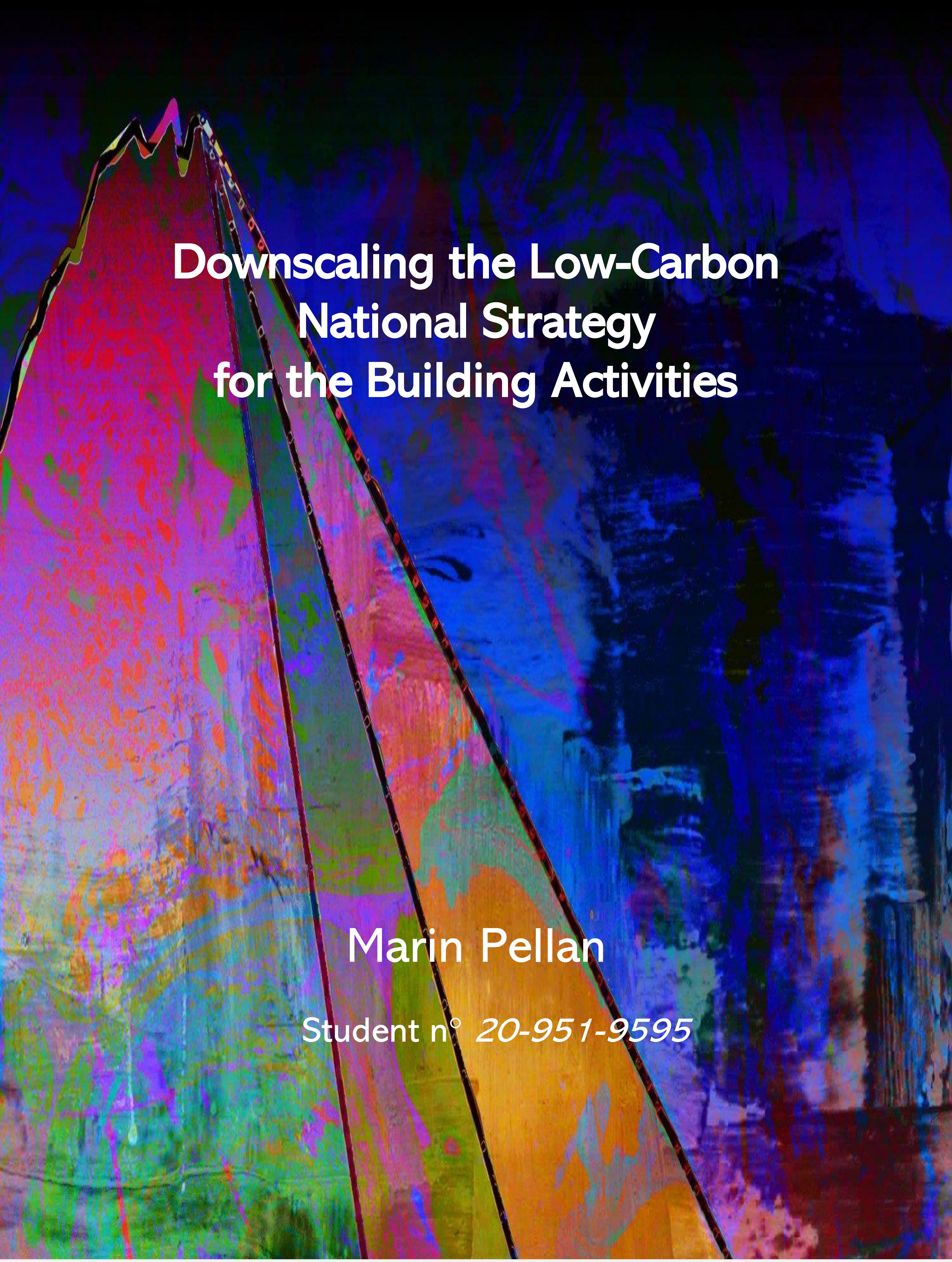

Downscaling the Low-Carbon National Strategy for the Building Activities

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Credits for the cover page go to Environmental Graffiti.

Abstract

With buildings responsible for 37% of global energy and process-related CO_2 emissions in 2021, their decarbonisation is pivotal in mitigating climate change. Positioned at the nexus of significant greenhouse gas emission reduction opportunities and sectors challenging to decarbonise, a thorough understanding of their life-cycle emissions and decarbonisation potential is imperative. While climate policies such as sectoral carbon budgets provide a necessary framework for climate action, and while multiple scenarios explore potential decarbonisation pathways across various sectors, the accounting framework in which they are embedded lack flexibility for activities that are international and at the crossroads of different sectors. This approach fails to provide a holistic accounting of emissions, thereby limiting the effectiveness of carbon budgeting and the development of appropriate decarbonisation strategies and models.

The primary objective of this thesis is to develop life-cycle carbon budgets for buildings and to model exploratory scenarios for life-cycle emissions trends up to 2050 at various scales—from modelling entire residential activities to the detailed performance modelling of new buildings. This work aims to better align sectoral policies (e.g., building regulations) with climate policies by leveraging a combination of environmental assessment methods, building stock modelling, prospective techniques, and particularly scenario analysis that are extensively described using the latest research findings. To achieve this, the work is divided in three main parts.

The first part establishes a robust methodology that captures the full spectrum of emissions from building activities. This methodology facilitates the projection of different carbon budgets for the various emission scopes identified, expanding beyond traditional sectoral carbon budgets that often limit their scope to direct operational emissions. This approach also identifies carbon budgets contingent on the decarbonisation of various upstream sectors, thus reflecting differing decarbonisation ambitions. Rather than creating new carbon budgets from scratch, this methodology enables to work with existing sectoral carbon budgets while expanding their scope and policy relevance.

The second part models explorative scenarios for residential activities. Leveraging a building stock database, the aim is to create a modelling framework that allows dynamic projection, facilitating the assessment of drivers and enabling the calculation of life-cycle Greenhouse Gases Emissions (GHGE) year by year and cumulatively by 2050. Within this framework, scenarios for the decarbonisation of upstream sectors influencing energy carriers and embodied benchmark values are integrated to assess their importance in achieving climate objectives. Ultimately, the goal is to evaluate how different decarbonisation strategies might or might not align with the previously determined carbon budgets.

Finally, the third part goes down to the building level, assessing how scenarios affecting upstream industrial and energy sectors influence the embodied performance of various building typologies. This final aspect focuses on new construction, leveraging a building Life Cycle Assessment (LCA) database along with prospective LCA tools that enable the integration of Integrated Assessment Models (IAMs) scenarios. Ultimately, the aim is to compare the future embodied performance of new building typologies modelled under this method with the previously proposed future benchmark values.

Key findings concerning accounting and carbon budgeting reveal that the French building stock emits 162 $MtCO_2eq$ in 2019, with embodied GHGE accounting for 36% of this total. The majority of embodied GHGE originate from the industry and energy upstream sectors. Notably, 20% of emissions occur outside national borders. By 2040, embodied GHGE are projected to become the predominant scope of emissions, constituting the larger portion of the building activities' carbon budgets under the current decarbonisation policies. This indicates that existing climate policies are insufficient and overly narrow and should incorporate a broader spectrum of emissions, especially as building legislation increasingly mandates reductions for the life-cycle emissions of buildings.

For decarbonisation pathways concerning residential activities, findings highlight a significant gap in GHGE that can result from different strategies. For example, policies targeting fossil fuel prove most effective in reducing operational GHGE than those focusing only on energy performance label. In ambitious scenarios with high renovation rates, embodied GHGE become predominant by 2040. Achieving ambitious carbon budgets will require a combination of sufficiency (e.g. through lower square meter per *capita*) and deep decarbonisation of energy carriers and construction materials.

Prospective LCA modelling of new construction suggests a high decarbonisation potential from upstream sectors, with reductions of around 60% in the most ambitious scenarios, in terms of emissions per square meter at the building level. However, meeting ambitious targets by 2050 will necessitate the deployment of additional levers, such as demand-side mitigation. When extrapolated to the national level, these findings seem to indicate that current construction practices (e.g. market share between different building typologies) are insufficient to align with ambitious carbon budgets, pointing to the need for further promoting low-carbon materials solutions.

Overall, this research contributes to the broader discourse on carbon budgets for buildings, calculation of prospective whole-life carbon emissions at large scale, and scenario analysis tailored for building activities. It provides valuable insights, methodological advancements, and tools that can enhance the refinement of existing climate policies, building legislation, and prospective modelling practices.

Keywords: *carbon budgets; whole-life carbon; embodied emissions; climate policies; decarbonisation pathways; life-cycle assessment; environmental benchmarks; stock dynamics; scenario analysis; prospective studies*

Résumé

En 2021, les activités du bâtiment sont responsables de 37% des émissions mondiales de CO_2 liées à l'énergie et aux procédés industriels, soulignant ainsi l'importance cruciale de leur décarbonation pour atténuer le changement climatique. Situées à l'intersection de secteurs offrant de grandes opportunités de réduction et de secteurs difficiles à décarboner, une compréhension approfondie des émissions sur l'ensemble du cycle de vie des bâtiments à grande échelle ainsi qu'une analyse holistique de leurs potentiels de décarbonation est impérative. Bien que les politiques climatiques, telles que les budgets carbone sectoriels, fournissent un cadre nécessaire à l'action climatique, et tandis que de multiples scénarios explorent des voies de décarbonation potentielles à travers différents secteurs, le cadre de comptabilité des émissions utilisé dans ces travaux manque de flexibilité pour les activités à la croisée de différents secteurs et présentant une portée internationale. En effet, il ne permet pas de fournir une comptabilisation holistique des émissions relevant des activités du bâtiment, limitant ainsi l'utilité des approches en budgets carbone pour développer des stratégies de décarbonation et des modèles abordant une approche en cycle de vie.

L'objectif principal de cette thèse est de développer des budgets carbone qui prennent en compte l'ensemble des émissions sur le cycle de vie des bâtiments à l'échelle nationale, et de modéliser des scénarios exploratoires à l'horizon 2050 à différentes échelles, de la modélisation de toutes les activités résidentielles jusqu'à une modélisation détaillée de la performance carbone des bâtiments neufs. Ce travail vise à mieux aligner les politiques sectorielles liées au secteur du bâtiment (par exemple, la nouvelle réglementation environnementale, RE2020) avec les politiques climatiques en s'appuyant sur une combinaison de méthodes d'évaluation environnementale, de modélisation du parc résidentiel et de méthodes prospectives, en particulier via l'analyse de scénarios. Ces méthodes sont extensivement documentées dans le manuscrit en utilisant les dernières recherches disponibles. Pour répondre aux enjeux, le travail est divisé en trois parties principales.

La première partie établit une méthodologie robuste qui permet de comptabiliser le spectre complet des émissions liées aux activités du bâtiment. Cette méthodologie facilite la projection de différents budgets carbone pour les divers types d'émissions identifiés, allant au-delà des budgets carbone sectoriels qui limitent souvent leur portée aux émissions opérationnelles directes. Cette approche identifie également des budgets carbone dépendant de la décarbonation des multiples secteurs intervenant dans la chaîne de valeur des activités du bâtiment, reflétant ainsi des ambitions de décarbonation diverses. Plutôt que de créer de nouveaux budgets carbone de zéro, cette méthodologie permet de travailler avec des budgets carbone sectoriels existants tout en élargissant leur portée et leur pertinence.

La deuxième partie modélise des scénarios exploratoires pour les activités résidentielles à l'horizon 2050. En s'appuyant sur une base de données du parc résidentiel, l'objectif est de créer un cadre de modélisation qui permet une projection dynamique du parc et intègre le calcul des émissions de gaz à effet de serre (GES) sur le cycle de vie des bâtiments de manière annuelle et cumulative d'ici à 2050. Des scénarios de décarbonation des vecteurs énergétiques ainsi que des scénarios d'évaluation des

performances carbone des matériaux et équipements (émissions *embodied*) sont intégrés pour évaluer leur importance dans l'atteinte des objectifs climatiques dérivés des budgets carbone préalablement calculés. En fin de compte, l'objectif est d'évaluer comment différentes stratégies de décarbonation à l'échelle du parc résidentiel peuvent ou non s'aligner avec ces objectifs.

Enfin, la troisième partie descend d'un niveau en s'intéressant à la modélisation fine au niveau des bâtiments neufs. Le but est d'évaluer quantitativement l'influence de la décarbonation des secteurs industriels et énergétiques sur les émissions *embodied* de différentes typologies de bâtiment. Cette dernière se concentre sur les nouvelles constructions, en exploitant une base de données d'Analyse du Cycle de Vie (ACV) des bâtiments ainsi qu'une méthode d'ACV prospectif permettant l'intégration de scénarios issus des Modèles d'Évaluation Intégrée (*Integrated Assessment Models* ou IAMs). L'objectif final est de comparer les futures émissions *embodied* pour différentes typologies sous divers scénarios de décarbonation caractérisés par des niveaux d'ambitions différents, et de les comparer avec des valeurs de référence futures préalablement établies.

Les principaux résultats concernant la comptabilité et les budgets carbone révèlent que les activités du bâtiment en France ont émis 162 $MtCO_2eq$ en 2019, les émissions *embodied* représentant 36% de ce total, provenant majoritairement des secteurs industriels et énergétiques en amont de la chaîne de valeur. Sur les 162 $MtCO_2eq$, 20% des émissions ont eu lieu hors des frontières nationales. Avec les politiques climatiques actuelles, les émissions *embodied* peuvent constituer le type d'émission majoritaire dès 2040. Cela renforce l'idée que les budgets carbone sectoriels existants devraient intégrer un spectre plus large d'émissions, alors même que les législations sectorielles imposent de plus en plus d'exigence de performance environnementale sur l'intégralité du cycle de vie des bâtiments.

Pour les stratégies de décarbonation du parc résidentiel, les résultats suggèrent un écart significatif en fonction des politiques de rénovation. Par exemple, les politiques ciblant l'élimination des combustibles fossiles s'avèrent plus efficaces pour réduire les émissions opérationnelles que celles axées uniquement sur l'étiquette de performance énergétique. Dans des scénarios ambitieux caractérisés par des taux de rénovation élevés, les émissions *embodied* deviennent prédominantes d'ici 2040. Atteindre des budgets carbone ambitieux nécessitera une combinaison de sobriété (par exemple, via une réduction du nombre de mètres carrés par habitant) et de décarbonation profonde des vecteurs énergétiques et des matériaux de construction.

La méthode d'ACV prospective appliquée sur plusieurs typologies de bâtiments neufs suggère un potentiel de décarbonation élevé résultant des transformations des secteurs en amont de la chaîne de valeur, avec des réductions de l'ordre de 60% à l'horizon 2050 dans les scénarios les plus ambitieux (i.e. en termes d'émissions par mètre carré). Atteindre des niveaux de réduction plus drastiques nécessite le déploiement de leviers supplémentaires, notamment du côté de la demande. Ces résultats semblent indiquer que les pratiques de construction actuelles (par exemple, les parts de marché entre différents principes constructifs) ne permettent pas de s'aligner avec des budgets carbone ambitieux. Cela souligne la nécessité de promouvoir davantage les solutions permettant de réduire l'impact carbone des matériaux et équipements.

Dans l'ensemble, cette thèse contribue aux recherches menées sur l'application de budgets carbone, le calcul d'émissions en cycle de vie à large échelle et l'analyse de scénarios adaptés aux activités de bâtiment. Elle fournit des avancées méthodologiques, des outils et des résultats qui peuvent améliorer le raffinement des politiques climatiques et sectorielles existantes, ainsi que des pratiques de modélisation prospectives.

Mots clés : *budgets carbone; politiques climatiques; trajectoires de décarbonation; analyse du cycle de vie; dynamique du parc résidentiel; analyse de scénarios; prospective*

Glossary

Avoided emissions *'The positive impact on society when comparing the GHG impact of a solution to an alternative reference scenario where the solution would not be used'* (Net Zero Initiative and WBCSD, 2023). An avoided emission does not necessarily reflect an absolute decrease in emissions.

