# Framework to Model Building Carbon Emissions

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## Framework to Model Building Carbon Emissions

**Abstract:** As part of the DynamicRenowave project on life cycle assessment and energy simulation of building renovation strategies activities, a new modeling framework has been created. Two objectives were set first to define a common modeling approach to assess operational GHG emissions in buildings. Secondly, define a standard life cycle assessment approach to assess the embodied GHG emissions allowing to compare different new and existing buildings and energy conservation measures worldwide. Several meetings and discussions took place between January and June 2024 to identify a systematic methodology for assessing the overheating risk in buildings and enable the comparative evaluation of carbon emissions of buildings and building services. The authors succeeded in identifying two major approaches based on international standards and in line with IPCC reports. The framework comprises ten decision modules that allow coupling the embodied, operational, and end-of-life emissions calculations based on international standards and materials databases.

**Keywords:** GHG emissions; calculation; uncertainty analysis; building stock, life cycle assessment

# 1. Introduction

Achieving the 2015 Paris Agreement's objective to limit warming to within 2°C of preindustrial levels requires non-state actors to adopt voluntary actions to sharply reduce greenhouse gas emissions (GHGs) and remove residual emissions, in line with global net zero by 2050 (UN, 2024).

The construction sector is responsible for 39% of global carbon emissions, of which 28% come from the operational energy used by our buildings and 11% from building materials. The need for more buildings is set to rise proportionally with the population growth. The construction sector will, therefore, play a major role in reducing carbon emissions in the buildings of the future (World et al., 2019). At a European level, the focus of attention is how to reduce environmental load from buildings via different initiatives. Since the introduction of the Energy for Buildings Directive in 2002 the focus of the European Commission has been mainly focused on reducing and decarbonizing operational emissions of buildings through the introduction of the energy performance certification. However, since 2023, the introduction of the EU Roadmap for Reduction of Whole Life Carbon of Buildings and the new EPBD recast embodied GHG emissions of buildings have gained huge attention (Maduta et al., 2023). In 2020, the EU building stock was responsible for 1,360 MtCO2-e, which corresponds to 40% of EU emissions, of which 79% were operational emissions and 21% were embodied emissions.

Despite the proliferation of different carbon emissions frameworks and models (Schmidt & Crawford, 2017), most of the existing models remain locally applied, restricted to narrow boundaries, and limited to the subjective hypotheses that can hardly be applicable worldwide (Beltrán-Velamazán et al., 2023). Also, most of the existing framework failed to couple building performance simulations for building operational emissions with life cycle assessment for building embodied and end-of-life emissions (Röck et al., 2021). Both fields are embedded in two competitive research communities, BPS and LCA, that hardly collaborate or adopt open-access practices.

Therefore, it is mandatory to guide this development towards a low carbon-built environment and building stock. Against this background, it is the motivation of the RENOWAVE Project in Belgium to assess solutions for low-carbon renovation of existing buildings and devise design solutions for new construction (Attia, 2023; Attia & Gobin, 2020). The decarbonization effort of the EU building stock should be used to denote low energy and low carbon design and renovation solutions that lower the GHG emissions to reduce and avoid carbon emissions-intensive materials and other associated impacts related to national energy mixes. It encompasses the assessment of embodied, operational, and end-of-life GHG emissions of buildings and building technologies of the following four groups:

1. Achieve Paris-goal compatible emissions reduction targets to stay below 2C of global warming through a whole-life carbon assessment (WLCA). The WLCA involves the evaluation of Global Warming Potential emissions from onsite combustion and grid-supplied electricity, accounting for the refrigerant leakage and tracking the upfront embodied carbon of major materials used in the structure and enclosure.

2. Ensure the integration of maximum energy-generating and saving technologies – including external shading, thermal insulation, solar systems, heat pumps, and district cooling and heating networks.

3. Remove and store GHG emissions through legally warranted permanent use of low-carbon materials up to 3000 to 8000 years– including biobased materials and low-carbon concrete and aggregates.

4. Control the low-building emissions during operation and end-of-life.

Therefore, RENOWAVE's main aim is to support a rapid transition to an environment where removing and reducing GHG emissions from buildings are the mainstream and preferred solutions for new construction and renovation in buildings. This report refers to the IPCC GHG emissions definitions that associate the $CH_4$ and $N_2O$ emission factors corresponding to the energy sources and consider the emissions of $CH_4$ and $N_2O$, which are uniformly converted to $CO_2$ emissions through GWP (Change, 2006). In this context, the Building Carbon Emissions Modeling Taskforce developed a framework to evaluate and model whole-life carbon emissions in buildings to assess and compare different design and renovation solutions and technologies. The framework can determine a building's emissions during its life cycle following a top-down and bottom-up approach.

