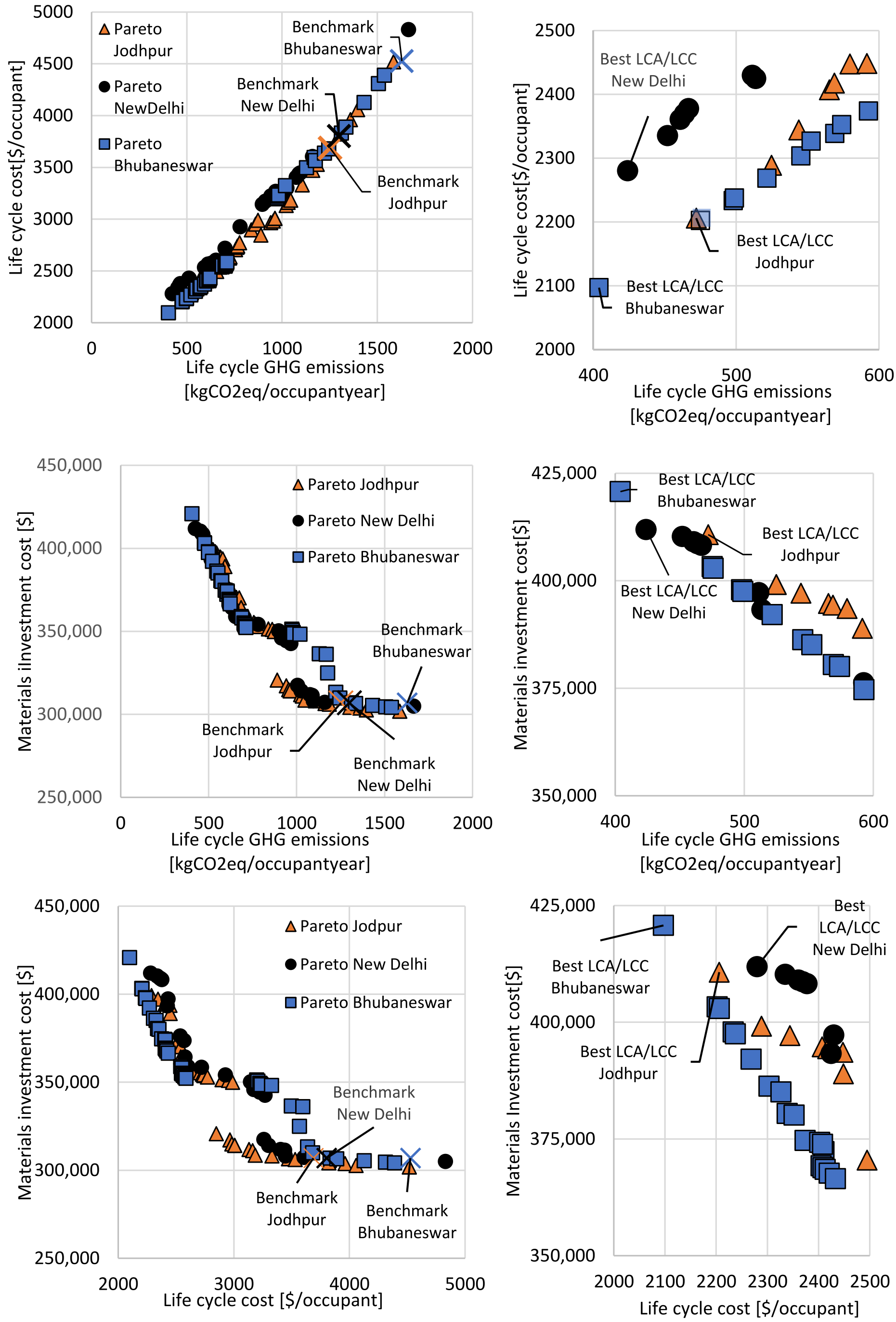

Fig. 13. Results of the multiobjective optimisation shown through three graphs combining the three objectives' functions.