Bottom-up and top-down The dichotomy between top-down and bottom-up is often used in different contexts. In the context of modelling, top-down models start with an aggregated view of a system that can be subsequently broken down in sub-systems, while bottom-up models begin with a detailed representation of a system's components, eventually aggregating them to represent the whole-system (Langevin et al., 2020). In the context of environmental benchmarks, top-down benchmarks help to derive science-based targets from environmental goals such as the RCB, while bottom-up benchmarks are more interested in statistical analysis of current empirical datasets (ISO, 2020).

Building activities The building activities (also called building 'field of action' (Trüger et al., 2022)) serves the needs of housing and shelter and contains multiple activities that are involved at different stages of a building life-cycle. To answer to these activities, several economic sectors are involved in the supply- chain. This definition recognises the cross-sectoral, international and life-cycle impacts of buildings, not only focusing on their direct impact from the use of fossil and biomass products.

Carbon capture and storage (CCS) *'A process in which a relatively pure stream of carbon dioxide (CO2) from industrial and energy-related sources is separated (captured),conditioned,compressed and transported to a storage location for long-term isolation from the atmosphere'* (van Diemen et al., 2022). When the CO2 is used in a product, the term Carbon Capture and Utilisation (CCU) is used. *'The climate effect of CCU depends on the product lifetime, the product it displaces, and the CO2 source'* (van Diemen et al., 2022)

Carbon footprint *'Measure of the exclusive total amount of emissions of carbon dioxide (CO_2) that is directly and indirectly caused by an activity or is accumulated over the lifecycle stages of a product'* (Wiedmann and Minx, 2008)

Climate neutrality *'(1) Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local bio geophysical effects of human activities that, for example, affect surface albedo or local climate. See also Net zero CO2 emissions. (2) Condition in which anthropogenic carbon dioxide (CO2) emissions associated with a subject are balanced by anthropogenic CO2 removals. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service and an* *event. Carbon neutrality is often assessed over the lifecycle including indirect ('scope 3') emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme. [Note 1: Carbon neutrality and net-zero CO2 emissions are overlapping concepts. The concepts can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms carbon neutrality and net-zero CO2 emissions are equivalent. At sub-global scales, net-zero CO2 emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while carbon neutrality generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by greenhouse gas (GHG) programmes or schemes can have a significant influence on the quantification of relevant CO2 emissions and removals'* (van Diemen et al., 2022)

Consumption-based emissions *'Emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region)'* (van Diemen et al., 2022)

Demand-side and supply-side *'Demand-side solutions for mitigation of climate change modify demand for goods and services by targeting choices/adoption of technology, consumption, behaviour, lifestyles, coupled production–consumption infrastructures and systems, service provision and associated socio-technical transition [...] Supply-side options involve changes in energy supply, production technologies and deployment of carbon dioxide-removal technologies that keep demand by end users invariant'* (Creutzig et al., 2021)

Direct and indirect emissions Direct emissions *'physically arise from activities within well-defined boundaries of, for instance, a region, an economic sector, a company, or a process.'* // Indirect emissions are *'a consequence of the activities within well-defined boundaries of, for instance, a region, an economic sector, a company or process, but which occur outside the specified boundaries. For example, emissions are described as indirect if they relate to the use of heat but physically arise outside the boundaries of the heat user, or to electricity production but physically arise outside of the boundaries of the power supply sector'* (van Diemen et al., 2022)

Downstream emissions *'Indirect GHG emissions from sold goods and services. Downstream emissions also include emissions from products that are distributed but not sold (i.e., without receiving payment)'* (GHG Protocol, 2011)

Embodied emissions *'The total emissions [water use, land use] generated [used] in the production of goods and services regardless of the location and timing of those emissions [water use, land use] in the production process. This includes emissions [water use, land use] within the country used to produce goods or services for the country's own use, but also includes the emissions [water use, land use] related to the production of such goods or services in other countries that are then consumed in another country through imports. Such emissions [water, land] are termed 'embodied'* *or 'embedded' emissions, or, in some cases, (particularly with water) as 'virtual water use'* (Davis et al., 2011)

Global carbon budgets *'An assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil fuel and cement emissions, land-use change emissions, ocean and land CO2 sinks, and the resulting atmospheric CO2 growth rate'* (Matthews et al., 2021)

Global Warming Potential *'An index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, carbon dioxide (CO2). The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere, and their effectiveness in causing radiative forcing'* (van Diemen et al., 2022)

Negative emissions *'Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, that is, in addition to the removal that would occur via natural carbon cycle or atmospheric chemistry processes'* (Matthews et al., 2021). The term carbon dioxide removal (CDR) is also used.

Offsets *'The reduction, avoidance or removal of a unit of greenhouse gas (GHG) emissions by one entity, purchased by another entity to counterbalance a unit of GHG emissions by that other entity. Offsets are commonly subject to rules and environmental integrity criteria intended to ensure that offsets achieve their stated mitigation outcome. Relevant criteria include, but are not limited to, the avoidance of double counting and leakage, use of appropriate baselines, additionality, and permanence or measures to address impermanence'* (van Diemen et al., 2022).

Pathways *'The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution- oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales'* (van Diemen et al., 2022)

Production-based emissions *'Emissions released to the atmosphere for the production of goods and services by a certain entity (e.g., a person, firm, country, or region)'* (van Diemen et al., 2022)

Reference scenario In the context of mitigation policies, it represents *'a reference case that represents the events or conditions most likely to occur in the absence of the policy or action (or package of policies or actions) being assessed'* (GHG Protocol, 2016). In the context of avoided emissions it is used to describe *'a reference case that represents the events or conditions most likely to occur in the absence of the assessed solution'* (Net Zero Initiative and WBCSD, 2023). The terms 'Counterfactual' and 'Baseline' scenarios are also used.

Remaining carbon budgets *'The estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a reference period,* *taking into account global surface temperature contributions of other GHGs and climate forcers'* (Matthews et al., 2021)

Scenario *'A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions'* (van Diemen et al., 2022).

Upstream emissions *'Indirect GHG emissions from purchased or acquired goods and services'* (GHG Protocol, 2011)

Acronyms

ADEME French Agency for Ecological Transition

AESA Absolute Environmental Sustainability Assessment

APS (IEA's) Announced-Pledges Scenario

AR (IPCC's) Assessment Report

ARM Association Rule Mining

BAU Business-As-Usual

BBC *Bâtiment Basse Consommation*

BDNB *Base de Données Nationale des Bâtiments*

BSM Building Stock Modelling

BU Bottom-up

CBA Consumption-Based Accounting

CBDR-RC Common But Differentiated Responsibilities And Respective Capacities

CCS Carbon Capture and Storage

CFC Consumption of Fixed Capital

D-EF Direct Emission Factor

DIM Direct Impact Multipliers

EE-IOT Environmentally Extended Input-Output Tables

EF Emission Factor

EPC Energy Performance Certificate

EPD Environmental Product Declaration

ESB Earth System Boundary

GCB Global Carbon Budget

GDP Gross Domestic Product

GFCF Gross Fixed Capital Formation

GHGE Greenhouse Gases Emissions

GIS Geographic Information System

GMST Global Mean Surface Temperature

HC Hierarchical Clustering

IAM Integrated Assessment Model

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

ISO International Organisation for Standardisation

LCA Life Cycle Analysis

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

LCSA Life Cycle Sustainability Assessment

LDA Linear Discriminant Analysis

MFA Material Flow Analysis

MIC Material Intensity Coefficients

MIP Model Intercomparison Project

MRIO Multi-Regional Input-Output

NDC Nationally Determined Contributions

NSA Non-State Actors

NZI Net Zero Initiative

NZS (IEA's) Net-Zero Scenario

PB Planetary Boundary

PBA Production-Based Accounting

RCB Remaining Carbon Budget

RCP Representative Concentration Pathway

RTE France's transmission system operator

SBT Science Based Target

SBTi Science Based Target Initiative

SDES French Statistical Data and Studies Department

SETAC Society of Environmental Toxicology and Chemistry

SNBC Low-Carbon National Strategy

SSP Shared Socioeconomic Pathway

TD Top-down

TRCE Transient Climate Response to Cumulative CO_2 emissions

TRL Technology Readiness Level

UNEP United Nations Environment Program

UNFCCC United Nations Framework Convention on Climate Change

WG (IPCC's) Working Group

WLC Whole-Life Carbon

Nomenclature

ω	WLC emissions in $MtCO_2eq$
θ	Operational GHGE in $MtCO_2eq$
ε	Embodied GHGE in $MtCO_2eq$
A	Inter-industry coefficient matrix
Dw	Dwelling
dwt	Dwelling type
E_f	Final energy consumption in kWh
e_f	Final energy consumption in kWh/m^2
E_p	Primary energy consumption in kWh
e_p	Primary energy consumption in kWh/m^2
epc	energy performance certificate label
F	Total impact matrix
f_θ	Operational emission factors in $kgCO_2eq/kWh$
f_ε	Embodied emission factors in $kgCO_2eq/m^2$
K	square meter per capita
L	Leontief Inverse
Lt	Dwelling
n	energy carriers type
P	Population
PEF	Primary Energy Factor
R	Renewal
S	Surface in m^2
X	Total output
Z	Inter-industry matrix

Contents

1

Introduction

Contents

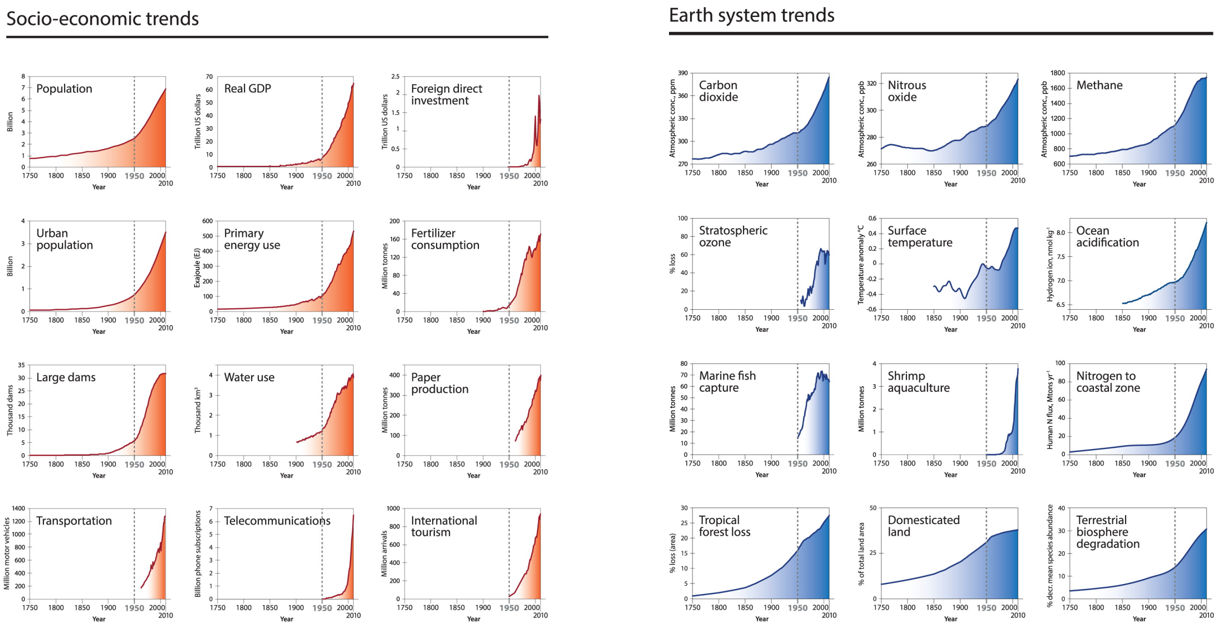
This chapter lays the foundation for this doctoral dissertation, providing essential context and outlining the research's scope and methodology. The first section – Context 1.1 – provides a comprehensive overview of the current environmental and climate crisis, emphasising the criticality of carbon budgets cascading. Special attention is given to the impact and significance of the building activities, highlighting their role in the current crisis. This section also introduces the framework of French climate and sectoral policies, setting the stage for a deeper exploration of how these policies intersect with and influence the building activities . The second section – Research objectives and thesis organization 1.3.1 –presents a clear vision of the intended contributions and outcomes, setting a defined path for the research. This section also elaborates on how the thesis is organised, detailing how each part and chapter aligns with and supports the achievement of these objectives

1.1 Context

1.1.1 The global environmental and climate crisis

The Anthropocene and the Planetary boundaries

The Anthropocene concept, popularised by Nobel laureate Paul J. Crutzen in 2000, marks a new epoch in Earth's history. It reflects the significant impact of human activities as a dominant force shaping the planet's natural systems, affecting climate, geology, and biodiversity. The start of the Anthropocene is debated, but it is often linked to the first Industrial Revolution, which saw widespread use of fossil fuels. The period after World War II, known as the Great Acceleration (Steffen et al., 2015), witnessed exponential growth in various socio-economic and Earth system indicators, as illustrated in Figure 1.1.



(a) Global socio-economic trends **(b)** Earth system trends

Figure 1.1: The Great Acceleration (Steffen et al., 2015)

The 12 socio-economic indicators, selected for their representation of key aspects of modern society, include demographic (population, urban population), economic (real gross domestic product (GDP), foreign direct investment), and consumption metrics (water use, primary energy use, fertilizer consumption). In parallel, the 12 Earth System indicators track significant changes in the structure and functioning of Earth's system (Steffen et al., 2015). Both socio-economic and Earth System trends display exponential growth patterns, underscoring the escalating human impact on the planet.

Central to understanding the challenges posed by the Anthropocene is the framework of Planetary Boundaries (PBs) (Rockström et al., 2009). This framework identifies critical thresholds within Earth's complex systems, encompassing factors such as climate change, biodiversity loss, ocean acidification, and nutrient cycles. Crossing these boundaries can lead to abrupt and irreversible environmental changes with potentially catastrophic consequences for humanity and the planet. Updated research shows that six of the nine planetary boundaries are already transgressed as illustrated in Figure 1.2.

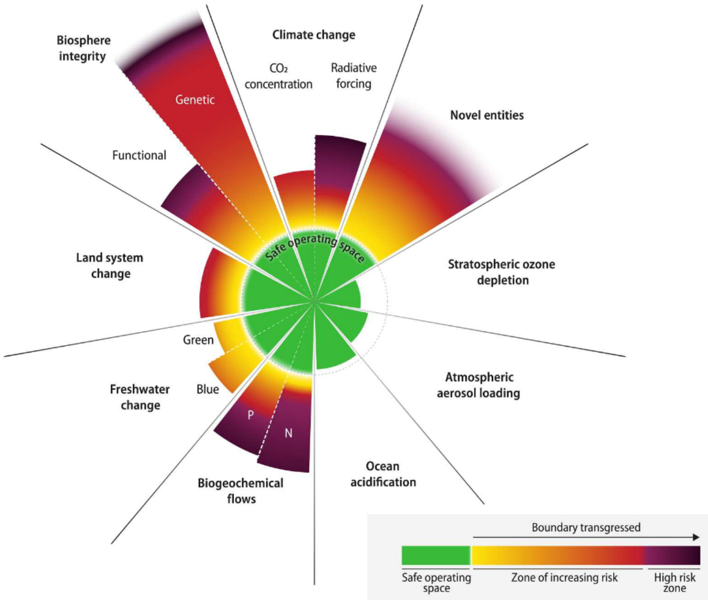


Figure 1.2: 2023 Updated status on the nine planetary boundaries (Richardson et al., 2023)

The green zone in this framework represents a 'safe operating space' characterised by stable and sustainable environmental conditions. However, once these boundaries are crossed, it leads to zones of escalating risk, culminating in high-risk areas. Among the nine identified PBs, only ocean acidification, atmospheric aerosol loading, and stratospheric ozone depletion remain within safe limits as of 2023.

This thesis delves deeply into one of the most urgent aspects of the Anthropocene: climate change. As a pivotal manifestation of human impact in this new epoch, climate change is a crucial focal point for understanding the complex nature of human-induced environmental changes and underscores the imperative need for effective mitigation and adaptation strategies.

The climate crisis

Among the Planetary boundaries and broader environmental concerns, climate change has emerged as a critically important issue in recent decades. The first Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC), published in 1990, brought attention to the rising risk of global temperature increase due to escalating greenhouse gas emissions (GHGE). Subsequent reports have unequivocally confirmed human influence on global warming, with significant impacts already observed in the atmosphere, oceans, and on land (Masson Delmotte et al., 2021).