The top-down calculation approach allows us to comply with environmental requirements using life-cycle assessments (LCAs) for new and existing construction. For example, the model allows testing the building's compliance with an existing emissions threshold (limit values for the environmental impact) during any or all its life cycles (embodied, operational, and end-of-life). The bottom-up approach allows calculating the emissions based on a classical approach while coupling the life-cycle assessment (LCA) of materials with energy performance during use and /or end of life.

The boundary conditions for the framework include the use of existing international standards and published life cycle assessment methodologies, excluding any monetization approach. The framework enables the integration of IPCC 2021 scenarios or future IPCC scenarios and allows the use of future weather files for most cities worldwide. The building energy efficiency requirements are based on ASHRAE 189 (ASHRAE, 2021) because it is the only standard that covers all climatic zones worldwide.

The task force activities started in May 2023. A literature review was conducted on calculation methods to evaluate Net-zero Whole Life Carbon Buildings, including the revised EPBD zero-emission buildings calculation approach.

A Net-Zero Whole Life Carbon Building (NZWLCB) achieves net-zero carbon emissions across its entire lifecycle, addressing both operational and embodied carbon. It considers all lifecycle stages as defined by EN 15978 standards, including the product stage (Modules A1–A3) covering emissions from raw material extraction, transportation, and manufacturing; the construction stage (Modules A4–A5) for emissions from material transport to the site and construction activities; the use stage (Modules B1–B7) accounting for energy use, maintenance, repair, replacement, and refurbishment; and the end-of-life stage (Modules C1–C4) addressing deconstruction, waste processing, and material disposal or recycling (CEN, 2019). Additionally, Module D accounts for avoided emissions through reuse, recycling, or recovery of materials beyond the building's lifecycle. Net-zero is achieved by minimizing emissions across all these stages and offsetting any remaining emissions, ensuring the building has no net carbon impact over its lifetime.

Four focus group discussions took place in 2023 and 2024. Also, two webinars took place in April and May 2024, involving worldwide experts to provide feedback on the framework. The methodological approach to establish the framework opted to select a reference building, which is an ideal building model defined based on experts' inquiries and assumptions. Also, the evaluation of emissions had to comply with the carbon calculation standards ISO 14044 and EN 15804+A2. Therefore, we avoided a real existing building with average characteristics concerning a specific building category due to the difficulty of finding a universal building that can represent eight climates. However, the developed framework allows for models of single or clustered buildings in a single zone and multiple zone building models. A comparative performance analysis of two renovation scenarios was conducted to test and validate the framework. The validation activities are not described in this report but can be found in the work of Bertini et al. 2025 (Bertini et al., 2025). The ongoing test phase is open to any voluntary researcher. We are ready to provide additional knowledge about the use of the framework.

Thus, the framework is novel and comprehensive, allowing the comparison of different renovation technologies according to various emissions calculation parameters and indicators, building functions, and archetypes. The framework is based on as much as possible of existing standards, including CEN 15804+A2 (CEN, 2019, 2021). The framework comprises ten modules that can also be used for a single building or the building stock. It can be used by building carbon emissions modelers who wish to assess the carbon footprint of new or existing buildings.

Finally, we encourage researchers to use and further develop the framework. The framework can be part of customized GHG modeling workflows and models, but it must be tested through case studies and application projects. Usability testing shall take place to customize the framework to different users and different design stages. We recommend to USER-Fit usability testing framework (Attia et al., 2024). Also, we invite the reader to our similar work on resilient cooling modeling (Attia et al., 2021; Rahif, Hamdy, et al., 2022) that was developed as part of IEA Annex 80 and the modeling applications (Amaripadath et al., 2023; Rahif et al., 2023; Rahif, Norouziasas, et al., 2022) that benefited from the framework.