Table 8
Performance indicators and design parameters values of the optimal (best) design scenarios, characterised by the lowest life cycle GHG emissions and cost.

	Location and climate zone		
	Bhubaneswar (warm and humid)	Jodhpur (hot and dry)	New Delhi (composite)
Performance indicators			
Energy consumption [kWh/ m^{2}year]	57.5	66.9	67.5
Renewable energy generation[kWh/ m^{2}year]	23.8	26.2	23.3
Annual energy balance [kWh/ m^{2}year]	33.7	40.7	44.1
Life cycle GHG emissions [kgCO2eq/ occupant/year]	404	472	423
Life cycle GHG emissions [kgCO2eq/ m2 year]	38.4	44.8	48
Embodied GHG emissions /Total GHG emissions [%]	20	17	16
Life cycle cost [$/occupant]	2097	2206	2280
Life cycle cost from materials production and replacement / Total life cycle cost [%]	63	57	55
Materials investment cost [$]	420,743	410,743	407,925
Thermal comfort level [%]	97	92	94
RETV [W/m2]	12.1	7.2	8.6
Optimised design values			
Apartment floor area: AA [m2]	30	30	30
Windows to floor ratio: WFR [%]	18	15	13
Ceiling fan air velocity: CF [m/s]	0.7	0.7	0.7
Equipment load: EQ [W/m2]	3	3	3
Cooling temperature setpoint [℃]	29	29	29
Roof coverage with photovoltaic (PV) [%]	90	90	90
Mechanical airflow (MVA) [m3/h person]	15	15	15
Solar heat gain coefficient (SHGC) [-]	0.25	n/a	n/a
Infiltration rate: AT [1/h]	1	n/a (3)	n/a (3)
Latent heat recovery (MVL) [%]	n/a (0)	75	75
Heating temperature setpoint (TH) [℃]	n/a (20)	20	20

of the air-conditioning energy consumption between 28 % in Bhubaneswar to 45 % in Jodhpur, which directly leads to the 14 %-29 % decrease of the lifecycle GHG emissions. The initial investment cost related to implementing a mechanical ventilation system is by average 15 % higher than the natural ventilation system.

Finally, the best solution for each location is characterised by the maximum value of the roof area coverage with the PV panels. Considering both high solar harvesting potential and emission-intensive Indian grid, the PV system's renewable energy generation covers 34 %(New-Delhi) to 40 %(Bhubaneswar) of the total energy consumption. Consequently, it leads to an average 35 % and 14 % reduction in lifecycle GHG emissions and life cycle cost accordingly. The initial investment cost is higher by an average of 20 % than compared to design without PV.

4. Conclusions and recommendations

The presented research combines the two-step global sensitivity analysis and multi-objective design optimisation based on the parametric, simulation building models, with the primary aim to explore the low life cycle GHG emission and cost design scenarios of the multifamily buildings located in the three climate zones in India: warm and humid (Bhubaneswar), hot and dry (Jodhpur) and composite(New-Delhi). The two-step global sensitivity analysis based on the Morris Elementary Effects and Fourier amplitude variance method (FAST) is conducted to identify the critical design parameters that significantly influence the life cycle GHG emissions and annual thermal comfort. The set of the most influential design parameters is further optimised using the multi-objective genetic algorithm, aiming to minimise the life cycle GHG emissions, life cycle cost, and initial material investment cost.

This study has found generally that for all investigated locations: apartment floor area, equipment load, windows-to floor ratio, mechanical ventilation airflow, and cooling temperature setpoint are the most influential design parameters concerning the lifecycle GHG emissions of the building in both global sensitivity analysis methods. On the other hand, mechanical ventilation airflow temperature setpoints and indoor air velocity (CF) were the most sensitive parameters to each investigated location's annual thermal comfort level, indecently on the used method. The heating temperature setpoint value is becoming more influential in Jodhpur and New Delhi due to the extended heating period than in the Bhubaneswar location. Additionally, the global sensitive results show that the ranking order of the most critical design parameters can vary when using different methods. For that reason, it is recommended not to limit the global sensitivity analysis to only one method.