In 2019, global net GHGE reached a historic peak of 59 (± 6.6) $GtCO_2eq$. Breakdown of the emissions include CO_2 emissions at 45 (± 5.5) $GtCO_2$, CH_4 emissions at 11 (± 3.2) GtCO2-eq, N_2O emissions at 2.7 (± 1.6) GtCO2-eq and fluorinated gases (F-Gases that comprise substances such as HFCs, PFCs, SF_6 and NF_3) contributing 1.4 (± 0.41) GtCO2-eq (Dhakal et al., 2022). When focusing on CO_2 emissions, global emissions are projected to reach 40.9 (± 3.2) $GtCO_2$ in 2023, marking a

47% increase since 1990. The primary source of these emissions is the combustion of fossil fuels contributing for 37.1 (± 2) Gt CO_2. Estimated land-use change emissions between 2013 and 2022 are 4.7 (± 2.6) Gt CO_2, although significant uncertainties persist in these estimates. Consequently, the atmospheric CO_2 concentration is expected to average 419.3 parts per million (ppm) in 2023 (Friedlingstein et al., 2023), well above the Planetary Boundary threshold of 350 ppm CO_2 and 1.0 Wm^{-2}, and alarmingly close to the upper zone of increasing risk at 450ppm CO_2 and 1.5 Wm^{-2} (Richardson et al., 2023). These figures indicate that we are already in a zone of increasing risk and approaching the high-risk zone if current emission trends continue.

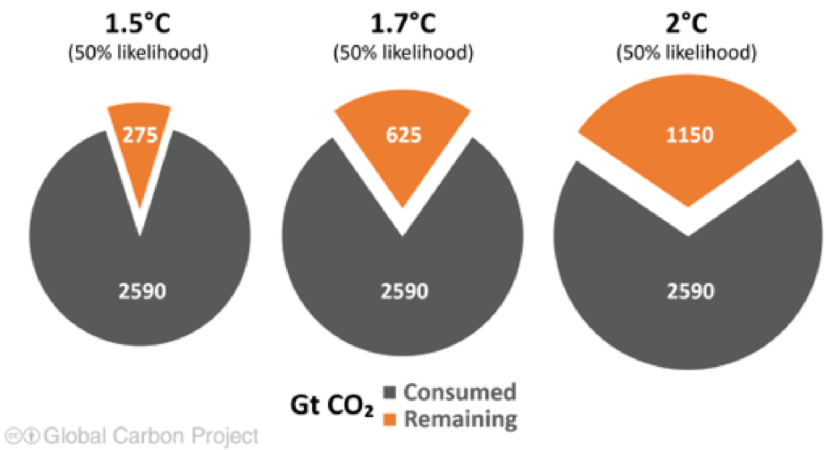
CO_2 removal from the atmosphere is facilitated by both anthropogenic and non-anthropogenic sinks. Anthropogenic sinks include human-made methods like afforestation and carbon capture. Meanwhile, the oceans and terrestrial biosphere, as primary non-anthropogenic sinks, absorb nearly half of the annual global CO_2 emissions and have played a crucial role in reducing the rate of increase in atmospheric CO_2 concentrations. However, there is growing concern that these sinks are showing signs of weakening due to the continual increase in atmospheric CO_2 levels and the cumulative impacts of climate change (Friedlingstein et al., 2023). This weakening of natural sinks points towards a broader, critical concept in climate science known as 'tipping points.' Tipping points are specific thresholds in the Earth's climate system, beyond which significant and potentially irreversible environmental changes are triggered.

The Paris Agreement and the Remaining Carbon Budgets (RCB)

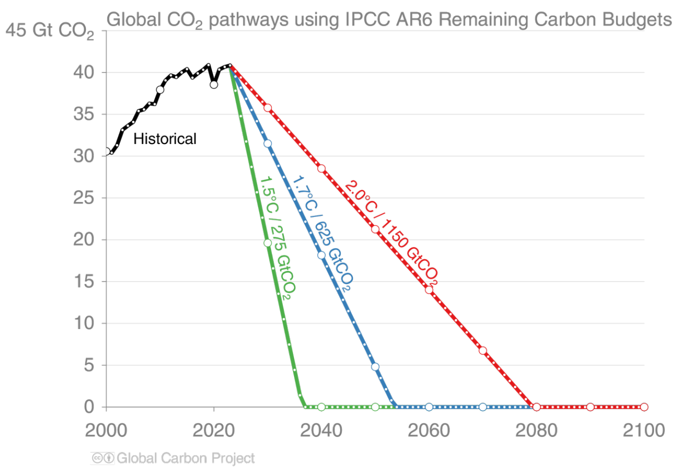
In 1992, the Rio Conference led to the formation of the United Nations Framework Convention on Climate Change (UNFCCC), followed by annual Conference of the Parties (COP) meetings starting in 1995. A critical milestone was the 2015 Paris Agreement at COP21, which established long-term temperature goals in Article 2.1 to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C. Furthermore, Article 4.1 emphasises the urgency of peaking GHGE as soon as possible and transitioning towards net-zero emissions defined as *'a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases'* (United Nations, 2015).

Central to understanding the Paris Agreement's objectives is the comprehension of the near-linear relationship between cumulative CO_2 emissions and global temperature rise. This relationship is quantified by the Transient Climate Response to Cumulative Carbon Emissions (TCRE), defined as the variation in average global temperature resulting from a specified amount of cumulative CO_2 (Matthews et al., 2021). In the AR6, it is estimated that each 1000 $GtCO_2eq$ of cumulative CO_2 emissions is likely to lead to a 0.45°C increase in global surface temperature as a central estimate, with a probable range of 0.27°C to 0.63°C (Canadell et al., 2021). Therefore, the TCRE elucidates that is necessary to achieve a state of net-zero emissions to limit the global temperature increase in line with the Paris Agreement. Furthermore, it facilitates the quantification of the permissible amount of cumulative CO_2 emissions to remain within a specified temperature threshold. The TCRE thus serves as a pivotal metric, providing a measurable connection between emissions and temperature increase, which in turn enables the determination of the Remaining Carbon Budget (RCB). Defined by the IPCC as *'the maximum amount of cumulative net global anthropogenic CO_2 emissions that would* *result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers'* (IPCC, 2022), the RCB is pivotal for assessing the Paris Agreement pledges. Specifically, it relates to the well-below 2°C target, with the term 'remaining' referencing a specified recent date.

The 2023 figures from the Global Carbon Project, shown in Figure 1.3, present the latest RCBs for three warming thresholds along with three pathways illustrating the steep emission reduction pathways required.



(a) Remaining carbon budgets with different temperature outcomes



(b) Global emission reduction pathways using different remaining carbon budgets temperature outcomes

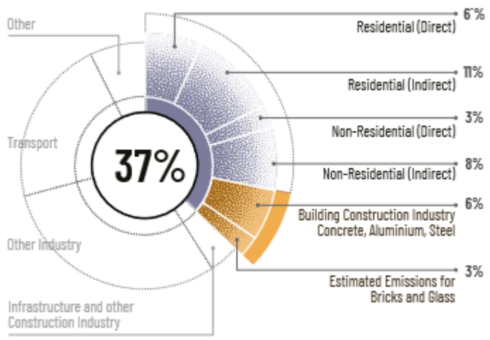
Figure 1.3: Perspectives on the remaining carbon budgets

Figure 1.3a presents the RCBs average figures from two estimates, namely Forster et al. (2021) and Forster et al. (2023) with a 50% likelihood. The RCBs to limit global warming to 1.5°C , 1.7°C and 2°C stands at 275 $GtCO_2$, 625 $GtCO_2$, and 1150 $GtCO_2$ respectively, against a backdrop of 2590 $GtCO_2$ already emitted since 1850. This equates to approximately 7, 15, and 28 years of emissions at the current rate. Figure 1.3b visually demonstrates the emission reduction trajectories needed for each target.

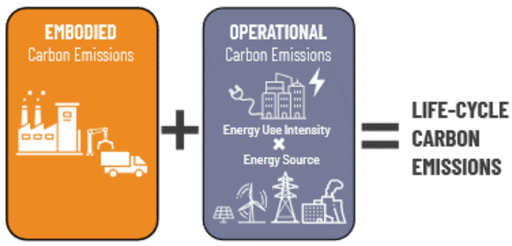
The value of the remaining carbon budget is expressed in probabilistic terms due to several uncertainties. They include historical and recent emission levels, the contribution of non-CO_2 emissions, climate feedback mechanisms (such as permafrost thawing), the role of aerosols, the current and future value of the TRCE, the potential warming post net-zero CO_2 emissions and unrepresented Earth system feedbacks (Matthews et al., 2020). These uncertainties lead to variations in budget estimations and underscore the complexity of predicting future climate scenarios (Rogelj et al., 2019). The concept of the RCB offers a simplified yet powerful means to understand and communicate complex physical climate mechanisms. It serves as an evocative indicator that aids in communicating the urgency and scale of climate action. However, recognising its limitations and the nuances in its calculation is crucial, especially when employing it as a pivotal indicator in climate policy decision-making. For accurate and reliable application, scientific studies estimating the remaining carbon budget should meticulously document their assumptions and methodologies (Matthews et al., 2020).

The pivotal role of the building activities

The Intergovernmental Panel On Climate Change (IPCC) estimates global GHGE from buildings at $12GtCO_2eq$ in 2019, comprising primarily of CO_2 emissions (95%), with halocarbons contributing 3% and a combined 0.08% from CH_4 and N_20 (Cabeza et al., 2022). When focusing only on energy and process-related CO_2 emissions[1], the building and construction sector accounts for 37% of worldwide energy and process-related CO_2 emissions and 34% of global final energy demand in 2021 (UNEP, 2022). As depicted in Figure 1.4, emissions for buildings are characterised in two main sources, namely operational and embodied emissions. On one hand, operational emissions



(a) Share of building and construction global energy and process-related CO_2 emissions



(b) Embodied, operational and life-cycle emissions of buildings

Figure 1.4: Global building and construction life-cycle CO_2 emissions (UNEP, 2023)

arise from energy consumption during the use-stage of buildings. These are further divided into direct operational emissions (on-site fossil fuel and biomass combustion, and F-gases emissions from systems like heating and cooling) and indirect operational emissions (off-site production of electricity and heat used in buildings). Embodied emissions, on the other hand, encompass the life-cycle

[1]Chapter 2.1.1 further explains the difficulties associated with having detailed data at global level that encompasses all GHGE

emissions of construction materials and goods used in building construction, maintenance, and end-of-life (Cabeza et al., 2022). According to UNEP (2022), when only focusing on energy and process-related CO_2, operational emissions comprise a significant 28% of global energy and process-related CO_2 emissions, with residential buildings leading at 17%, followed by non-residential buildings at 11%. Embodied emissions represent 9% of global energy and process-related CO_2 emissions, without any breakdown by building types.

The building and construction sector's decarbonisation is crucial for achieving the Paris Agreement goals, yet it is currently off track for the necessary reductions by 2050 (UNEP, 2022). Indeed, material production emissions for infrastructure development alone could consume up to 60% of the remaining carbon budget by 2050 for a 2°C target (Müller et al., 2013). While operational emissions have been the primary focus in research and policy, life-cycle assessment (LCA) studies reveal that embodied emissions are increasing in absolute and relative terms, particularly in new energy-efficient buildings (Röck et al., 2020). With significant new construction expected in the Global South and the need for extensive renovations in the Global North, embodied emissions are projected to increase, potentially constituting up to 50% of life-cycle emissions by 2050 (UNEP, 2023).

1.1.2 From global to scalable carbon budgets and decarbonisation pathways

Allocation principles

While the Planetary Boundaries (PBs) such as the Remaining Carbon Budget (RCB) in the climate context serve as vital global compass, translating them into actionable tools require additional methodologies. The cascading exercise of downscaling to sub-levels necessitates the allocation of effort (or burden) among diverse entities, guided by allocation principles. This process aims to connect the Planetary Boundaries to actors at various scales, influencing target setting, policy formulation, implementation and benchmarking. This sequential approach ensures that actors can use scientific metrics to inform, assess, and compare their impacts, ultimately aligning them with the PBs (Bai et al., 2024).

Beyond its scientific dimensions, the distribution of the Planetary Boundaries (such as the Remaining Carbon Budget for climate change) among sub-entities is inherently political and tied to climate justice considerations. The IPCC notes that it *'depends strongly on considerations of equity and other value judgments'* (Matthews et al., 2021). Effort-sharing and allocation principles reflect underlying principles of distributive justice, such as egalitarianism, prioritarianism, utilitarianism, or sufficientarianism (Hjalsted et al., 2021). The scientific literature is dense and introduces diverse terminologies. Höhne et al. (2014) present seven categories based on three effort-sharing approaches (e.g. responsibility, equality, capability) and a cost-effectiveness approach based on lower marginal cost of abatement. The seven categories represent direct implementations of the effort-sharing approaches or combination of them, for instance the 'equal cumulative per *capita* emission' mixes equality and responsibility, the 'responsibility, capability and need' mixes responsibility and capability, and the 'staged approaches' mixes the three effort-sharing principles. van den Berg et al. (2020) add grandfathering as a fourth effort-sharing approach and present six different approaches: 'per *capita* con-

Table 1.1: Effort-sharing approaches in Bai et al. (2024)

Effort-sharing approach	Description of the sharing process	Sensitive to / Metrics
Grandfathering (or legacy)	In proportion to current impact or footprint (status quo)	Consumption or production footprint
(Historic) Responsibility	Accounting for cumulative historical impacts over time	Start date considered
Equality	In proportion to population size	Convergence year considered
(Economic) Capability	Accounting for the ability to take (financial) actions, e.g., relative to the CBDR-RC principle	Wealth (GDP), effective governance
Sovereignty	In proportion to the current stocks and flows of natural capital in the entity's boundary	Resources in the national territory (renewable and non-renewable resource stocks, lands, etc)
Economic contribution/value-added (or final consumption expenditure)	In proportion to the current contribution (such as GDP)	GDP, gross value added, company/sector production volume or revenue
Social contribution	In proportion to the current contribution (such as employment)	Number of employees, salaries or taxes contribution
Resource efficiency	Accounting for resource efficiency and its comparison from global average	Resource consumption per relative unit (product, service)
Basic needs	Accounting a largest part to human basic needs (such as food)	Resources necessary to grow food, calorific content
Green incentive	Accounting a largest part to virtuous entities (such as those with low emission intensity)	Emission intensity, share of renewable energy, philantropy programmes
Development rights	Taking into account the socioeconomic context (in particular concerning poverty rate)	Poverty rate, HDI

vergence', 'equal cumulative per *capita* emissions', 'ability to pay', 'greenhouse development rights', 'grandfathering' , and 'cost-optimal' allocation.

Table 1.1 provides a summary of effort-sharing approaches from Bai et al. (2024), along with the metrics used and the resulting sensitivity that it can bring to the results.

Equality and legacy are the most used principles in the review, while basic needs and economic contribution are also prominent. Climate change is the most studied PB, followed closely by nitrogen and/or phosphorus cycles, while land-system change and freshwater use are also quite studied.

In practice, effort-sharing principles are rarely addressed in isolation, as practitioners combine them at different levels. Bai et al. (2024) categories four ways sharing approaches are applied: (a) a single one to a single scale, (b) a single one to multiple scales, (c) multiple ones to a single scale and (d) multiple ones to multiple scales. When combined, the value of weighting factors and value judgments between different effort-sharing approaches can significantly influence the results. As shown in Table 1.1, other factors inherent to the definition of effort sharing approaches (such as the convergence year for 'Equality' or the historical start year for 'Responsibility') are also critical factors (van den Berg et al., 2020). Practical implementation of allocation principles demands granular data, with higher-level downscaling requiring less normative decision-making and data collection effort (Horup et al., 2022).