## 2. Methodology

The task force activities, a collaborative effort that began in May 2023, involved a comprehensive literature review on calculation methods to evaluate Net-zero Whole Life Carbon Buildings, including the revised EPBD zero-emission buildings calculation approach. Four engaging focus group discussions were held in 2023 and 2024, fostering a sense of shared understanding and progress. Additionally, two informative webinars were conducted in April and May 2024, providing a platform for global experts to contribute their valuable insights. (Attia & Petersen, 2024; Bertini & Dasse, 2024) Involving worldwide experts to provide feedback on the framework. The methodological approach to establish the framework opted to select a reference building, which is an ideal building model defined based on experts' inquiries and assumptions. Also, the evaluation of emissions had to comply with the carbon calculation standards ISO 14044 and EN 15804+A2. Therefore, we avoided a real existing building with average characteristics concerning a specific building category due to the difficulty of finding a universal building that can represent eight climates. However, the developed framework allows for models of single or clustered buildings in a single zone and multiple zone building models. A comparative performance analysis of two renovation scenarios was conducted to test and validate the framework. The validation activities are not described in this report but can be found in future work. The ongoing test phase is open to any voluntary researcher. We are ready to provide additional knowledge about the use of the framework.

The methodology adopted to execute this framework should combine the use of building performance simulations for operational building emissions calculations with life cycle assessment calculations for embodied and end-of-life emissions calculations. We strongly recommend using reliable building performance simulation software like EnergyPlus, IDA ICE, TRNSYS or others and produce the operational emissions and visualize them in spreadsheets. All operational emissions calculations will be based on ISO 52016-17 (ISO, 2021c, 2021d, 2021e) and ISO 17771-2 (ISO, 2021a). Next, a spreadsheet-based calculation approach should include LCA equations, materials inventories and emissions and be coupled with the building simulation results. We suggest performing the coupling in a spreadsheet or a programming code such as Phyton or others. We strongly recommend avoiding the use of LCA tools. The framework is designed to build in the operational emissions simulation results and couple the outcomes with the LCA material quantities and emissions for the different identified stages.

We recommend performing the embodied and end-of-life emissions calculations hand in hand with operational emissions modeling. As indicated in the framework, it is important to provide the modeling input for Modules 3-6 in parallel.

# 3. Results

The decision-making flow chart illustrated in Figure 02 groups ten key decisions or modules that need to be made to perform any comparative environmental analysis. The ten key decisions allow to conduct of comparative simulations for different existing or newly built or renovation scenarios and decarbonization solutions of buildings or building stock based on the following Modules:

1. **Approach: Climate Change Scenarios vs GHG Budget**

At the early stage of decision-making to calculate the total life cycle emissions of buildings, it will be necessary to determine the purpose of GHG emissions calculations (Vuarnoz et al., 2020). Module 1 of the framework allows us to adopt one of the two main approaches (Hollberg et al., 2019) for estimating GHG emissions (Vuarnoz et al., 2020): a bottom-up approach and a top-down (carbon budget) approach (Habert et al., 2020; Hoxha et al., 2016).

The first approach (Top-down) to calculating the GHG emissions budget falls under the planetary boundary system paradigm (Brejnrod et al., 2017) based on GHG emissions potency (Newmarch et al., 2022). Life-cycle impact assessment is based on quantifying the environmental performance of products and technologies in relation to Planetary Boundaries. A top-down limit of emissions or emissions budget of annual GHG equivalent will set a safe emissions budget (Petersen et al., 2022) for the building beforehand (Marin et al., 2024). Several countries are moving towards imposing mandatory limit values that consider the life-cycle greenhouse gas emissions (GHG) of new construction projects (Bai et al., 2024; Balouktsi et al., 2024). The calculation approach seeks compliance, and alternative scenarios seek lower emissions intensity values that fall under the budget limits.

The second approach (Bottom Up) to calculating a climate change scenario starts with evaluating an existing building's embodied, operational and end-of-life emissions as a baseline. Bottom-up benchmarks relate to the values of the existing level of GHGE based on an empirical dataset. They are developed at a granular level (materials level), considering specific characteristics of buildings and delving into factors like building size, age, materials and energy consumption patterns. When considering the building level, multiple studies have contributed to the field. Their strength lies in their ability to offer practical and tailored decarbonization strategies (Norouzi et al., 2023). Improvements through energy conservation measures, renewable energy systems and low-carbon materials should be introduced to create alternative designs with lower emissions and compare the baseline to the alternatives.

## 2. Climate and Location

Defining accurate boundary conditions is crucial for reliable building simulations. Climatic factors play a significant role in determining building performance, particularly energy consumption for heating and cooling (Rostam & Abbasi, 2023). Therefore, selecting representative climates and accurate weather data is essential. Various methodologies for generating future weather files have been explored, offering unique advantages and considerations. For instance, the use of Bias-adjusted Typical Meteorological Years (TMY) weather files based on the CORDEX project provides a comprehensive dataset that accounts for future climate scenarios, ensuring robust simulation outcomes (Nik & Kalagasidis, 2013).