As the result of the multi-objective optimization, significant reductions: 62–75 % in life cycle GHG emissions and 40–54 % life cycle cost were achieved compared to the baseline 7-storey multi-family design scenario based on the Indian energy conversation code. At the same time, initial material investment costs were 25–34 % higher.

Further, results served to propose some general recommendations for the design of low GHG emissions and implementation of some of these principles in the further development of energy policy and building energy code in India:

Considering the dominant influence of the operational GHG emissions in the life-cycle profile of residential buildings in India, the energy policy should predominantly focus on improving the energy efficiency of the buildings and decarbonisation of the local electricity grid.

Implementation of the maximum value of the residential envelope heat transmittance (RETV) less than 15 W/m^2 as a core requirement in the Energy Conversation Code for Residential Buildings is a successful measure, being in the with the results of the optimisation framework. Minimising windows solar heat gain coefficient, envelope surface area, and the windows to floor ratio leads directly to reducing the RETV values contributing to the decrease of the GHG life cycle emissions and cost. However, the energy code is now missing the consideration, requirements, and design guidelines for building systems and on-site renewable energy generation. This study shows that implementing the hybrid cooling system based on the combination of the ceiling fans and airconditioning operation is an energy-efficient strategy, which leads to significant life cycle GHG emission and cost reduction satisfactory thermal comfort despite high cooling temperature setpoint values. Moreover, despite relatively high initial investment costs, the design of the mechanical ventilation system with both sensible and latent heat recovery should be recommended to reduce the heat gains and moisture coming from the uncontrolled natural ventilation airflow based on windows opening. Mechanical ventilation with a filtration system is also advised, considering high outdoor air pollution and high Covid virus spread in India. Finally, taking into consideration high solar energy potential in terms of global irradiance and the GHG emission intensity of the electricity grid in India, the maximisation of renewable energy generation should be recommended and supported by further development of the energy conversation codes for residential buildings to reduce the life cycle GHG emissions and cost significantly.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112596.

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Appendix

Global sensitivity analysis and optimisation of design parameters for low GHG emission lifecycle of multifamily buildings in India.

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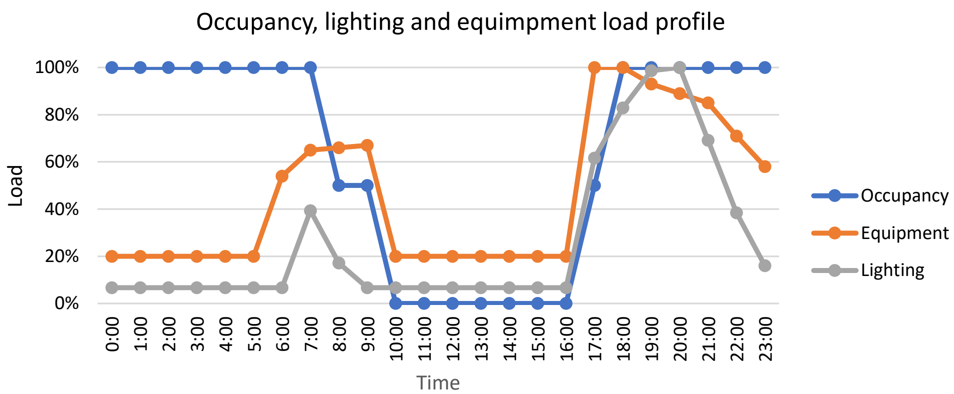
Figure A1. Occupancy, lighting and equipment load profile.



A1. Building energy model

This section presents additional information and assumptions related to the building energy modelling of the multifamily building.

A1.1 Energy zoning

The building energy model was created based on five main energy zones: four residential zones and one staircase/corridor. The energy consumption and thermal comfort metrics were calculated separately for each floor in each energy zone. The staircase/corridor zone is assumed to be not air-conditioned.