National carbon budgets

In the comprehensive literature review conducted by Bai et al. (2024), five levels of translation for Planetary Boundaries are differentiated: country/supranational, city/municipality, sector/industry, company and product. Another level could be the individual level which have been studied for example in Chakravarty et al. (2009) and Pottier et al. (2021). The most extensively studied level of downscaling is the national level, aligning with the principle of 'common but differentiated responsibilities and respective capacities' (CBDR-RC) articulated in Article 3 of the 1992 Rio Convention (UNFCCC, 1992). This principle asserts that developed countries, owing to their historical emissions, bear a greater responsibility for mitigation and should act as leaders in the fight against climate change. The national level is also the level in which GHG inventories are conducted, following the United Nations Framework Convention on Climate Change (UNFCCC) guidelines, and where Nationally Determined Contributions (NDCs) are established for 2030 as stipulated by Article 4.2 of the Paris Agreement, alongside net-zero targets by 2050.

While historical studies primarily applied effort-sharing principles to global emission pathways, recent research extends these principles to the Remaining Carbon Budget (Raupach et al., 2014). This top-down downscaling approach has the potential to complement the bottom-up approach of NDCs. Indeed, states often adopt allocation principles aligning with their interests (Robiou du Pont and Meinshausen, 2018) (Rogelj et al., 2021), where the grand-fathering approach corresponds to the NDCs of so-called developed countries. Notably, all sharing approaches, except the grandfathering principle, yield smaller Remaining Carbon Budgets for developed countries compared to a cost-effectiveness-based approach, raising concerns about fairness and equity with the latter. Simultaneously, the implementation of certain effort-sharing approaches may face challenges, such as the potential for large negative Remaining Carbon Budgets, rendering domestic reductions unattainable (van den Berg et al., 2020).

Comparing top-down allocation and NDCs contributes to understanding and quantifying the emission gap, stimulating discussions on necessary efforts allocation. To align with climate ambitions, more ambitious NDCs are imperative, and a complementary top-down approach can ensure coherence. Tools like the Climate Action Tracker [2] prove relevant for monitoring states' actions. Moreover, concerns have been raised regarding the credibility of net-zero targets. Rogelj et al. (2023) introduces a credibility rating based on confidence in reaching stated targets, considering factors like

[2] https://climateactiontracker.org/

the legally binding nature of targets, the creation of a credible policy plan guiding implementation, and whether a country's near-term policies already set emissions on a downward path over the next decade.

Non-State Actors carbon budgets

The Paris Agreement emphasises the collaborative involvement of both parties (countries) and non-party stakeholders. This group of non-party stakeholders, also known as Non-State Actors (NSAs), encompasses civil society, the private sector, financial institutions, cities, and other sub-national authorities. NSAs are encouraged to not only accelerate climate efforts but also to report on their progress, playing a pivotal role in enhancing and complementing national initiatives (United Nations, 2015). Over the years, the role of NSAs has gained unprecedented significance. In 2023, more than 13,000 members have joined the United Nations Framework Convention on Climate Change's Race to Zero campaign, including over 7,000 SMEs, 3,000 large companies and 1,000 cities (Race to Zero, 2023).

For example, sub-national entities such as regions or cities often have objectives that complement those of national governments. They exercise legislative power over various environmental issues, including land-use and urban policy (Dubash et al., 2022). Networks such as the C40 city networks are vital in this context, providing resources and a platform for cities to share best practices (C40, 2022a) and enhance their contributions to Nationally Determined Contributions (C40, 2022b). Additionally, the private sector's role in climate action is increasingly recognised. Companies face pressures from a range of stakeholders, from consumers to investors. However, the actual impact of their actions on climate mitigation is a subject of ongoing investigation, which is further discussed in the Method section 2.1.1. Initiatives such as the Science-Based Target Initiative (SBTi), established in 2015, are crucial for guiding industry-wide decarbonisation efforts in line with Planetary Boundaries. The SBTi plays a key role in ensuring that corporate climate targets are in alignment with the goals of the Paris Agreement, acting as a certifier for these targets.

1.1.3 Overview of climate and building sectoral policies in France

The French Strategy for Energy-Climate (*'Stratégie française énergie-climat'*, SFEC) is the key policy package in the Government's ecological planning, both serving mitigation and adaptation purposes. It comprises four main elements namely the First Energy and Climate Programming Law (LPEC), the Third Edition of the National Low-Carbon Strategy (SNBC3), the Third Edition of the National Plan for Climate Change Adaptation (PNACC3) and the Third Edition of the Multi-annual Energy Programming (PPE3). Together, they define a coherent a comprehensive approach to define the trajectory and policy priorities for energy, climate mitigation and adaptation actions. This section makes a focus on the SNBC, detailing its key components and limits.

Low-Carbon National Strategy (SNBC) and its limits

The National Low Carbon Strategy (*'Stratégie Nationale Bas Carbone' (SNBC)*) is the national translation of the Paris Agreement (Ministère de la Transition Écologique et Solidaire, 2020a). Serving as the guiding framework for decarbonisation, the SNBC outlines a comprehensive plan to reduce GHGE across the entire economy, including a 40% reduction by 2030 (compared to 1990) and a net-zero emissions objective by 2050. To this end, the SNBC outlines specific orientations and concrete measures to be implemented in public and sectoral policies. A crucial aspect of the SNBC is the establishment of carbon budgets per macroeconomic sectors. These are caps on GHGE that should not be exceeded at the national level over five-year periods.

The SNBC is developed based on a scenario process exercise common to the PPE. This scenario relies on additional public policy measures (referred to as the 'With Additional Measures' or AMS scenario) beyond those currently in place (the 'Existing Measures' or AME scenario). These additional measures are designed to ensure that France meets its climate and energy objectives in the short, medium, and long term without relying on carbon credit offsetting nor significant demographic or macro-economic big assumptions.

The SNBC was first established in 2015 under the Law for Energetic Transition and Green Growth's Article 173 (Ministère de la Transition Écologique et Solidaire, 2015b) and adopted by a first decree (Ministère de la Transition Écologique et Solidaire, 2015a). Currently in its second version (SNBC-2), revised and published in March 2020 and adopted by decree in Avril 2020 (Ministère de la Transition Écologique et Solidaire, 2020b), the SNBC anticipates its third edition (SNBC-3) in 2024 with subsequent updates every five years.

Figure 1.5 illustrates the quantified SNBC-2 carbon budgets, differentiating between emissions (in blue) and absorption by carbon sinks (in green). The carbon budgets are set for a period of five years

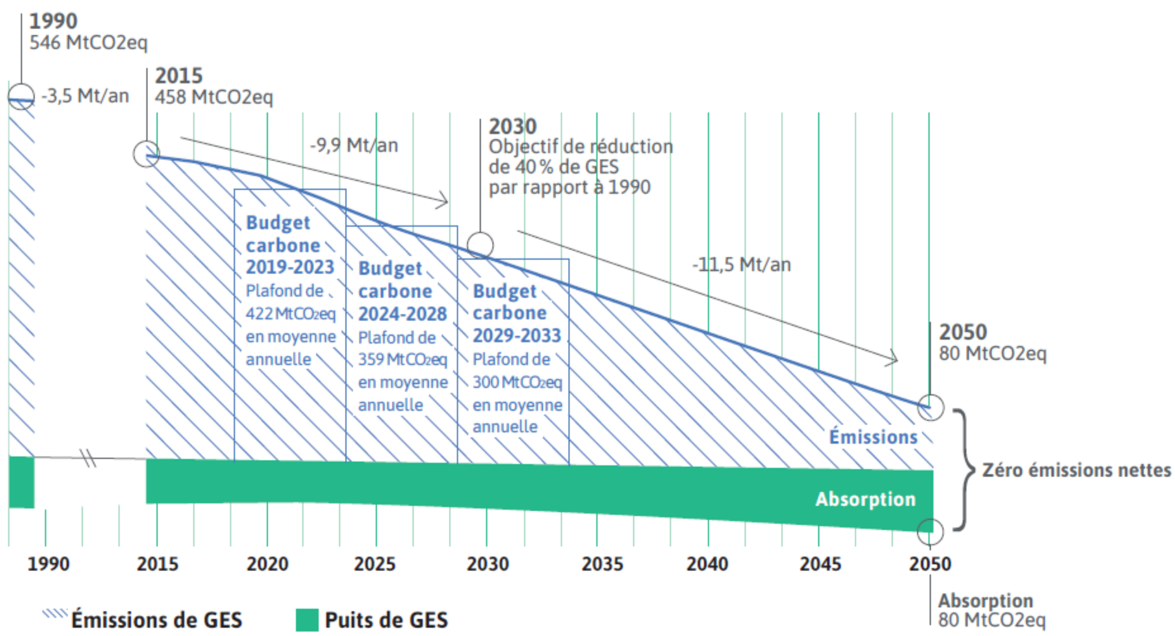


Figure 1.5: The French National Low-Carbon National Strategy (SNBC) pathway, defined by carbon budgets and the 2050 carbon neutrality objective

until 2033. By 2050, residual emissions are expected to be 80MtCO_2eq, balanced by carbon absorption, thus achieving net-zero emissions. The carbon budgets are further divided by macroeconomic sectors defined in the French SECTEN inventory format (CITEPA, 2023). This format is tailored to climate policies and derived from the national inventory report that is sent to the UNFCCC (detailed information will be given in Section 2.1.1). It encompass the energy, transport, residential-tertiary buildings, industry, waste, agriculture as well as land-use and land-use changes sectors. For each of them, sectoral carbon budgets are defined depending on the identified decarbonisation opportunities and their availability through time. As an example, residential-tertiary buildings and energy sectors have very ambitious objectives, respectively a -49% and -33% objective in 2030 compared to 2015 levels and are expected to reach almost complete decarbonisation by 2050. In contrast, the industry sector has a -35% objective in 2030 compared to 2015 levels and a -81% objective by 2050, reflecting the fact that certain industrial GHGE are hard to abate (Davis et al., 2018). The agriculture sector has a -18% objective in 2030 compared to 2015 and a -46% objective by 2050, when GHGE should reach 48MtCO_2eq (e.g. 60% of the remaining GHGE) , mainly because of methane (CH_4) emissions.

The pillars of the SNBC are the complete decarbonisation of energy production by 2050 (relying mainly of low-carbon electricity), a reduction of energy consumption through enhanced energy-efficiency, circular principles and shifts in consumption patterns, as well as the enhancement of natural and technological carbon sinks to offset remaining agricultural and industrial GHGE. Additionally, the SNBC aims to reduce the French population's overall carbon footprint, particularly focusing on the carbon content of imported products. This goal is approached without detailed quantified targets by sectors, differentiating it from territorial GHGE objectives. A dashboard tool [3] provides comprehensive tracking of the SNBC's implementation across various indicators.

The High Council on Climate (HCC) is an independent body that provides recommendations and insights on national climate policies. In its 2023 report (Haut Conseil pour le Climat, 2023), the HCC underscores the need for enhanced efforts and more effective policies across various sectors to meet France's ambitious emission reduction and carbon neutrality goals. They underline the need to put structural and long-term policies in place. The indicative gross carbon budgets for 2019-2022 set by the SNBC-2 are likely to be respected even if certain sectors like industry or energy have exceeded their sectoral carbon budgets. Nevertheless, the anticipated carbon storage is significantly lower than anticipated by the SNBC-2, due to higher than expected tree mortality and lower forest productivity. Thus, net emissions goals are likely to be exceeded. Notably, the current emission reduction rate need to double to align with the European Union's 'Fit for 55' legislative package 2030 objective of –55% GHGE reduction compared to 1990. Currently, the 'residential-tertiary' sector is the only sector that would respect these target, mostly because of cyclical factors (warm winter and the Ukraine-Russia conflict driving energy prices). Yet, the rate of energy consumption reduction in buildings is too slow, and the increase in renewable electrical energy production is three times slower than required. Current policies are not effectively promoting a sufficient number of comprehensive and efficient renovations. Although improvements were made in 2023 to facilitate global renovations, funding and market organization for such renovations remain insufficient. The sector faces challenges in skill availability and qualifications needed for comprehensive renovations.

[3] https://indicateurs-snbc.developpement-durable.gouv.fr/

The SNBC has also faced criticism for its optimistic assumptions concerning carbon sinks (Grimault et al., 2022). Notably, technical and market feasibility concerns are raised regarding the projected increase in long-duration wood products usage. The strategy's dependency on successfully shifting wood use, coupled with increased harvest, poses risks to the forest and wood carbon sink. The study also points out that policies and investment changes are crucial to achieve goals in areas like soil carbon storage and land-use change prevention.

Lastly, in terms of effort-sharing approaches (detailed in Section 1.1.2), the SNBC does not explicitly specify the methodology employed for deriving national carbon budgets, though it mentions the principle of Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC). More details could be thus be added, as France was responsible for approximately 2.38% of the cumulative CO2 emissions since the Industrial Revolution as of 2017 (Haut conseil pour le climat, 2021), placing it among historically emitting countries that are expected to demonstrate leadership in climate action.

Building sectoral policies in France

In 2022, France transitioned from the thermal-focused 'RT2012' to the 'RE2020', a more holistic environmental regulation for new construction. The RE2020 [4] expands beyond energy consumption to include GHGE metrics across a building's life-cycle, from material production to end-of-life. This regulation builds upon the 'E+C-' experiment and integrates Life-Cycle Assessment (LCA) into construction standards, making it a pioneering move in sustainable building practices (CEREMA, 2024).

The RE2020 aims to enhance energy efficiency, decarbonise energy sources, reduce carbon footprints, and ensure thermal comfort in high temperatures. Initially targeting residential buildings, the regulation will gradually include offices, educational buildings, and specific tertiary buildings like hotels and commercial spaces. For assessing the climate impact of new buildings, the RE2020 introduces a holistic approach encompassing four key areas (called 'contributors') namely 'components', 'energy', water', and 'construction site'. In this framework, each construction product, equipment, and service (including energy and water) is evaluated based on environmental product declarations (EPDs) across 36 environmental criteria. The RE2020 focuses primarily on regulating the GHGE, with the climate impact expressed per regulatory surface area in $kgCO_2eq/m^2$. Two key indicators, the 'energy' and the 'components and construction site' indicators, are regulated with degressively diminishing values set for 2025, 2028 and 2031, respectively. For energy, thresholds for primary and non-renewable primary energy consumption are established and converted into GHGE metrics, while construction products are directly regulated in GHGE terms.

In parallel, other policies focus on renovation, aligned with the SNBC's objective of upgrading the building stock to low-energy consumption levels (*'Bâtiment Basse Consommation'*) by 2050, with an annual target of 500,000 efficient renovations (specifically 370,000 for the 2015-2030 period and 700,000 for the 2030-2050 period). Article 155 of the 2021 Climate and Resilience law defines 'efficient' and 'global' energy renovations, focusing on improvements in energy classes (e.g. A-B energy

[4] https://rt-re-batiment.developpement-durable.gouv.fr/textes-de-la-re2020-en-version-consolidee-a617.html

performance post-renovation, with exceptions) and addressing six key areas: insulation (wall, floor and roof), joinery, ventilation, heating and hot water systems. 'Global' renovations are those completed within specified time frames (e.g. 18 months for single-dwellings and 24 months for multiple dwellings), addressing all six areas comprehensively (Ministère de la Transition Écologique et Solidaire, 2021). The legislation introduces a new Energy Performance Certificate (EPC) framework that now amalgamates both an energy efficiency rating and a climate impact label, providing a more holistic assessment of a building's environmental footprint (MTES, 2021)

Several key measures exist for improving the building stock. They include the phased rental ban on energy-inefficient housing and on new oil boilers (Ministère de la Transition Écologique et Solidaire, 2022). In terms of investments, initiatives like the 4 billion euro public buildings renovation plan and 'MaPrimeRénov' for private owners support these renovation efforts. The National Observatory for Energy Renovation (*'Observatoire National de la Rénovation Energétique'*, ONRE) plays a role in enhancing the understanding of energy renovation dynamics within the residential and tertiary building sectors facilitating the tracking of energy renovation initiatives. Detailed data and insights regarding the status and effectiveness of these renovation efforts are accessible through a monitoring dashboard [5], which offers comprehensive statistics and trends in energy renovation.