Urban Heat Island (UHI) effects, which are significant in urban settings, can markedly influence operational emissions. Modelers must make a conscious decision about including or excluding UHI effects in their weather files. Including these effects provides a more realistic assessment of operational emissions, particularly in densely populated urban areas (Vardoulakis et al., 2013).

Uncertainties from Global Climate Models (GCMs), statistical downscaling, and Regional Climate Models (RCMs) must be addressed to ensure reliable results. The framework suggests using different combinations of weather files to account for these uncertainties, enhancing the robustness of the analysis (Nik & Kalagasidis, 2013).

The framework recommends using cities listed in Figure 2 as representative climates to facilitate international comparisons. These cities, based on ASHRAE 169, cover all climate zones worldwide, making them suitable for universal evaluations (ASHRAE, 2021). Additionally, the study by IEA Annex 80 provides a solid foundation for selecting these representative cities (Attia et al., 2021).

There are Bias-adjusted Typical Meteorological Years (TMY) weather files data sets available based on the CORDEX project on the IPCC 2021 Shared Socioeconomic Pathways (SSP) for 2000-2020, 2040-2060, and 2080-2100 (Machard et al., 2024). Otherwise, we advise the use of Meteonorm software or national weather datasets. The most important aspect of the weather dataset selection is to ensure that the modelers use historical and future TMYs that are in line with the latest IPCC reports. For example, the use of SSP scenarios based on the IPCC 2021 report should be prioritized compared with the RCP scenarios of the IPCC 2026 report. The choice of historical or future TMY or XMY remains a choice of the modeler.

## 3. Building Characterization

Module 3 identifies and determines the representative model. The framework allows for modeling new constructions and the existing buildings for renovation. The choice of modeling object includes a shoebox, a representative archetype, a real or theoretical benchmark building, or the whole building stock on a national, regional or international level. The modeling framework presented in this report can address all those scales. Therefore, we present the logical sequence of decision-making from a single shoebox to the building stock.

For shoebox and real building modeling, the geometry, function and occupancy schedules must be chosen. We suggest using already existing shoebox models, such as the BESTEST models. (Neymark et al., 2002; Neymark & Judkoff, 2002)The indoor environmental quality conditions should be defined based on ISO 17771-2 (ISO, 2021a, 2021b), which sets input parameters for the design and assessment of buildings' energy performance. The occupancy schedules should be defined based on ISO 18523 (ISO, 2018), which specifies the schedule and condition of building, zone and space usage for energy calculation.

For building stock modeling, which is a bottom-up approach, the framework recommends the use of existing building stock models (Heisel et al., 2022). The U.S. Department of Energy (DOE) developed commercial and residential building energy Prototype Building Models by participating in industry review and update processes and providing technical analyses to support both published model codes and potential changes (DOE, 2024). DOE publishes its findings to ensure transparency in its support and to make its analysis available for public review and use. In Europe, the European Building Stock Observatory datasets (EU, 2024), the EPISCOPE and the TABULA datasets include many representative building stock models. China also has its approach to building stock modeling (An et al., 2023). It is important to note that the modeling can be for the whole building stock as one entity or as representative agglomerated models.

For structures and finishes, the representation of the building stock should address the structure and finishes, as shown in Modules 3c and 3d in Figure 2. The structure, envelope composition, and finishes must be determined and quantified. We strongly recommend the use of spreadsheets that quantify the materials based on 3D models or BIM-based software.

## 4. Building Envelope and Renovation Measures

As the global environment changes drastically, low-carbon building, which has energy savings and carbon emissions reduction advantages, becomes the direction of future development. Existing studies show that building envelope impacts energy consumption extremely highly and thus has a significant influence on carbon emissions reduction (Lin et al., 2021; Mostafavi et al., 2021). Therefore, building envelope parameters should be chosen carefully to reduce carbon emissions impacts.

The climate intensity mainly influences the choice of the building envelope performance requirements. The key parameters for envelope performance are the window-to-wall ratio, shading coefficient, conductivity, airtightness and heat capacity. It is crucial to adhere to existing standards and energy performance certification schemes that determine the requirements of building performance in different climate zones. Therefore, the framework strongly recommends the use of ASHRAE 169 for international comparative studies (ASHRAE, 2021). The standard covers all climate zones and can advise on the performance requirements needed for all cities listed in Module 2.2 of the framework. We recommend the use of national building codes for national studies. The building envelope characteristic can be defined on two levels: low-energy buildings or ultra-low-energy buildings.