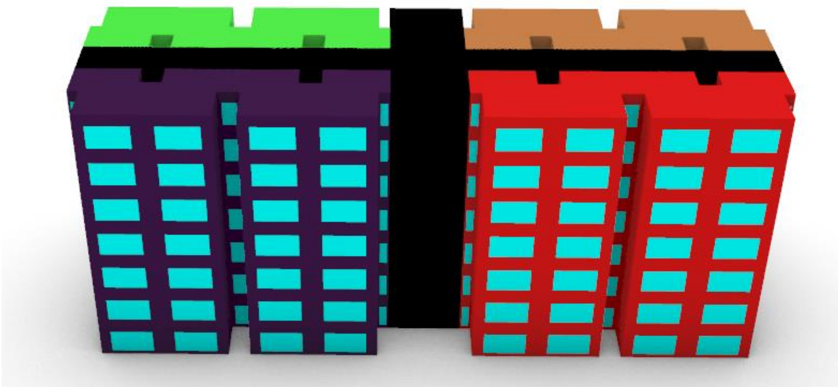


Figure A1 Energy zoning in building performance model (black zone – staircase/corridor, colour zones – residential parts)

A1.2 Building systems

A1.2.1 Ventilation system

The type of ventilation system applied in the parametrical multifamily building energy model strictly depends on the mechanical air flow (MVA) design parameter (Table 3). If the value of this parameter is 0, the ventilation of the building is assumed to be based on the natural ventilation forced by building infiltration and windows openings. The calculated infiltration airflows are depended on the building infiltration (AT) parameter (Table 3) and the wind velocity. Windows natural ventilation airflow is based on the windows opening, determined by temperature constraints, presented in Table A1.

Table A1 Temperature constraints of opening windows in the multifamily building. TC is defined as cooling setpoint temperature (Table 3)

Minimum indoor temperature ℃	Maximum indoor temperature ℃	Minium outdoor temperature ℃	Maximum outdoor temperature ℃
18℃	TC-1℃	12℃	TC

In the design scenarios with the positive values of the mechanical airflow parameters, the ventilation system is assumed to be mechanical with three possible configurations of heat recovery: no recovery, heat recovery (sensible), and energy recovery(both sensible and latent heat). The choice of mechanical ventilation type is depended on the sensible heat recovery efficiency (HRS) and latent heat recovery efficiency (HRL) design parameters (Table 3). The mechanical ventilation airflow system is assumed to be constant (CAV). Specific fan power (SFP) of balanced ventilation system with heat recovery is assumed to be 2.5 [kW/(m^3/s)], whereas with no heat recovery system 1.5 [kW/(m^3/s)], according to Air Infiltration and Ventilation Centre, 2015(AIVC) recommendations [1].

A1.2.2. Domestic hot water system

The calculation of the hourly heating loads related to domestic hot water production in the multifamily building was based on the LadyBug component [2], which follows the methodology developed by the Berkley National Laboratory. 1996 [3]. The quantity of the used water is depended on the domestic hot water use (DHW)(Table 3) design parameter, being in the range between 35-75 (l/person day). The delivery temperature is set as 55°C, and the inlet, cold water temperature is calculated based on the Christiansen and Burch Method,2004 [4] and used in Energy+ assuming the cold water supply pipes depth from 0.3 to 1.0m and unknown soil type. The final energy use related to the production of the domestic hot water system is strictly dependent on the energy efficiency ratio domestic hot water design (SCOP) parameter (Table 3), which varies between 0.9 (local, electric heaters) to 3.0 (air-water heat pump). The domestic hot water system can be coupled with the solar heating system, described in the section below, which leads to the lowering of the heating demand and related energy consumption.

1.2.3 On-site renewable energy systems

The developed parametric building energy models include the possibility of on-site renewable energy generation from the thermal solar collectors, photovoltaic modules, or a combination of these instaled on the building roof surface. The roof area coverage of solar and photovoltaic modules depends on input design parameters PV and SC (Table 3). The technology of thermal solar collectors and PV modules are based on the glazed plate collectors and the crystalline silicon (c-Si) PV modules, which detailed characteristic is presented in Table A2. The calculation of the renewable energy generation from solar thermal and PV system is based on the components provided by the Ladybug plugin, which follows the modelling methodology developed by National Renewable Energy Laboratory [5,6].