1.2 Research gaps and motivation

1.2.1 Emissions accounting challenges for top-down carbon budgets

The adoption of sector-specific carbon budgets provides a structured framework for effectively attributing efforts across diverse sectors. This sectoral approach benefits from established nomenclatures, which are often used in emission pathways and scenarios. However, the selection of the appropriate sectoral classifications is a critical choice. Common examples include those used in the United Nations Framework Convention on Climate Change (UNFCCC) GHG inventory reporting (e.g. energy, industrial processes and product use, agriculture, forestry and other land use, and waste), as well as international standards like the International Standard Industrial Classification (ISIC) or the Statistical Classification of Economic Activities in the European Community (NACE).

As outlined in Section 1.1.1, the substantial impact of the Building activities calls for a dedicated budget. However, sectoral classifications often overlook cross-cutting activities that span multiple sectors. The complexity arises from the overlapping nature of the building activities, which include construction, maintenance, operation, and end-of-life considerations, with the UNFCCC sectors. Global supply chains further complicate matters, with construction materials contributing to embodied greenhouse gas emissions produced globally. The conventional derivation of carbon budgets from the concept of a building 'sector' is thus misleading due to its narrow scope, focusing solely on direct operational emissions.

To address this, an alternative perspective introduces the concepts of the 'area of activities' (encompassing construction, refurbishment, and end-of-life) and the 'area of needs' (encompassing the operation of buildings) along the traditional sectoral approach (Habert et al., 2020b) (Lützkendorf,

[5] https://www.statistiques.developpement-durable.gouv.fr/tableau-de-suivi-de-la-renovation-energetique-dans-le-secteur-residentiel

2021). Figure 1.6 illustrates these concepts in the downscaling framework of the Remaining Carbon Budget. Acknowledging the cross-sectoral nature of building activities facilitates the integration of

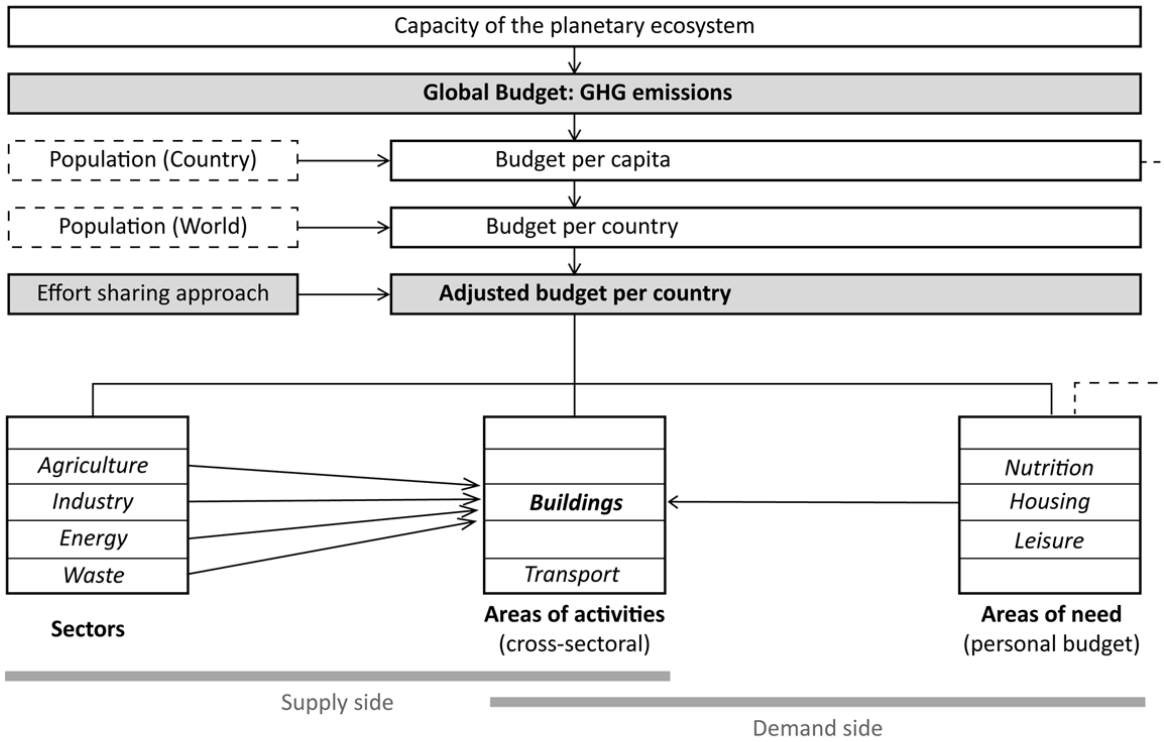


Figure 1.6: Sectors, area of activities and areas of need in the downscaling process (Habert et al., 2020b)

various sectors involved in these activities and addresses the needs they meet for the population. The sectoral approach might better reflect supply-side solutions, while the 'area of needs' perspective emphasises demand-side solutions (see Demand-side and supply-side), and may also relate to per *capita* downscaling.

Effectively implementing these concepts requires sound and flexible emission accounting methods, which are not yet widely adopted in mainstream practices (Steininger et al., 2020). The linkage between emission accounting and decarbonisation efforts is fundamental. To derive accurate carbon budgets, one must first understand fully the extent of their impacts. Similarly, for any actor to initiate decarbonisation efforts, a comprehensive grasp of their emission scope is essential. While traditional GHG inventories often lack the detail necessary to meet these challenges, there remains a gap in research for a unified methodology that bridges the sectoral approach with the concepts of 'area of activities' and 'area of needs'. Such methodologies should encompass a full scope, providing clear guidance for stakeholders involved in building activities. Therefore, developing solutions to these accounting challenges is crucial for advancing research in this field.

1.2.2 Combining top-down and bottom-up benchmarks

Establishing ambitious goals for environmental performance that take into account the entire life cycle of buildings is regarded as a crucial move towards significantly diminishing the environmental footprint of the building activities, ensuring it operates within the limits of the Remaining Carbon Budget (Lützkendorf et al., 2023). The International Standard on sustainability in buildings and civil engineering works (ISO 21678:2020) (ISO, 2020) provides a comprehensive framework to guide the creation of sustainability frameworks, adaptable through either a top-down or a bottom-up approach. Top-down benchmarks are informed by the necessity to meet the requirements of absolute environmental limits such as the Remaining Carbon Budget (or occasionally specific policy objectives), setting science-based targets that echo these imperatives. This approach involves scaling down the Remaining Carbon Budget using allocation principles (described in 1.1.2) to address various scales, from building activities and stocks to individual buildings or specific life-cycle stages (Habert et al., 2020a). Conversely, bottom-up benchmarks leverage existing datasets and case studies to gauge what is achievable in terms of technical and economic viability through statistical analysis of the environmental performance of current buildings. It is critical to understand that benchmarks focus on performance without favoring specific products or technologies, maintaining neutrality towards the types of buildings or materials required to achieve certain performance levels (Lützkendorf et al., 2023).

Both top-down and bottom-up benchmarks evolve over time, reflecting the latest scientific findings and potential shifts in technology and economic landscapes. They consist of different performance levels illustrated in Figure 1.7. The reference (or baseline) value is described as the median or

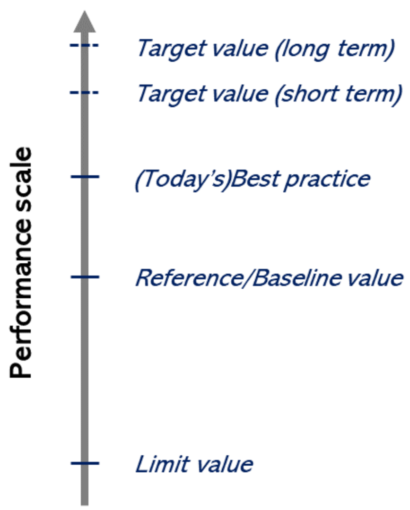


Figure 1.7: Performance levels in ISO21678

average value, representing the current performance based on available data. The upper or lower acceptable value is defined as the limit value, whereas best practice can be seen as today's state of the art in terms of environmental performance. Target values, aiming for short-term or long-term goals, set the ambitions higher. In the context of dynamic benchmarks, what are now target values will serve as future limit values.

In practice, limit values can help to ensure compliance with binding requirements, which have been put in place in several European countries such as France, Denmark or the Netherlands (Buildings Performance Institute Europe, 2021). Reference values can help to position compared to the baseline while target value can serves as guide (Lützkendorf et al., 2023). For example, during early-design stage, target values at component level can help designers and architects optimise environmental performance (Hollberg et al., 2019).

Determining how methods combining top-down and bottom-up approaches can help to decrease the environmental pression from building activities is a critical and ongoing area of research. Several studies have tried to compare top-down and bottom-up benchmarks at building level by studying the performance gap between current reference values and science-based target values. For example, Chandrakumar et al. (2020b) compare the current performance of a new individual house in New Zealand to its cascading target in 2050 and offer a comparison by life-cycle stages. Similarly, Andersen et al. (2020) uses a similar approach with six representative dwellings in Denmark. The two studies found that absolute sustainability targets are out of reach given the actual performance of buildings. A notable drawback of downscaling to lower resolutions is that it leans more towards normative prescriptions (Horup et al., 2022), and it potentially disconnects the target values from the societal functions served by different types of buildings. Notably, Heide et al. (2023a) questions the allocation per area, emphasising that larger buildings may receive a larger share of the Remaining Carbon Budget regardless of societal necessity. They propose an alternative sharing principle based on the 'Fulfillment of human needs' (Heide et al., 2023b), applying a proof of concept to residential buildings, universities, hospitals, and kindergartens. Another set of studies focus on the derivation of top-down benchmarks for embodied GHGE using reference values derived from bottom-up benchmarks combined with a stock-dynamic scenario. Notably, the Science Based Target Initiative's Buildings Guidance draft report (Ryberg et al., 2023) uses stock dynamics scenarios from Deetman et al. (2020) and the International Energy Agency (IEA) Net Zero Scenario (IEA et al., 2020) alongside average emission factors for residential and non-residential emission factors in $kgCO_2eq/m^2$ from Röck et al. (2020) to determine baseline emission shares for different typologies, subsequently applied to downscaled building construction shares.

Ultimately, the pursuit of net-zero emissions is meaningful primarily at the planetary and national scales (Carbone 4 and Net Zero Initiative, 2021) (ADEME, 2021b). While setting top-down benchmarks at the building or component level can aid the design process, the crucial factor within the context of building activities is meeting the assigned overall carbon budget. In top-down benchmarks, it is widely recognised that future shifts in the building stock, construction materials, and energy sources must be incorporated into the carbon budgeting for specific buildings (Priore et al., 2023). However, the task of modelling these dynamics from a bottom-up perspective, to verify their alignment (or lack thereof) with broader top-down benchmarks, such as those pertaining to building activities within a particular country, remains under-explored in research. The expanding availability of data from building stock and new construction databases presents an opportunity to showcase a broad spectrum of Whole-Life Carbon emissions resulting from various combinations, ultimately facilitating the assessment of their compliance with top-down benchmarks for the building activities at national level. A notable example of such an approach include Li et al. (2022) who explore how different renovation scenarios compare to different carbon budgets in the UK. Yet, a comprehensive approach that integrate all stock-level activities and adress future potential performance is lacking, indicating a significant research gap that needs to be addressed to foster methods combining top-down and bottom-up benchmarks.

1.2.3 Mitigation pathways for the building activities

Global, national and sectoral mitigation pathways play an important role to guide actors in climate action. Scenarios from the IPCC and the IEA serve as key examples of influential frameworks (later detailed in Chapter 3). However, akin to the challenges with carbon budgets, these pathways often adopt a sectoral perspective that neglects a holistic view of the mitigation potential within the building activities. This oversight leaves stakeholders without a comprehensive basis for crafting effective mitigation strategies (Giesekam et al., 2018a).

As discussed in Section 1.1.1, operational and embodied emissions present differing reduction potentials. Operational emissions are more straightforward to address through enhancements in energy efficiency, stringent building regulations, and the integration of renewable energy sources. These interventions are cost-effective and offer additional benefits, such as improved health and comfort for occupants (UNEP, 2023). Conversely, reducing embodied emissions, especially from the production of materials like cement and steel, is more challenging and costly due to the current limitations in decarbonisation technologies and practices (Davis et al., 2018). While existing pathways focus on reducing operational emissions, they frequently fail to fully incorporate all types of emissions and to distinguish their respective reduction potentials over time and across sectors. Filling this gap appears essential for a better understanding of the trade-offs between reducing operational emissions and the potential increase in embodied emissions, an area that remains largely unexplored (Verhagen et al., 2021) (de Oliveira Fernandes et al., 2021). On the demand side, reflecting the 'area of needs' concept, the integration of sufficiency measures that lower the demand for energy and materials is also underdeveloped and insufficiently incorporated into modelling approaches (Saheb, 2021). Thus, a more integrated examination of the mitigation potential across the various sectors involved in building activities is necessary. Such an approach would enhance the understanding of the building activities mitigation potential and lead to the development of more comprehensive modelling tools.

1.2.4 Life-cycle modelling of buildings at macro scale

Life-cycle assessment (LCA) has quickly become the preferred approach for evaluating the environmental impacts of buildings (Fnais et al., 2022). While traditionally applied at individual building scales, LCA studies are increasingly addressing broader scales, from urban district to transnational levels (Mastrucci et al., 2017). This expansion is beneficial for assessing cumulative environmental impacts and informing urban planning and national policy on energy efficiency and sustainable construction practices.

Nonetheless, scaling up LCA studies introduces significant challenges, particularly in data collection and management. Expanding analyses to account for the life-cycle impacts of construction materials and equipment demands extensive data, complicating modelling efforts and necessitating novel scientific approaches (Röck et al., 2021). While building stock data is increasingly available, it remains fragmented at the macro scale, with only a few countries having detailed national-level building stock information, often focusing mainly on residential buildings. High-resolution data covering aspects like building age, geometry, material composition, energy systems, and usage patterns can significantly improve the specificity and effectiveness of sustainability strategies (Milojevic-Dupont et al., 2023). Accounting for the heterogeneity of buildings in large-scale LCA studies introduces additional complexity, requiring methods that can precisely capture the varied attributes of buildings and their impacts across different scales. This complexity often results in a balance between the granularity of the model and its relevance to policy (Allacker et al., 2019), a dilemma illustrated in Figure 1.8.

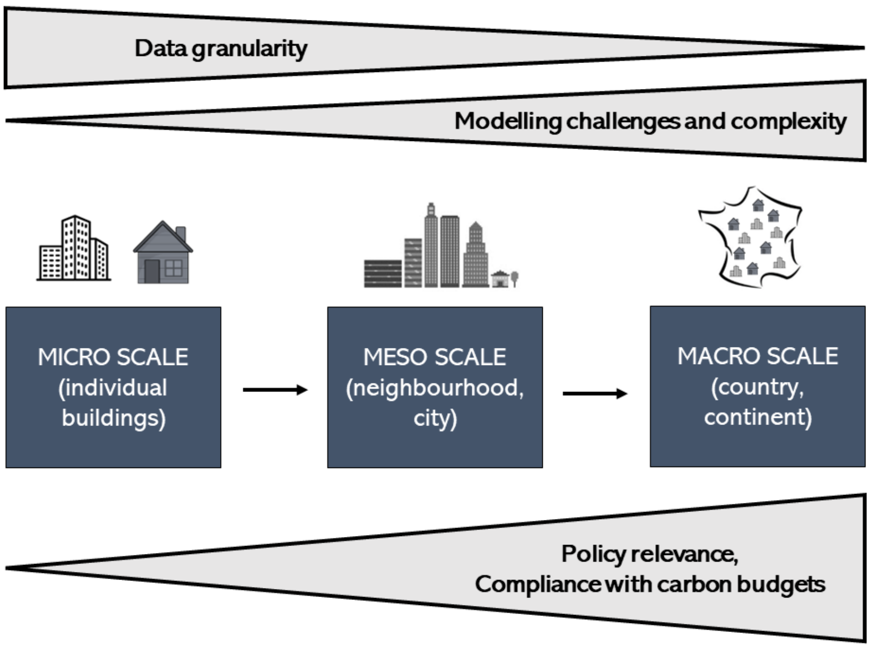


Figure 1.8: Trade-offs across scales (adapted from Allacker et al. (2019))

The challenge lies in achieving policy relevance while navigating the intricacies of large-scale analysis and the potential scarcity of detailed data. In bottom-up modelling that aims to assess alignment with carbon budgets, it involves yearly assessments of operational emissions, offering a dynamic framework for accounting. Rather than applying LCA alone, it requires the coupling of diverse methods to evaluate the effectiveness of mitigation strategies (Lanau et al., 2021). Thus, significant challenges remain to propose sound methodologies at macro scale that enables to achieve policy relevance and display what strategies can comply with top-down carbon budgets.