Again, as shown in Module 4 in Figure 2, materials must be re-quantified based on the chosen envelope characteristics. The selection of the insulation type and thickness, shading technology, glazing surface and wall layers and finishes will require a new calculation of material quantities. We strongly recommend the use of spreadsheets that quantify the materials based on 3D models or BIM-based software.

The calculations of the embodied and end-of-life carbon emissions should take place at this stage of all envelope materials based on the material quantification. The calculation should be based on ISO 14040, ISO 14044 (Finkbeiner et al., 2006) and 15978 and EN 15804-A2 (Van Gulck et al., 2022). Moreover, the building envelope's calculation should adhere to ISO 52022-1:2017 (ISO, 2017b), which outlines simplified methods for evaluating the thermal, solar, and daylighting properties of building components and elements. These characteristics are necessary for the assessment of energy efficiency and the optimization of energy utilization in buildings. Integration of these factors into energy performance calculations is facilitated by the standard, which is particularly beneficial for the design and evaluation of building envelopes. The emissions data should be based on reliable and local databases, including ÖKOBAUDAT (BWSB, 2024), KBOB (KBOB, 2024), ecoinvent (ecoinvent, 2024), GABI (WRI, 2024), EPIC (Crawford et al., 2022), INIES (CSTB, 2024) and other local databases where self-reported data and data collection audits were conducted for the production, transport and end-of-life stages. The use of Environmental Product Declarations should be avoided in this modeling framework due to their low reliability (Olanrewaju et al., 2024). Despite the proliferation of generic EPD and specific EPD, this framework aims to collect data from reliable sources. The Global Warming Potential indicator should be used in the calculation based on the IPCC 2021 LCA characterization method (del Hierro et al., 2021). The allocation of material production impact and transport will be based on allocation scenarios partitioning the input and/or output flows and using the cut-off linking method.

Negative emissions or biogenic carbon calculations should be based on a legally warranted storage permanence of thousands of years (Cullenward, 2023) for biobased materials, charcoal concrete and carbonized cement aggregates (3000 to 8000 years, which is equivalent to 100 to 300 generations (Frischknecht, 2022)). For low-carbon products incorporating bio-based materials, we recommend the use of the –1/+1 criterion to calculate the GHG emissions (Hoxha et al., 2020).

## 5. Life Cycle Assessment

For life cycle assessment, all calculations shall comply with ISO 14040 and CEN 15804-A2. The framework supports attributional and consequential LCA addressing global warming (Weidema et al., 2018), absolute sustainability, and system boundaries. It also encourages users to apply dynamic LCA methods. The LCA characterization method should be based on the IPCC 2021, and the key performance indicator shall be Global Warming Potential.

The Intergovernmental Panel on Climate Change (IPCC) provides the generally accepted values for GWP, which changed slightly between 1996 and 2001, except for methane, which had its GWP almost doubled. An exact definition of how GWP is calculated is to be found in the IPCC's 2001 Third Assessment Report (Houghton et al., 2001). The GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas. See Equation (1):

$$GWP = \frac{\int_0^t A_{GHG} \cdot C_{GHG}(t)dt}{\int_0^t A_{CO_2} \cdot C_{CO_2}(t)dt} \qquad (1)$$

$A_{GHG}$: are the specific radiative forcing per unit mass; $A_{CO2}$ = 1.76 × 10–15 Wm–2 kg–1; $A_{CH4}$ = 1.28 × 10–13 Wm–2 kg–1; $A_{N2O}$ = 3.90 × 10–13 Wm–2 kg–1
$C_{GHG}$ are decay patterns a GHGs' pulse emission in the atmosphere

The framework of this report, based on 15804-A2, is limited to Modules A, B, and C, as shown in Figure 1. We advise modelers to create their inventory of materials and quantities using mass (kg), volume (m3), and surface (m2), depending on the material. The calculation should consider all measurement units and execute the quantities calculation in the different mass, volume, and surface metrics.