Table A2: Characteristic of solar thermal and PV system implemented in the building energy model

Solar thermal system characteristic	
Collector type	Glazed flat plate
Collector optical efficiency	70%
Collector thermal loss	4 W/m^{2}K
Incidence angle modifier	0.1
Collector active area	90%
Working fluid type	Water
Working fluid thermal capacity	4190 J/kgK

Pump efficiency	85%
Delivery water temperature	55℃
Tank size	2x daily average hot water use
Tank loses	15%
PV system characteristic	
Module material	crystalline silicon (s-Ci)
Mounting type	Close(flush) roof mount
Module efficiency	16%
Temperature efficiency coefficient	-0.4%/℃
DC/AC conversion efficiency	85%
Module effective area	90%
Tilt angle	5°

A2.1 The excepted service life of building materials and number of their replacements during the building life-span

Table A3 The excepted service life of building materials and number of their replacements during the building life-span

Building materials/elements	Expected service life (years)	Number of replacements during building lifespan of 50years
Concrete based materials	>50	0
Cement based materials	>50	0
Steel	>50	0
Bitumen	>50	0
Timber based materials	25	1
Windows	25	1
Doors	25	1
Ceramic tilles	20	2
Thermal insulation	>50	0
Ceiling fans	15	3
Ventilation unit	15	3
Airconditioning unit	15	3
PV panels/	25[2]	1
Solar collectors	25	1
Internal paint	5	8
External paint	10	4

A2.2 Construction systems and material layers

A2.2.1 Foundations and ground floor

Table A4 Construction system of foundation and ground floor in the multifamily building

Material layer	Thickness	Notes
Gravel and sand layer (aggregate)	**30cm**	
Ready-mix concrete	**5cm**	The type of concrete (standard or low-carbon) depends on the design parameter (CT) (Table 3)
Bitumen felt (membrane)	**0.3cm**	
Ready-mix concrete	**5cm**	The type of concrete (standard or low-carbon) depends on the design parameter (CT) (Table 3)
Reinforced concrete	**70-120cm**	The thickness of the concrete layer depends on the floor's height(FH) and floors number (FN) parameters (Table 3). Additionally, the type of concrete (standard or low carbon) depends on the design parameter (CT) (Table 3). The estimated quantity of steel rebar (reinforcement): 80kg/m^3
Cement mortar	**4cm**	
Wood laminated flooring	**2cm**	

A2.2.2 External walls

The construction system of the external walls in the parametrical building model depends on the construction type: exterior walls (CTW) design parameter (Table 3). The three possible combinations based on the primary construction material are investigated: masonry(clay-brick), reinforced concrete and autoclaved aerated concrete.

Table A5 Construction systems of external walls in relation to primary construction material in the multifamily building

Masonry construction system		
Material layer	**Thickness**	**Notes**
External paint	**0.005 cm**	The solar reflectance of the paint depends on the solar reflectance design parameter (SA)(Table 3)
Cement plaster	**2cm**	The type of concrete depends on the design parameter (CT) (Table 3)
Cement mortar	**0.6cm**	
Clay bricks	**30cm**	
Plasterboard	**1.2cm**	
Thermal insulation	**0-15cm**	The thickness and type of thermal insulation depends on the insulation wall type (IT) and insulation wall thickness(IWT) design parameters (Table 3)
Vapour barier	**0.4cm**	
Plasterboard	**1.2cm**	
Cement plaster	**2cm**	
Reinforced concrete construction system		
External paint	**0.005 cm**	The solar reflectance of the paint depends on the solar reflectance design parameter (SA)(Table 3)
Cement plaster	**2cm**	
Cement mortar	**0.6cm**	
Reinforced concrete	**20cm**	The type of concrete depends on the design parameter (CT) (Table 3).