1.3 Research objectives and organisation of the thesis

1.3.1 Research objectives

The decarbonisation of the building activities is a crucial aspect of national and European climate policies. Positioned at the intersection of significant GHG reduction opportunities and sectors challenging to decarbonise, a comprehensive understanding of its life-cycle emissions and decarbonisation potential is imperative. To effectively guide stakeholders and policymakers, the use of scalable carbon budgets for the building activities, employing a life-cycle perspective emerges as a key indicator (Habert et al., 2020a). This top-down approach offers a clearer and more effective indicator for setting targets and defining necessary decarbonisation actions compared to traditional sectoral classifications, ultimately offering to link the Remaining Carbon Budget to actionable levels for various stakeholders (Lützkendorf, 2021).

Current sectoral policies prioritise techno-economic aspects over climate imperatives (Pálenský and Lupíšek, 2019). The consequence is that current reference values at building level are far from science-based targets derived from top-down benchmarks (Chandrakumar et al., 2020a). This mismatch leads to a shortfall in climate-proof strategies, underscoring the need to embrace a more holistic approach to consider how the building activities might cope with the stipulated carbon budgets. This calls for the integration of stock-level activities dynamics scenarios (along with their underlying drivers) with current and future reference values, which are influenced by the decarbonisation of energy carriers and construction materials used in building activities. As such, we can question the effectiveness of different decarbonisation levers. Are the current performance sufficiently ambitious given the stock dynamics levels?

Resolving these questions enables further exploration into how different building typologies, modelled through a bottom-up approach, can or cannot achieve performance that meets carbon budgets under different stock-dynamics scenarios. Based on current data, how do different typologies position themselves on the performance scale? Under decarbonisation scenarios for the main construction materials and energy carriers, how would the different typologies perform and compare against different target values?

Therefore, the primary objective of this thesis is to develop life-cycle carbon budgets for buildings and to model exploratory scenarios for life-cycle emissions trends up to 2050. These scenarios will consider the decarbonisation of various sectors and the dynamics of the building stock, aiming to align sectoral policies (e.g., building regulations) more closely with climate policies that are inspired by sectoral carbon budget approaches. To answer these challenges, three central interconnected problematic are investigated and are detailed below:

1. **What methodology can be developed to accurately account for the life-cycle emissions of buildings within a country? Expanding upon this, how can existing sectoral carbon budgets, primarily focused on territorial emissions, be refined and complemented by a more comprehensive approach that encompasses all activities related to buildings, thereby**

highlighting the significance of the various sectors involved in building activities decarbonisation?

a) Understanding current building-related emissions is critical for exploring decarbonisation potential by 2050. However, a unified and holistic emissions accounting method that reconciles the inter-sectoral nature of building-related activities is currently lacking. National climate policies often use production-based accounting, while environmental assessments of buildings adopt a life-cycle approach, including cross-sectoral emissions. This gap at the national level hampers holistic assessments of GHGE related to buildings, which is crucial for effective decarbonisation planning.

b) Upon establishing a detailed inventory of life-cycle emissions, the next step involves broadening the scope of current sectoral carbon budgets that focus narrowly on direct operational emissions that occur in the national territory. The goal is to introduce a methodology that not only complements existing frameworks with a consumption-based perspective but also captures the carbon mitigation potential across the diverse sectors linked with building activities.

2. **How might a prospective framework, incorporating scenarios for the dynamics of stock-level activities along with present and future bottom-up benchmark values, facilitate the evaluation of Whole-Life Carbon emissions from residential activities? Furthermore, how could this framework assist in determining the bottom-up conditions necessary to achieve carbon budgets derived from top-down approaches?**

   a) Enhanced building stock databases are increasingly aiding our understanding of residential building stock characteristics, current performance, and potential outcomes under various renovation scenarios.

   b) While building regulations are beginning to address Whole-Life Carbon emissions, aligning building activities with established carbon budgets relies not only on performance values but also on the dynamics of the stock, influenced by socio-economic and political factors. Integrating these dimensions is key to assess Whole-Life Carbon emissions.

   c) Considering expected transformations in supply sectors, how can we integrate these changes in a framework to explore future reference values and energy emissions factors?

3. **How do different typologies of new construction compare on the performance scale when analysed at the building level? Which typologies fall below or exceed target values when considering decarbonisation scenarios for the main construction materials and energy carriers?**

   a) Building LCA databases improve our understanding of the performance of new constructions and their potential compliance with future regulatory limit values. Yet, the widespread availability of thousands of building LCA studies is a recent development.

How can we identify building typologies from a data-driven analysis of a building LCA database?

b) How do these typologies currently perform and compare to actual and future regulatory limit values?

c) When applying scenarios from Integrated Assessment Models, what are the impacts on these typologies, and how might they perform against future target values?

1.3.2 Organisation of the manuscript

The organisation of the doctoral thesis is structured into four principal sections that are described below.

1. Initially, Chapter 1 introduces the environmental, societal and scientific context in which the thesis is conducted.

2. Following this, Chapter 2 and Chapter 3 offer an examination of the environmental assessment and building stock modelling methods, as well as a description of existing climate and decarbonisation scenarios. Subsequently, Chapter 4 synthesises the application of these methods and scenarios within the research, illustrating their integration to address the research questions.

3. The core of the thesis, encompassing Chapters 5, 6 and 7, consists of three individual papers that have been accepted or submitted to peer-reviewed scientific journals. Each chapter responds to one of the aforementioned research questions and includes the articles in their entirety. Contributions from all authors are explicitly acknowledged within these chapters. Their goal is briefly described below:

   a) Chapter 5 - *'Integrating consumption-based metrics into sectoral carbon budgets: a cross-sectoral approach for building activities in France'*. This paper tackles the first problematic 1 by outlining a methodology to capture the life-cycle emissions of buildings in France. Upon this, it also proposes to extend existing sectoral carbon budgets towards a more holistic and consumption-based approach.

   b) Chapter 6 - *'From limit values to carbon budgets: assessing comprehensive building stock decarbonisation strategies'*. This paper addresses the second problematic 2. It introduces a methodological framework designed to explore the potential evolution of dwelling stock emissions in a life-cycle approach and assess their alignment with climate objectives.

   c) Chapter 7 - *'Assessing current and future embodied emissions of new buildings: a prospective analysis through a building LCA database'*. This paper examines the third problematic 3. It presents a methodological framework for identifying building typologies through the national building LCA database and evaluating their current and potential future embodied performance when decarbonisation scenarios for the industrial and energy sectors are integrated.

4. The last section includes Chapter 8 which provides a critical perspective on the doctoral thesis, while Chapter 9 concludes the thesis with a comprehensive summary of its contributions and outlines future research directions

2

State of the art of environmental assessment and building stock modelling methods

Contents

This chapter begins to offer a comprehensive overview of the environmental assessment methods that are pivotal to this research. It encompasses a range of methods and techniques including emissions accounting, prospective studies and scenarios, Life Cycle Assessment (LCA), Input-Output Analysis (IOA) and hybrid methods. Particular emphasis is placed on the application of these methods within the context of building activities, with examples drawn specifically from this area. Then, a dedicated section is devoted to the life-cycle modelling of building stocks, which describes in details building stock characterisation, energy and material inventory modelling as well as the spatio-temporal dynamics of building stocks. For convenience, Table 2.12 summarises these methods, serving as recap and aiding in navigation of the content.

This methodological exploration aims to present the current state of these techniques, drawing on the latest research findings. It lays the groundwork for the detailed analysis presented in subsequent chapters. Specifically, this chapter serves as a precursor to Chapter 4, which delves into the application of these methods in the analyses conducted in Chapters 5, 6 and 7.

2.1 Environmental assessment methods

2.1.1 Emissions accounting and net-zero framework

This section first introduces the concept of emissions accounting at national level, before delving into specific methodologies and frameworks used in the French context. It then looks into methods applied at the organisational level.

Introduction

Emissions accounting offers a systematic framework for categorising emissions, facilitating the tracking, analysis, and mitigation of environmental impacts associated with various activities. Emission accounting and decarbonisation efforts are intrinsically linked. To embark through decarbonisation, companies must first understand the extent of their emissions. Accurate emission accounting is the compass that guides them towards setting meaningful decarbonisation targets. Despite its apparent simplicity, the concept evolves into a complex network of terms and classifications, presenting significant navigational challenges. In the thesis, methods for emissions accounting at different levels, from national to building level, are extensively discussed and applied in Chapter 5.

Beyond its technical and methodological aspects, emissions accounting encompasses moral and ethical considerations, influencing the allocation of responsibility among different actors and entities. The choice of an emissions accounting system significantly impacts rankings, such as those of countries and sectors (Steininger et al., 2018). Using clearly defined typologies for emissions reporting is thus a crucial aspect of understanding the different scopes of emissions arising from multiple sources and actors, while also serving to identify emission reduction opportunities in potentially complex supply-chains. The intricacy of emissions typologies arises from several factors. First, a multitude of terms and classifications coexist, making it difficult to discern and translate the nuances of their definitions accurately. Secondly, emissions assessments occur at various levels, ranging from the organisational and sectoral to the national and global scales. This multiplicity of levels introduces complexity, particularly when dealing with activities that are at the crossroads of these different frontiers. Finally, emissions classifications often involve intricate interrelationships between entities, adding layers of complexity to the overall picture.

To navigate this complex landscape, several tools and initiatives have emerged. These include the Net Zero Tracker[1], the Transition Pathway Initiative Centre[2], and the UNFCCC Non-State Actor Zone for Climate Action platform[3] , all of which help in monitoring and tracking climate initiatives.

Emissions accounting at national level

Established in 1997, the Kyoto Protocol marks the creation of a harmonised international accounting framework. Annex-I countries, predominantly developed nations, are mandated to submit national

[1] https://zerotracker.net/
[2] https://www.transitionpathwayinitiative.org/
[3] https://climateaction.unfccc.int/

GHGE inventories to the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 1998). These inventories use common reporting formats. In contrast, Non-Annex I countries report less frequently and with varied methodologies. This discrepancy results in incomplete time-series GHG data available globally. To address this gap, the scientific community frequently updates and provides comprehensive datasets. For instance, the dataset used by the IPCC in its latest assessment report (Dhakal et al., 2022) was compiled by Minx et al. (2021). More recently, Jones et al. (2023) introduced an extensive historical dataset covering CO_2, CH_4 and N_2O emissions from 1851 to 2021. These datasets rely on a limited range of original data source that have comprehensive coverage in terms of sectors, countries, and GHGE as reviewed in Dhakal et al. (2022) and Climate Watch (2024). Examples of such databases include the Emissions Database for Global Atmospheric Research (EDGAR) database compiled by the Joint Research Center (Crippa et al., 2023) and the Potsdam Real-time Integrated Model for Probabilistic Assessment of Emissions Paths (PRIMAP) database compiled by the Potsdam Institute for Climate Impact Research (Gütschow et al., 2016). It is to be noted that global GHGE data are updated less frequently and with more significant reporting delays compared to specific data such as CO_2 from fossil fuels and industry. In particular, large data gaps exist for F-Gas emissions while CO_2 from land-use changes depict large uncertainties (Dhakal et al., 2022).

The UNFCCC inventories adhere to a production-based accounting (PBA) method, aligning with the 2006 IPCC guidelines (revised in 2019) (IPCC, 2019). They are compiled based on a territorial approach, focusing on where emissions physically occur, and are breakdown into four primary sectors: (a) Energy, (b) Industrial processes and product use (c), Agriculture, forestry, and land use (AFOLU) and (d) Waste. Notably, emissions associated with international maritime and aviation transportation are reported separately and are not included in national inventories, a practice that has attracted considerable criticism for excluding significant emission sources (Peters, 2008).

Under the Paris agreement, carbon emissions targets are based on the UNFCCC system. While it remains the most widely used and communicated approach, alternative methodologies have emerged and gained varying levels of acceptance (Steininger et al., 2015). Largely due to the numerous studies highlighting the growing emissions associated with international trade, particularly from developing to developed countries (Peters et al., 2011), consumption-based accounting (CBA) method have particularly emerged as an important complement to PBA. Contrasting with PBA, CBA attributes emissions to the regions where the final consumption occurs, accounting for emissions embedded in international trade. In order to operationalise this concept and provide robust metrics to policymakers, a multitude of models and databases have been developed in the last decades (Wood et al., 2020).

Methodologically, since all accounting systems are derived from PBA, they inherit its uncertainties and face additional challenges related to the use of supplementary data (Steininger et al., 2015). In the case of CBA, methodologies rely on foreign trades data to allocate emissions to the countries of the final demand. UNFCCC inventories are modified to be consistent with the System of National Accounts (SNA) and are latter combined with Input-Output Tables (IOT, for which more theoretical content will be given in 2.1.4) in order to take into account international transfers, thus removing export-related emissions and adding import-related emissions.

While each accounting system has its strengths and weaknesses, it is crucial to evaluate the outcomes of these systems comparatively. As an example, Figure 2.1 illustrates the distribution of fossil CO_2 emissions for five geographical zones, using three methodologies: PBA, CBA and a cumulative approach of PBA since 1870. This comparison is further enriched by juxtaposing these emission metrics with the global population and gross domestic product (GDP) (both in Market Exchange Rates (MER) and Purchasing Power Parity (PPP)) figures for 2020.

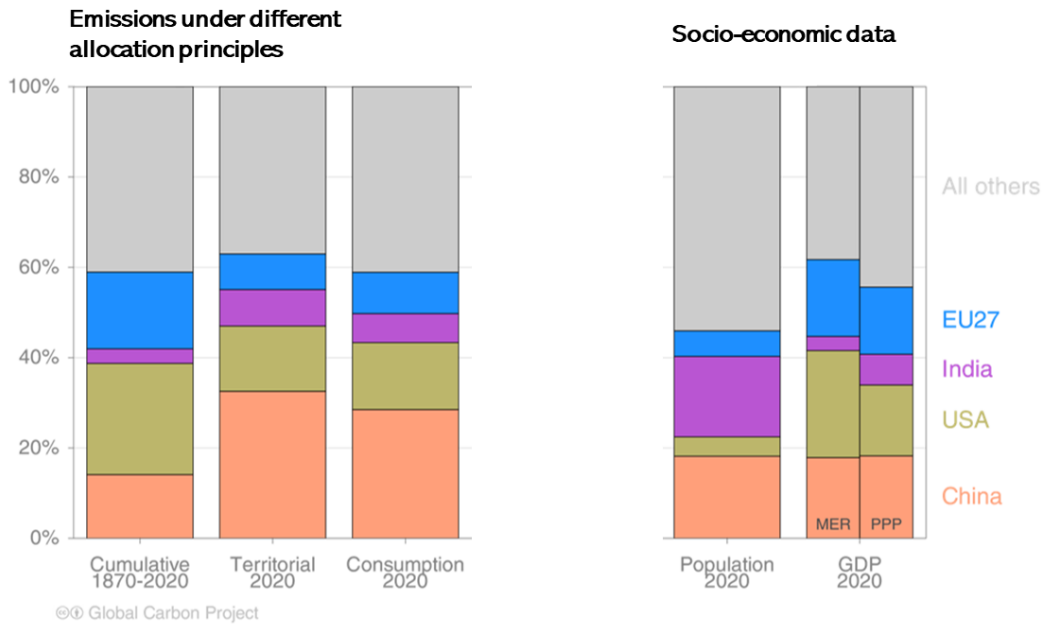


Figure 2.1: Three perspectives on emission responsibility: cumulative, territorial and consumption-based emissions (Friedlingstein et al., 2023)

Such an analysis offers diverse perspectives based on the chosen emissions accounting methodology. As of 2022, employing the PBA method reveals that the top six emitters, constituting two-thirds of global emissions, are China (31%), the United States (14%), India (8%), the EU (7%), Russia (4%), and Japan (3%) (Friedlingstein et al., 2023). Notably, despite its substantial global population share, India contributes a relatively smaller fraction of emissions across all accounting systems. Conversely, the EU accounts for a significant portion of cumulative emissions, while its shares in PBA and CBA emissions are comparatively lower.