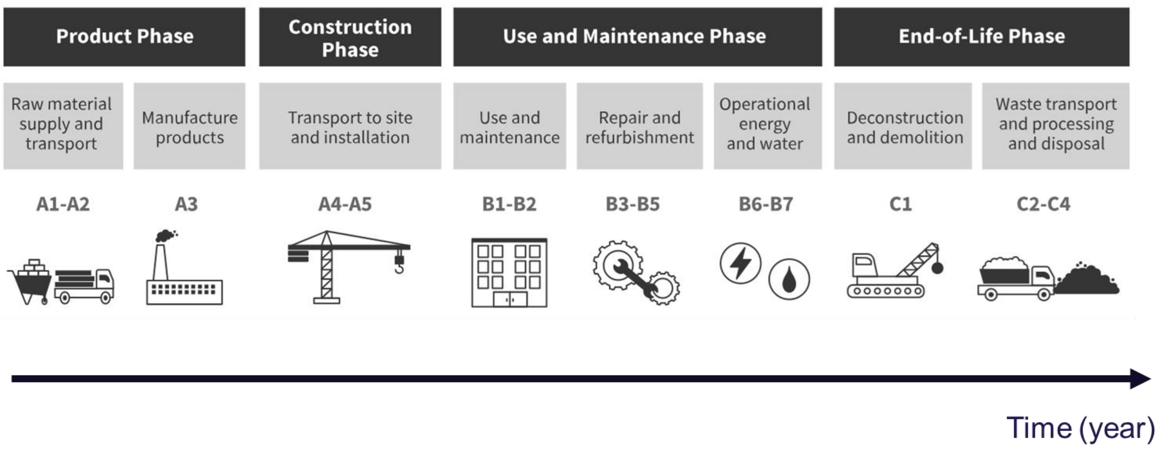


Figure 1, Modules of Life Cycle Assessment that are covered by the GHG emissions calculation framework.

## 6. HVAC, Electrical & Storage Systems

For HVAC systems, a building performance simulation for operation energy emission should take place. Manual quantification of materials should take place to calculate the embodied and end-of-life carbon emissions. The use of technical sheets and CIBSE TM65 guidelines is important (Mazzei et al., 2024; TM65, 2021). Engaging in discourse with the manufacturer is of the utmost importance in procuring data about the system components, the weight of the materials utilized, the method of transport, and the presence of EPDs. Furthermore, supplementary instruments such as the OneClick LCA MEP Carbon Tool can be employed for validation (Hoxha & Jusselme, 2017).

For the LCA calculation of building services, we advise to the follow the approach adopted by Francis et al. and Garcia-Sanz-Calcedo (Francis et al., 2017; García-Sanz-Calcedo et al., 2021). The emissions in the production, transportation, construction, operation (only for refrigerants), and recycling stages are composed of the emissions in the upstream stage of equipment (pipeline) materials, the emissions generated by energy consumption in equipment processing, and the emissions in the upstream stage of energy used (García-Sanz-Calcedo et al., 2021). The calculation formula should include the emission from all stages in $kgCO_2$, the weight of the material type of equipment, the proportion of the material contained in the equipment and the amount of energy consumed by processing equipment per unit mass in kg, the emissions from transportation of energy system equipment (including ducts) from the manufacturing plant to the project site, the material of equipment transportation distance in km. The proportion of the material type of equipment using the types of transportation mode, transport intensity of the mode of transport, $kgCO_2/(km \cdot kg)$, and a correction factor for the mode of transport.

For the HVAC operational emissions stage, the formula should address the amount of refrigerant type charged by the equipment, the annual leakage rate of refrigerant in kg, the device's operating year, the GWP value of the r refrigerant, and the amount of material consumed to maintain the equipment.

The GHG emissions generated in the operation stage include the emissions generated by the energy consumption of HVAC equipment operation, the GHG emissions equivalent generated by refrigerant leakage, the emissions generated by equipment maintenance, and the emissions generated in the upstream stage of energy. The emissions in the operation stage can be calculated by equation (2). An assumption of 5% leakage for refrigerant is part of the calculation boundary conditions:

$$GHG_{Operation} = \sum_n \sum_k W_{n,k} \cdot (GHG_k + GHG_{up,k}) + \sum_n \sum_r G_{nr} \cdot \tau_n \cdot \omega_r \cdot \alpha + \sum_n \sum_j M_{n,j} \cdot GHG_{up,j} \quad (2)$$

where $GHG_{Operation}$: the GHG equ. Emissions during the operation stage in $kgCO_2$;

$W_{n,k}$ : The amount of energy k consumed by the operation of the HVAC type of equipment (pipeline);

$G_{n,r}$: The amount of type r refrigerant charged by type n equipment, kg;

$\tau_n$: Operating year of the HVAC device, year;