		The estimated quantity of steel rebar (reinforcement): 100kg/m^3
Plasterboard	**1.2cm**	
Thermal insulation	**0-15cm**	The thickness and type of thermal insulation depends on the insulation wall type (IT) and insulation wall thickness(IWT) design parameters (Table 3)
Vapour barier	**0.4cm**	
Plasterboard	**1.2cm**	
Cement plaster	**2cm**	
Autoclaved aerated concrete construction system		
External paint	**0.005 cm**	The solar reflectance of the paint depends on the solar reflectance design parameter (SA)(Table 3)
Cement plaster	**2cm**	
Cement mortar	**0.6cm**	
Autoclaved aerated concrete	**25cm**	
Plasterboard	**1.2cm**	
Thermal insulation	**0-15cm**	The thickness and type of thermal insulation depends on the insulation wall type (IT) and insulation thickness -exterior walls (ITW) design parameters (Table 3)
Vapour barier	**0.4cm**	
Plasterboard	**1.2cm**	
Cement plaster	**2cm**	

A2.3.3. Roof

Table A6 Construction system of the roof in the multifamily building

Material layer	**Thickness**	**Notes**
Ceramic tiles	**1.5cm**	
Cement mortar	**2cm**	
Plasterboard	**1.2cm**	
Thermal insulation	**0-15cm**	The thickness and type of thermal insulation depends on the insulation wall type (IT) and insulation thickness roof(ITR) design parameters (Table 3)
Vapour barier	**0.4cm**	
Plasterboard	**1.2cm**	
Reinforced concrete slab	**15cm**	The type of concrete depends on the design parameter (CT) (Table 3). The estimated quantity of steel rebar (reinforcement): 80 kg/m^3
Cement plaster	**2cm**	

A2.3.4 Internal floors

Table A7 Construction system of the internal floors in the multifamily building

Material layer	**Thickness**	**Notes**
Cement plaster	**2cm**	
Reinforced concrete slab	**12cm**	The type of concrete depends on the design parameter (CT) (Table 3). The estimated quantity of steel rebar (reinforcement): 80 kg/m^3
Cement plaster	**1.2cm**	
Wood laminated flooring	**2cm**	

A2.3.5 Internal walls

The construction system of the internal walls in the parametrical building model depends on the construction type: interior walls (IWC) design parameter (Table 3).

Table A8 Construction system of the internal walls in the multifamily building

Concrete system		
Material layer	**Thickness**	**-Notes**
Cement plaster	**2cm**	
Ready-mix concrete	**10cm**	The type of concrete depends on the design parameter (CT) (Table 3).
Cement plaster	**2cm**	
Mansory(brick system)		
Cement plaster	**2cm**	
Cement mortar	**0.6cm**	
Clay brick	**8cm**	
Cement plaster	**2cm**	
Autoclaved aerated system		
Cement plaster	**2cm**	
Autoclaved aerated concrete	**10cm**	
Cement plaster	**2cm**	
Tiber frame system		
Cement plaster	**2cm**	
Timber frame	4.5cm	
Particleboard	2cm	
Cement plaster	2cm	

A3. Residential envelope transmittance value (RETV)

Residential envelope heat transmittance (RETV) is the net heat gain rate (over the cooling period) through the building envelope (excluding the roof) of the dwelling units divided by the area of the building envelope of the dwelling units. RETV characterises the thermal performance of the building envelope. Limiting the RETV value helps reduce heat gains from the building envelope, thereby improving the thermal comfort and reducing the electricity required for cooling.

RETV formula takes into account the following:

- Heat conduction through opaque building envelope components (wall, opaque panels in doors, windows, ventilators, etc.)
- Heat conduction through non-opaque building envelope components (transparent/translucent panels of windows, doors, ventilators, etc.),

- Solar radiation through non-opaque building envelope components (transparent/translucent panels of windows, doors, ventilators, etc.)