In conclusion, examining various emissions accounting systems in tandem is insightful, as they each offer unique insights. This multifaceted approach is particularly relevant in discussions of climate negotiations and climate justice, underscoring that no single system can be deemed universally superior (Steininger et al., 2020).

Specificity in the French context

As an Annex-I country and a European Union member, France is mandated to maintain a precise emissions accounting system and set specific emissions reduction targets over time. France's national inventory, recalculated annually, is conducted by the Technical Interprofessional Center for the Study of Atmospheric Pollution (CITEPA). This inventory serves as the primary source of emissions data. Based on this inventory, France employs various reporting formats that offer diverse geographic and sectoral breakdowns.

The SECTEN report (an acronym for *Secteur émetteur* and *énergie*) is pivotal in national policy frameworks like the National Low Carbon Strategy (SNBC). The data is published for year N-2, with an estimation for year N-1. It compiles data from inventories of atmospheric pollutants reported to the United Nations Economic Commission for Europe (UNECE) and GHG data reported to the UNFCCC, with a different aggregation. It includes 31 air pollutants and GHGE that are classified by fuel type for seven sectors, each of which include subcategories:

- Energy (9 subcategories)
- Industry (9 subcategories)
- Agriculture (10 subcategories)
- Transportation (24 subcategories)
- Residential and tertiary (12 subcategories, 7 for residential and 5 for tertiary)
- Waste (4 subsectors)
- Land-use, land-use change and forestry (9 subsectors)

When moving to CBA, the responsibility falls to the French Statistical Data and Studies Department (SDES). The methodology for this approach is detailed in Baude (2020). This system has faced criticism for its inadequate detailed data for non-European countries, especially when compared to the more detailed Multi-Regional Input-Output (MRIO) databases used by countries like Sweden or the UK (Malliet, 2020) (Haut conseil pour le climat, 2020).

Corporate emissions accounting and net-zero framework

The surge in Non-State Actors (NSAs) climate pledges has been accompanied with significant methodological developments in emissions accounting, target-setting and net-zero strategies. The landscape of NSA climate action has been notably shaped by the Science Based Targets initiative (SBTi) and its Net Zero Standard (SBTi, 2020), alongside the United Nations recommendations for credible corporate climate targets (Nations, 2022), the ISO 14064 guidance for quantification and reporting of GHGE and removals and the ISO 14068 (ISO, 2018) guidelines for achieving and demonstrating carbon neutrality (ISO, 2023). These initiatives underscore the growing recognition of the need for standardised and credible climate targets.

Numerous methods and frameworks are available to assist NSAs measure, report, and ultimately reduce their GHG emissions. Among them, the GHG Protocol, developed through collaboration between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), stands as a the most widely used GHG accounting and reporting standards worldwide. In its Corporate Standard (GHG Protocol, 2004), it categorises emissions into three distinct scopes:

- **Scope 1** encompassing direct emissions under a company's control
- **Scope 2** extending to emissions associated with purchased energy not directly owned but used in operations
- **Scope 3**, the broadest category, covering value-chain emissions stemming from the entity's activities, including those upstream and downstream.

The Corporate Value Chain (Scope 3) standard (GHG Protocol, 2011) transitions from optional to mandatory inclusion of scope 3 emissions. They are further divided into 15 categories, covering eight upstream (such as purchased goods and services and capital goods) and seven downstream (such as use and end-of-life treatments of sold products) activities. It also helps companies set their organisational boundaries, using the equity share (GHG emissions from operations according to its share of equity in the operation), operational control or financial control consolidation approaches. The consolidation approach affects the categorisation of emissions in the different scope.

Other standards are tailored to estimate the GHG effects of policies and actions (GHG Protocol, 2016), or progress towards GHG reduction goals (GHG Protocol, 2017). In addition to its standards, the GHG Protocol offer several guidance reports tailored to various requirements and entities (e.g. corporations, cities, public organisation). For instance, the 'Scope 2 Guidance' (GHG Protocol, 2015) introduces two methods for reporting scope 2 emissions. The 'location-based' method uses average emissions factors based on regional or national electricity grids. In contrast, the 'market-based' method accounts for specific emissions factors corresponding to the electricity that a company has intentionally procured through contractual instruments, such as renewable energy certificates (RECs) or power purchase agreements (PPA).

Alongside the GHG Protocol, the SBTi has emerged as a pivotal player in corporate environmental governance. Established in 2015 through a partnership between the Carbon Disclosure Project (CDP), the United Nations Global Compact, the World Resources Institute (WRI), and the World Wildlife Fund (WWF), the SBTi aims to bridge the gap between global climate goals and corporate climate action. It creates the necessary infrastructure for the target-setting process, providing standards, tools, and certification programs. The primary outcome of this process is the formulation of specific science-based targets (SBTs), typically expressed as percentage reductions in emissions between a base year and a target year. Companies must establish Scope 3 targets if they account for at least 40% of their total Scope 1, 2, and 3 emissions. Furthermore, these targets must cover at least two-thirds of the company's Scope 3 emissions (SBTi, 2020). All SBTs must span a minimum of 5 years and a maximum of 15 years from the submission date to SBTi for approval. Typically, SBTs are expressed as percentage reductions in absolute emissions or emission intensities. Scope 2 targets also permit an alternative approach, targeting an increased procurement of renewable electricity. In the case of Scope 3, companies can opt for supplier or customer engagement targets, focusing on motivating partners to set their own SBTs. SBTi recommends two primary target-setting methods: the Absolute Contraction Approach (ACA) and the Sectoral Decarbonization Approach (SDA) (SBTi, 2021b). ACA entails each company reducing emissions at the same annual rate required globally to achieve a specific temperature goal, following the 'grandfathering' principle. Conversely, SDA relies on the 'Convergence' principle, assuming that all companies within a sector will converge toward a common emission intensity by 2050 (SBTi, 2015). ACA is broadly applicable, while SDA suits a select group of 'homogenous' sectors (SBTi, 2021a).

While evidence suggests that the adoption of SBTs aligns with effective climate action, several studies indicate the necessity for further research to expand methodological approaches. This research aims to ensure SBTs contribute to a safe and just future (Bjørn et al., 2022). Indeed, the governance framework of the SBTi has come under scrutiny (Tilsted et al., 2023). Critics highlight that the selection of scenarios and method development, along with stakeholder engagement, may be influenced by factors prioritising growth and profitability. This could restrict the variety of approaches and perpetuate existing emission patterns. Furthermore, the use of Renewable Energy Certificates (RECs) to meet SBTs has been criticized for lacking additionality, a fundamental criterion for offsets (Bjørn et al., 2022), which refers to GHG reductions that would not have occurred in the absence of the specific offset initiatives. The limited scope of SBTi's jurisdiction allows companies to meet their targets through diverse, sometimes questionable, means. This raises concerns about the feasibility of relying on untested nature-based and technological solutions instead of fundamental changes in business models. Another significant issue is the low adoption of SBTs in the most polluting industries and in low- and middle-income countries (Bjørn et al., 2022). Lastly, recent communications from the SBTi board regarding the use of offsets for managing an organisation's scope 3 emissions have raised significant concerns over the potential for greenwashing and the misapplication of the latest scientific findings (SBTi, 2024).

The Net Zero Initiative (NZI) proposes a distinct approach to net-zero strategies, centered around three main pillars, as depicted in Figure 2.2. This strategy aligns with a perspective in which the state of net-zero emissions should be defined at global and national levels rather than at the level of individual NSAs, a position also promoted by the French Agency for Ecological Transition (ADEME) (ADEME, 2021b) and the EU green claims directive (European Commission, 2023). As such, NSAs are encouraged not to focus solely on achieving an arithmetic state of net-zero through measures like heavy reliance on offsets. Instead, they should actively contribute to each of the three pillars as part of a broader, more holistic climate action strategy.

As illustrated in Figure 2.2, the NZI emphasises the importance of separately assessing, managing, and reporting on three distinct levers. These levers collectively aim to achieve two primary objectives: significantly reducing GHGE and enhancing the removal of carbon dioxide through carbon sinks.

- **Pillar A**, which aligns with the broader goal of global emissions reduction, focuses on an organization reducing its own emissions. This includes emissions within its direct control as well

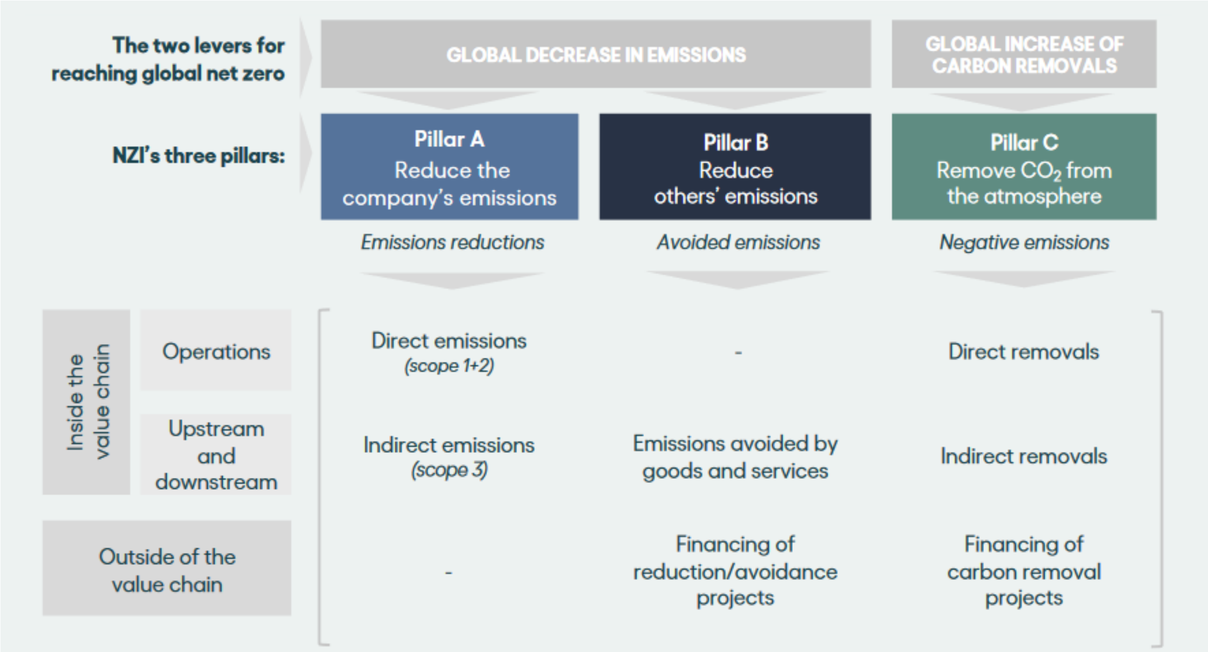


Figure 2.2: Net Zero Initiative Dashboard (Carbone 4 et al., 2021)

as those upstream and downstream in its value chain. Tools like the GHG Protocol, *Bilan GES* and Bilan Carbone in the French context, ISO 14064 and ISO 14067, along with target-setting and performance tracking frameworks like the SBTi, support this pillar.

- **Pillar B** contributes to the global decrease in emissions by helping other entities reduce their emissions. It is associated with the concept of 'avoided emissions', which may manifest through the sales of goods and services or the financing of projects.
- **Pillar C** aims to increase global carbon removal solutions, thereby contributing to negative emissions both within and beyond the organization's value chain. A key aspect of this pillar is ensuring that an organization's carbon sink-to-emissions ratio consistently aligns with the sink-to-emissions ratio of the 1.5°C/2°C scenario relevant to its region.

The innovative aspect of the framework is particularly evident in Pillar B, which is associated with 'avoided emissions,' a concept not currently covered by the SBTi. This notion is increasingly prevalent among corporations making claims about the GHG impact of their products or services in comparison to a hypothetical scenario where these products or services do not exist. While Pillar A focuses on the principle of 'doing less harm,' Pillar B aligns with the concept of 'doing more good' and falls into the category of intervention accounting (Net Zero Initiative and WBCSD, 2023). However, methodological challenges exist in validating the relevance and credibility of such claims, especially in terms of assessing emissions and defining the counterfactual scenario. To qualify for avoided emissions claims, (Net Zero Initiative and WBCSD, 2023) outlines three critical steps:

- Climate action credibility: The company must have committed to clear, transparent, and full-scope emissions reporting.

- Alignment with latest climate science: The solution must align with current scientific recommendations (e.g., from the IPCC or IEA) and should not be applied to the fossil fuel supply chain.
- Contribution legitimacy: The solution should directly and significantly contribute to decarbonisation.

Furthermore, the NZI emphasizes the importance of reporting avoided emissions separately and clarifies that these should not be used to claim an individual state of net-zero. It advocates for solutions and reference scenarios to be evaluated from a life-cycle perspective, taking into account potential rebound effects and burden-shifting issues.

To assist stakeholders in navigating Pillar B, the NZI has developed additional guidelines to establish a 'Compatibility Score with the Paris Agreement' (Carbone 4 and Net Zero Initiative, 2022). This approach challenges organizations to evaluate whether their products and services contribute to the global net-zero goal. It distinguishes between solutions that decarbonise high-carbon activities, which may not be viable in a future low-carbon world, and those that enhance overall decarbonisation. The compatibility score is determined by comparing the GHGE footprint of a product or service (e.g., $kgCO_2eq/m^2/year$ for building usage) to the average global GHGE footprint derived from various prospective scenarios, such as those defined by the IEA.

The literature acknowledges various operational challenges and difficulties that organizations encounter in their emissions accounting and target-setting processes. A notable study by de Bortoli et al. (2023) identifies 24 specific challenges faced by organizations in these tasks. They propose addressing these challenges through a structured 'Measure-Reduce-Neutralise-Control' framework. Here, 'Control' specifically refers to tackling the issue of burden-shifting that often arises in mono-criterion environmental strategies, such as those focusing solely on carbon neutrality. They advocates for the field of industrial ecology to address the challenges by harmonising and updating standards, tools and databases to support robust accounting to ensure reliability, comparability, and transparency in emission metrics and targets. It comprises enhancing the development of comprehensive, open source and high quality life-cycle inventory databases that includes uncertainty qualification.

2.1.2 Prospective techniques and scenarios

This section delves into scenario typologies and methodologies, including a detailed look at Integrated Assessment Models (IAMs). While it presents general concepts, the illustrations and examples are specifically applied to building activities.

Methods, techniques, typologies, challenges

Scenario development in future studies, a diverse and non-standardised field, embraces various methodologies without a universal consensus (Bishop et al., 2007). Future scenarios can adopt numerous approaches but typically unfold in five iterations phases presented in Figure 2.3.