$\omega_r$: GWP value of the *r* refrigerant;

$\alpha$: Annual leakage rate of refrigerant;

$M_{n,j}$ : The amount of type ***j*** material consumed to maintain type n equipment (piping), kg;

The emissions from the recycling stage are composed of the emissions from the removal of equipment (including construction machinery and workers), the emissions from the recovery of equipment materials (including transportation of recycled materials, landfilling of solid waste, and leakage of refrigerant that has not been recovered), and the emissions from the upstream stage of energy used. The emissions in this stage are calculated considering the emissions in $kgCO_{2equ}$ from equipment removal, the emissions from material recycling, the recovery rate of material, the transportation distance of the material to the recycling plant, the emissions intensity of solid waste landfill in $kgCO_{2.equ}$/kg, and the collection rate of the refrigerant.

For electrical systems and cables, a similar approach to HVAC systems shall be adopted (Hoxha et al., 2021). The IEA EBC - Annex 90 / SHC Task 70 - Low Carbon, High Comfort Integrated Lighting aims to identify and support implementing the potentials of lighting (electric, façade: daylighting and passive solar) in decarbonization with a global perspective. The focus is on lighting appliances in non-domestic buildings.  The annex is a unique research project that studies low carbon emission for fulfilling the lighting services in a life cycle assessment (LCA) / circular economy context.

For storage, the introduction of hot water or cold-water tanks and/or Phase Change Materials (PCM) in the building envelope or structure should be modeled as part of the operation of building performance simulations (Zhang et al., 2023). The results of the building performance simulation should address Module B6 or the use stage. The rest of the Module's embodied and end-of-life emissions calculation should adopt an identification approach of Module 5, HVAC and electrical systems.

### 7. Energy Mix and Carbon Factors

Depending on the historical energy mixes, the energy mix emissions should be used. For emissions characterization modeling, we advise using official national or regional published emissions factors for the different energy carriers (ISO, 2017a).  The use of prospective energy mix scenarios is debatable and should be carefully investigated (Alaux et al., 2023).

### 8. Additional Parameters

Under Module 8, additional parameters can be added to the framework to customize the calculation approach for specific indicators or parameters. For example, the carbon tax can be calculated to specific carbon limit thresholds.

**9. Evaluation Scenarios and Functional Unit**

Module 9 is focused on reporting the calculation findings and the selection of the reporting functional unit. The Module allows us to compare and evaluate different carbon emissions reduction scenarios. Currently, the most common functional unit used to report emissions is $kgCO_2e/m^2$/year per building type. The Module also allows reporting of emissions in euros or any other world currency per square meter of occupied space. However, it is up to the user to use other functional units that are not based on efficiency. During the last year, the concept of sufficiency gained momentum, and many researchers report emissions metrics such as $CO_2$e./occupant/year per building type (Attia, 2020; Petersen et al., 2022).

**10. Sensitivity Analysis and Uncertainty Analysis**

Module 10 is the final step of the calculation approach that comprises a sensitivity analysis and uncertainty analysis. Uncertainty and sensitivity analyses for LCA calculations are recommended according to ISO 14040/14044. Life cycle assessment calculations are affected by several sources of uncertainties and variabilities. Therefore, performing a sensitivity analysis (Häfliger et al., 2017) and uncertainty analysis must be part of the analysis to report the range error or uncertainty of the quantities of the materials (Hoxha et al., 2017) and impact results. By default, all life cycle analysis calculations suffer from low levels of confidence due to the lack of calibration compared to building performance simulations. Therefore, the building performance simulation model must be calibrated, and the LCA must be validated through quadrangulation methods (Hoxha et al., 2014) to ensure that the uncertainty and range or error of data input, methodological assumptions, background LCI and EPD databases, and boundary conditions are reduced to the minimum.