RETV for the building envelope (except the roof) for four climate zones, namely, Composite Climate, hot-Dry Climate, Warm-humid Climate, and temperate Climate, shall comply with the maximum RETV value of 15 W/m2

The RETV calculation of the building envelope should be based on the equation presented below

$$RETV = \frac{1}{A_{envelope}} * \left(\left(a * \sum_{i=1}^{n} (A_{opaquei} * U_{opaquei} * \omega_i \right) \right) + \left(\left(b * \sum_{i=1}^{n} (A_{non-opaquei} * U_{non-opaquei} * \omega_i \right) \right) + \left(\left(c * \sum_{i=1}^{n} (A_{non-opaquei} * SGHC_{eqi} * \omega_i \right) \right) [Equation\ A1]$$

where:

$A_{envelope}$: envelope area (excluding the roof) of dwelling units. It is the gross external wall area (includes the area of the walls and the openings such as windows and doors) [m^2]

a,b,c – coefficients for RETV formula for different climate zones (for detailed values, refer to Table 3 in Energy conservation building code for residential buildings (ECBC)

$A_{opaquei}$ – Area of diffrent (i) oapaque building envelope partitions [m^2]

$A_{non-opaquei}$ – Area of diffrent (i) non-oapaque (transparent) building elements [m^2]

$U_{opaquei}$ - Thermal transmittance values of different (i) opaque building envelope components [W/m^2K]

$U_{non-opaquei}$ - Thermal transmittance values of different (i) non-opaque building envelope components [W/m2K]

$SHGC_{eqi}$ - equivalent solar heat gain coefficient values of different non-opaque building envelope components (for detailed values, refer to Annex 7 in ECBC)

ω_i - orientation factor of respective opaque and non-opaque building envelope components; it is a measure of the amount of direct and diffused solar radiation that is received on the vertical surface in a specific orientation (for detailed values, refer to Annex 7 in ECBC)

A4. Results

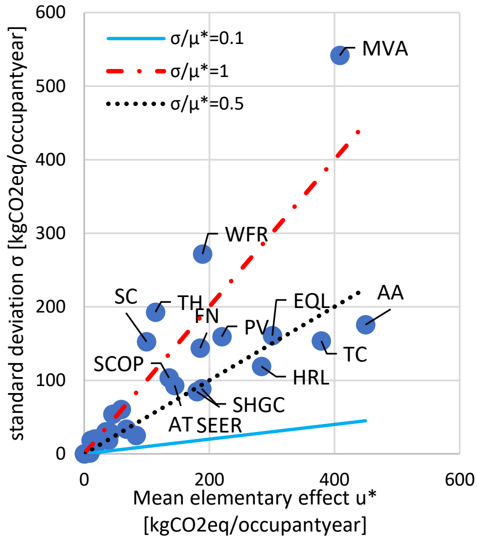


Figure A3 Mean elementary effect u* and standard deviation σ of the design parameters related to life cycle GHG emissions in Bhubaneswar location (warm and humid climate)