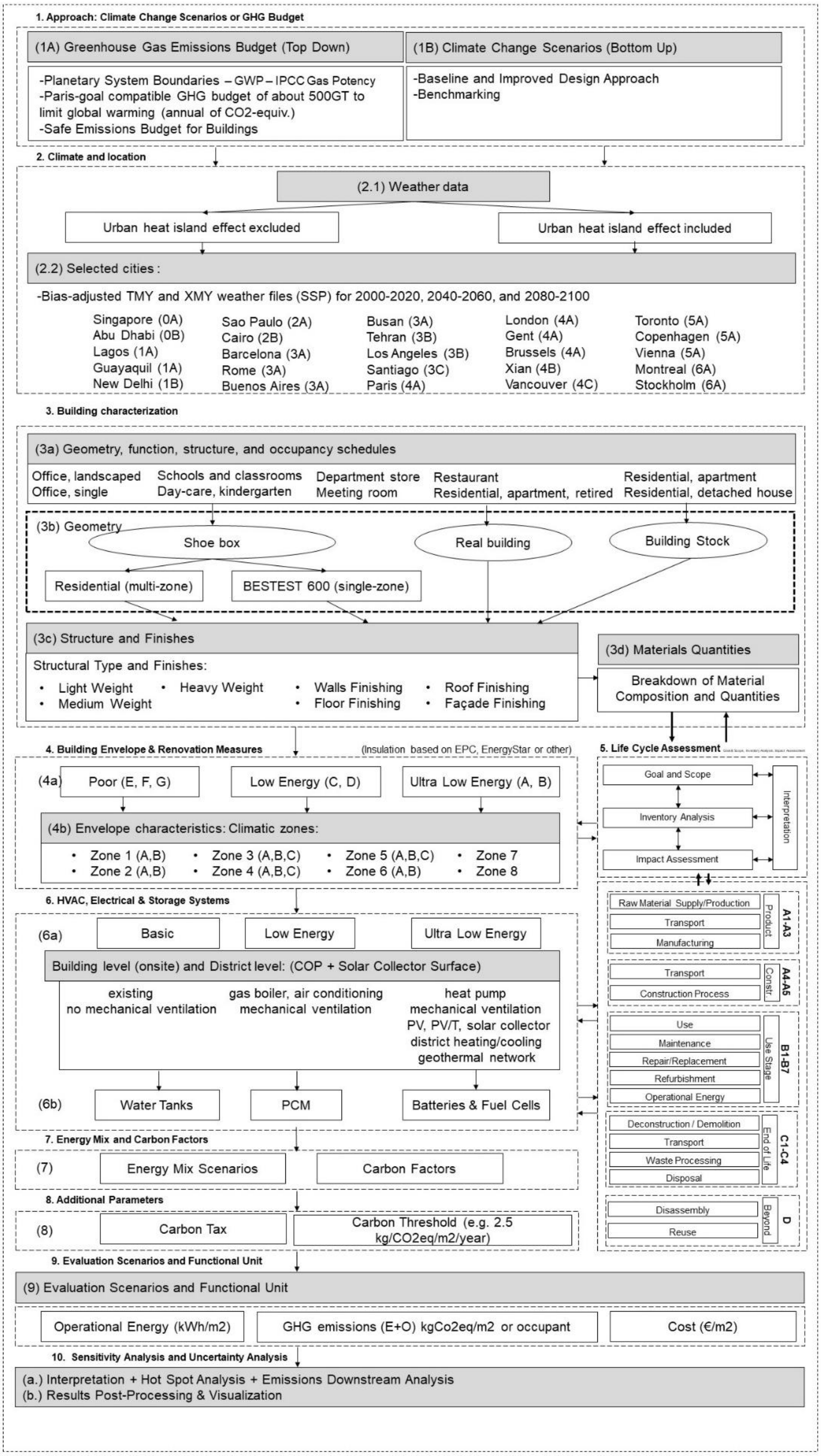


Figure 2: GHG emissions calculation framework of buildings based on ten modules that couple the embodied, operational and end-of-life emissions calculations.

# 4. Conclusion

Comparative building environmental modeling seeks to evaluate the GHG emissions intensity of buildings during construction, operation, and end-of-life cycle. Moreover, building environmental modeling aids in comparing different new construction and renovation technologies or measures in buildings with identical boundary conditions. In this report, we developed a framework that allows performing a relative comparison of individual or multiple building-integrated technologies as part of the RENOWAVE project. The framework was developed representing different climates, building users, materials, and material flows. The strength of this framework is its ability to compare different buildings under future climate change conditions. Moreover, importantly, the framework allows the modeling of a top-down approach based on carbon emissions limits and a bottom-up approach for existing carbon building emissions. The selection of weather data and the calculation of carbon emissions are based on unique approaches for coupling building emissions evaluation methods in buildings. The framework consists of systematic coupling of building performance simulation for Module B6 and the construction and end-of-life modules A and C according to EN 15804-A2. The multizonal modeling approach can represent real situations in buildings, including zones with variable HVAC systems and material compositions. The framework is flexible and allows for personalization to evaluate a complete building stock and renovation technologies under real and hypothetical conditions.

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