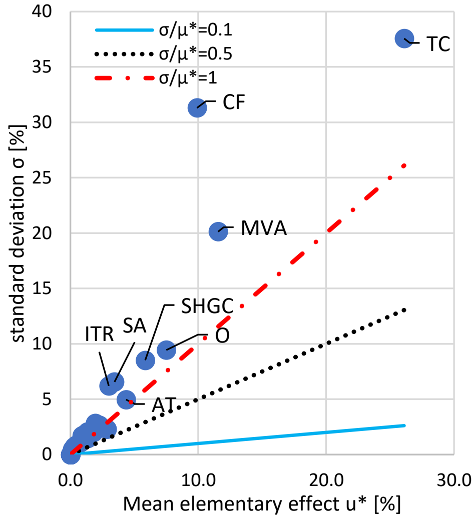
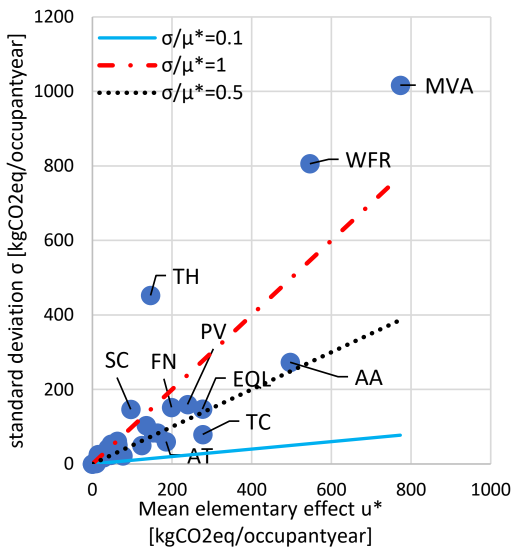
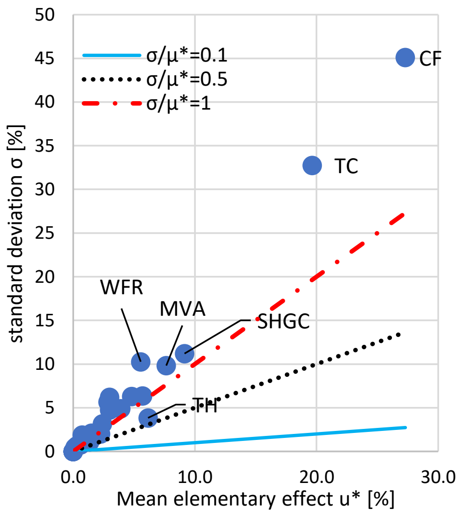


Figure A4 Mean elementary effect u* and standard deviation σ of the design parameters related to the annual thermal comfort level in Bhubaneswar location (warm and humid climate)





2

Figure A5 Mean elementary effect u* and standard deviation σ of the design parameters related to life cycle GHG emissions in Jodhpur location (hot and dry climate)

Figure A6 Mean elementary effect u* and standard deviation σ of the design parameters related to the annual thermal comfort level in Jodhpur location (hot and dry climate

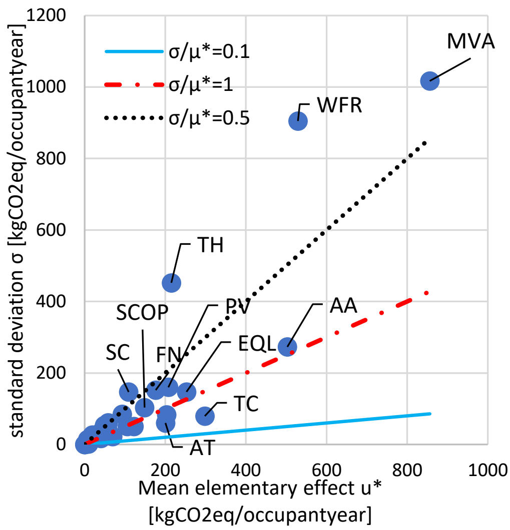


Figure A7 Mean elementary effect u* and standard deviation σ of the design parameters related to life cycle GHG emissions in New Delhi location (composite climate)

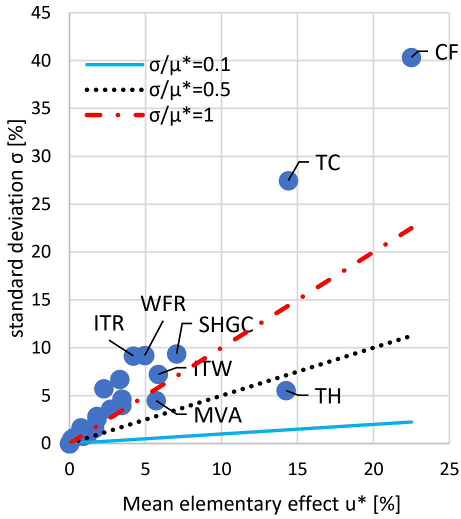


Figure A8 Mean elementary effect u* and standard deviation σ of the design parameters related to the annual thermal comfort level in New Delhi location (composite climate)

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