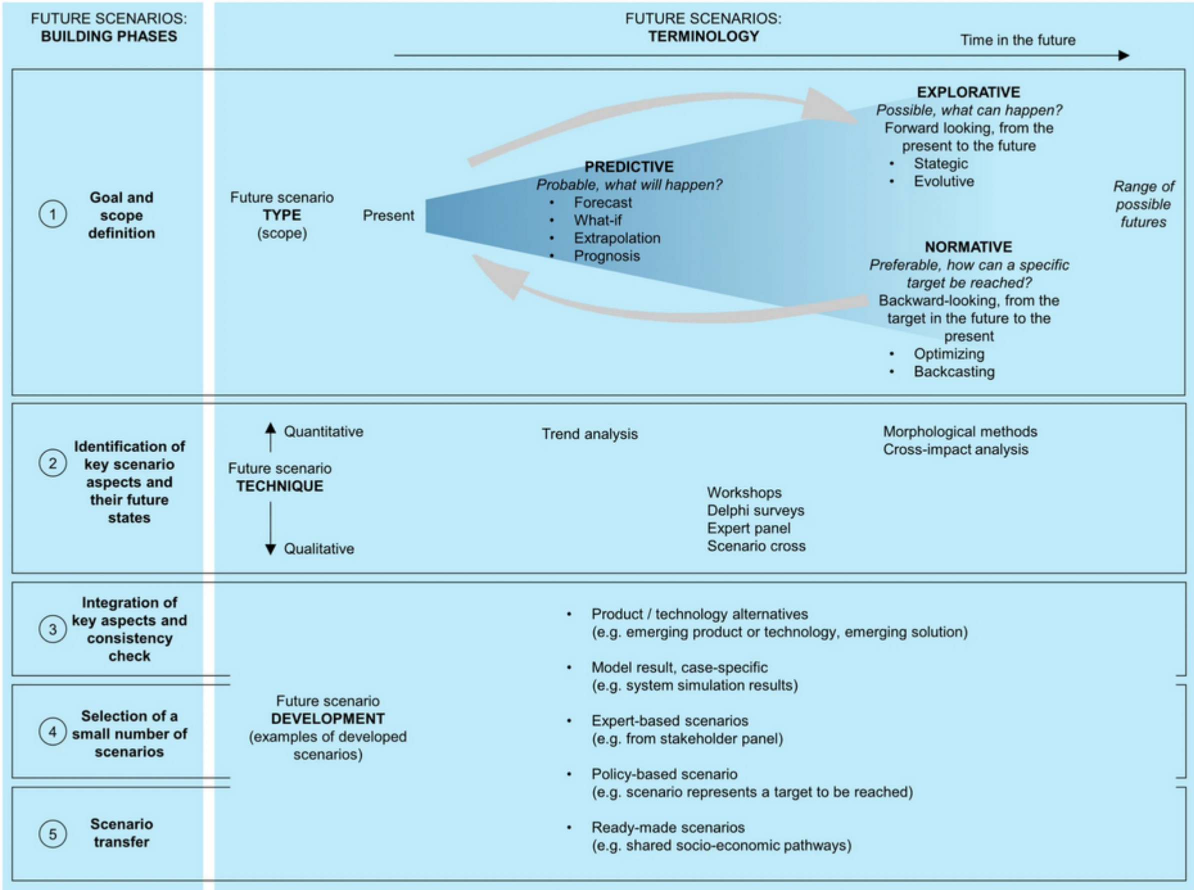


Figure 2.3: Generic scenario typology from Bisinella et al. (2021)

The initial phase involves defining goals and scope using for instance Borjeson's typology (Börjeson et al., 2006)'s typology, which categorises scenarios into predictive (*'what will happen?'*), explorative (*'what can happen?'*), and normative (*'how can a specific target be reached?'*).

- **Predictive scenarios**, including forecasts and 'what-if' scenarios, attempt to predict future events, often using probability estimates. Forecasts hinge on the most likely developments, while 'what-if' scenarios consider the implications of specific near-future events.
- **Explorative scenarios**, divided into external and strategic types, explore possible situations or developments. External scenarios [4] examine the potential changes in external factors, while strategic scenarios focus on the outcomes of specific actions. These scenarios typically cover a broad range of possibilities to allow for significant structural changes over a long time horizon.
- **Normative scenarios**, differentiated by their treatment of system structure, include preserving and transforming types [5] . Preserving scenarios explore how targets can be achieved through adjustments to the current situation, suitable when goals appear attainable within the existing system structure. In contrast, transforming scenarios are relevant when systemic changes are necessary, often rejecting traditional structural modeling.

[4] Bisinella et al. (2021) uses the term evolutive scenario
[5] Bisinella et al. (2021) uses the terms optimizing and backcasting scenarios

The subsequent phases illustrated in Figure 2.3 involve identifying key aspects and variables, assigning them future values quantitatively or qualitatively, combining these elements into consistent scenarios, and then distilling them into a manageable number for application to specific case studies.

Following the structured development of scenarios, a significant challenge emerges in comparing different future scenario studies. This difficulty arises from the diversity in methods, indicators, and scopes used, which are often tailored to specific questions and target audiences. Such diversity not only reflects the multidisciplinary nature of future studies but also introduces a degree of political influence. Future studies, aiming to impact political debates or decision-making processes, often embed ideologies and interests within complex computational models, sometimes obscuring their underlying assumptions. Recognising these challenges, experts advocate for a more integrated and transparent approach in energy and sustainable development scenarios. In particular, enhancing the integration of scientific principles is crucial for ensuring internal consistency in future studies. This includes a rigorous adherence to physical laws, recognition of planetary boundaries, and the inclusion of insights from social sciences (The Shift Project, 2019b). Additionally, fostering transparency in scenario development processes and promoting the involvement of stakeholders in both the production and reporting of scenarios are essential for broader acceptance and understanding. Uncertainty analysis is also a critical aspect that can enhance the robustness and relevance of scenario outputs (Guivarch et al., 2017). Indeed, a few highly detailed scenarios can create bias and mask other plausible alternative and the underlying uncertainties (DeCarolis, 2011). By addressing uncertainties explicitly, scenario developers can provide more reliable insights and guidance for decision-makers.

Integrated Assessment Models (IAMs)

Integrated Assessment Models (IAMs) are crucial tools in climate change scenarios, designed to understand the interplay between human development, societal choices, and the natural world, including climate change. These models are especially designed to capture the dynamics between human activities, such as energy use, land-use patterns, and technological development, and the biosphere, with a particular focus on climate change and its effects. IAMs are composed of linked modules representing the global economy, energy, land, and climate systems. The modules are then linked together through computer code ('hard-linking') or through data files ('soft-linking'), allowing results from one module to influence others.

In IAMs, inputs are assumptions about future developments in demographics, technology, economics and policy, which influence how societies and populations evolve. Outputs encompass economic outcomes, land-use changes, GHGE, and energy use and development pathways. To translate GHG and aerosols emissions into atmospheric concentrations, radiative forcing and global average temperature change, IAMs rely on simple climate models (also called 'emulators'). Some parts of IAMs are based partly on physical laws (e.g. climate models) while other rely on economic theory and historical data simulation. They often assume perfect information and rational decision-making by agents. For example, IAMs use economics to drive decisions based on prices, supply and demand, with 'agents' in various sectors making rational decisions to maximise welfare or minimise costs.

IAMs can be either 'prescient'—taking into account all future decisions in choices made today—or 'myopic,' focusing only on current time steps without considering future decisions (Evans and Hausfather, 2018).

IAMs are sometimes criticised for a bias towards technological solutions and for simplifying modelling compared to dedicated sectoral models. They face challenges such as the need for improved integration of scientific disciplines and greater transparency. They have been criticised for missing important dynamics like climate damages, economic co-benefits of mitigation, demand-side responses, and rapid technological progress. Concerns also exist regarding their potential bias in exploring only a subset of relevant futures (Trutnevyte, 2016). It remains a constant challenge for IAMs to capture all relevant perspectives due to their very large scope. Notably, research is involving to include more focused on demand-side solutions, low-demand scenarios focusing on sufficiency, and less focus on technological and immature solutions like negative emissions (O'Neill et al., 2020). Future advancements in IAMs will likely focus on improving the representation of heterogeneous actors, technology diffusion, capital markets, and the interconnections between economic activities and environmental outcomes (Keppo et al., 2021).

From an industrial ecology standpoint, IAMs face significant criticism for their inadequate representation of the complex interactions between biophysical and economic systems (Pauliuk et al., 2017). A core critique is the fragmented portrayal of technological life-cycle impacts. Indeed, IAMs often fail to account for the comprehensive environmental effects of technologies throughout their entire life-cycle, from resource extraction and production to usage and disposal. This oversight particularly affects the understanding of indirect impacts associated with energy systems' material requirements and emissions during construction and manufacturing phases. Moreover, IAMs predominantly concentrate on energy flows, overlooking essential physical balances like material cycles, thus neglecting the wider environmental implications present in supply chains. Lastly, they tend to view the economy from a production-centric perspective limits the analysis of consumption-driven environmental effects and the intricate web of inter-sectoral relationships (Pauliuk et al., 2017). The links and further ongoing research between IAMs, Life-Cycle Assessment (LCA) and Input-Output Analysis (IOA) are further developed in Section 2.1.3 and 2.1.4 respectively.

2.1.3 Life-Cycle Assessment (LCA)

This section 2.1.3 first reminds the theoretical framework in which LCA is rooted. It then explores the diversity of LCA approaches with a particular focus on future-oriented LCA. Finally, an overview of the application of LCA at the building level is proposed.

Introduction

Life Cycle Assessment (LCA) is an established methodology for evaluating the environmental impacts of products and services across their entire life cycle, from raw material extraction to end-of-life disposal. It is defined by the ISO 14040-44 standards as the *'compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle'*. This methodological framework enables a comprehensive analysis of environmental burdens, addressing both direct and indirect impacts. It helps to quantify possible trade-offs between environmental impacts or life-cycle stages, and helps to provide recommendations for better conception at the product level that avoid sub-optimisation for a single step. LCA offers a structured approach encompassing four critical phases:

1. **Goal and scope definition**: This foundational phase establishes the objectives, system boundaries, and functional unit for the assessment. It determines the depth and breadth of the study, ensuring relevance and focus. The system boundary can range from cradle-to-grave (encompassing the entire life cycle from raw material extraction to disposal) to more specific scopes like cradle-to-gate (ending at the factory gate)

2. **Life Cycle Inventory (LCI)**: This phase involves data collection and quantification of inputs and outputs within the system boundary. It includes all elementary flows such as raw material extraction, energy use, emissions, and waste generation, providing a detailed picture of the system's life cycle.

3. **Life Cycle Impact Assessment (LCIA)**: Here, the elementary flows in the LCI are characterised into potential impacts using characterisation factors. This includes aspects like climate change, resource depletion, and ecosystem quality. Impacts are often categorising into midpoints (direct impacts) and endpoints (ultimate effects).

4. **Interpretation**: The final phase involves analyzing results, evaluating uncertainties, and formulating conclusions and recommendations. It provides insights into the most significant environmental impacts and identifies opportunities for environmental improvements.

The evolution of LCA since the 1970s highlights a transition from a variety of individualised approaches to a standardised practice, particularly evident from the 1990s. This standardisation, facilitated by the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organisation for Standardisation (ISO), offered a common framework and language, though it was clear that ISO did not aim to define a single LCA methodology. Advancements continued into the early 2000s with the establishment of the Life Cycle Initiative, which underscored the increasing importance of LCA in policy-making, especially for climate mitigation. Recently, significant methodological developments have occurred within LCA, with a notable shift towards Life Cycle Sustainability Assessment (LCSA) to broaden the analysis scope and integrate economic and social dimensions, establishing LCSA as a *'transdisciplinary integration framework of models rather than a model in itself'* (Guinée et al., 2011).

Increasingly, LCA is applied well beyond its initial product-level focus. Methodologies like dynamic LCA, hybrid models combining LCA with Input-Output Analysis (IOA), and region-specific LCIA methods have address the need for more detailed and context-sensitive assessments (Hellweg and Milà i Canals, 2014). It is now being applied in sector-specific applications, such as in the building and construction sector, a prominent example being the new Environmental Regulation (RE2020) in France. At the economy-wide level, integrating LCA with other assessment tools, including future scenarios, significantly broadens its scope. This integration underscores LCA's capacity and potential to steer transformative strategies towards environmental and sustainable development goals across various scales. However, the complexity of these tools also introduces challenges in standardisation, which are crucial to ensure the robustness and comparability of prospective studies encompassing multiple indicators (Hellweg et al., 2023).

Computational structure of LCA

The LCI stage is crucial in LCA and is often represented through process flow diagrams and matrix algebra. Matrix algebra, in particular, offers a structured approach to quantifying environmental impacts and is suitable for complex systems with multiple products and internal loops (Suh and Huppes, 2005). Table 2.1 provides standard notation and dimensions, along with descriptions for matrices and vectors typically employed in LCA.

Table 2.1: Common notations in Life Cycle Assessment (LCA)

Notation	Description	Dimension
A	Technology matrix representing process interactions	$p \times q$
B	Intervention matrix detailing environmental exchanges	$r \times q$
C	Characterisation matrix for impact assessment	$p \times q$
f	Final demand vector in the context of the product system	$p \times 1$
h	Characterised inventory matrix or overall environmental impact	1×1
p	Number of products or commodities	-
q	Number of activities or processes	-
r	Number of elementary flows or environmental interventions	-

LCA seeks to assess the environmental impacts across a system's entire life cycle, from cradle to grave. The essence of LCA can be encapsulated in a single formula, which integrates these matrices and vectors:

$$h = CBA^{-1}f \tag{2.1}$$

In this equation, f represents the final demand for a product or service, $A^{-1}f$ calculates the required inputs across the supply chain (life cycle inventory), $BA^{-1}f$ quantifies the environmental interventions associated with satisfying this demand, and $CBA^{-1}f$ characterises these interventions into measurable environmental impacts. To disaggregate the total environmental impact by process, enabling the identification of significant contributors or hotspots, the formula is adjusted as follows:

$$h_{\text{process}} = CB\,\text{diag}(A^{-1}f) \tag{2.2}$$

This modification allows for the allocation of the overall environmental burden to individual processes within the product system, highlighting areas where environmental performance improvements can have the most significant impact.

A key characteristic of the technology matrix is that it is often not square, reflecting the multi-functionality of product systems. Multi-functionality occurs when a process or a product system produces more than one function or output. In that case, there is a need for an allocation step that distributes the environmental burdens associated with the process or product system among its multiple outputs or functions (Finnveden et al., 2009). Allocation allows to transform a rectangular matrix into a square one to apply matrix inversion techniques. Several allocation approaches exist depending on the nature of the multi-functionality and the availability of data. They include:

- **Physical allocation** allocates environmental impacts based on physical relationships between the products. Common physical allocation bases include mass, volume, energy content, or other physical properties that reflect the causal relationship between the environmental burdens and the co-products.
- **Economic allocation** allocates environmental impacts based on the economic value of each co-product. This approach assumes that the economic value is a proxy for the environmental burden each product carries. Economic allocation is often used when physical relationships between the products do not adequately reflect their environmental burden distribution.
- **System expansion** also known as substitution or avoided burden, this method avoids allocation by expanding the system boundaries to include the additional functions of the co-products. The environmental benefits or burdens of the co-products are then accounted for within the expanded system, typically by crediting the system for avoiding the production of these functions elsewhere. It is closely associated with consequential LCA, as it better captures the environmental impacts of changes in system behavior over time.

A diversity of LCA approaches

LCA encompasses a variety of approaches, each tailored to specific objectives and methodological choices. Central to these approaches are attributional LCA (ALCA) and consequential LCA (CLCA), both core components of the ISO standards but differing in their focus and application. ALCA is primarily descriptive, aiming to quantify the environmental burdens associated with the physical flows in a product's life cycle and its subsystems. This approach typically uses average data representing the typical environmental impacts for producing a unit of a product or service within the system. It provides a snapshot of the environmental footprint of a product or service, based on existing production technologies and consumption patterns. In contrast, CLCA adopts a change-oriented perspective. It seeks to understand how environmental flows will vary in response to specific decisions or changes in the system. This approach often uses marginal data, focusing on the environmental effects of incremental changes in the output of goods or services. Consequential LCA is particularly relevant for policy analysis and decision-making, as it helps in understanding the environmental implications of potential changes in production or consumption patterns.

Table 2.2: LCA approaches described in Guinée et al. (2018). Descriptions are generic while questions are focused on the building activities.

Type	Description	Typical questions
Attributional LCA (ALCA)	Focuses on identifying global environmental impacts associated with a specific system's life cycle.	*What is the current environmental impacts of a residential building in France?*
Back-casting LCA (BLCA)	Aims to assess the life-cycle impacts of reaching a defined long-term target.	*What is the necessary number of renovations operations in 2030 to reach an energy efficient building stock in 2050?*
Consequential LCA (CLCA)	Aims to understand environmental consequences resulting from decisions, typically changes in product demand.	*What are the consequences of an increased demand for timber construction?*
Decisional LCA (DLCA)	Builds upon CLCA, using actual or expected financial interactions between economic agents for impact assessment.	*Which effect does the decision to purchase an additional kWh of electricity have on the electricity market?*
Integrated LCA (ILCA)	Integrates LCA with various modeling approaches (Input-Output Analysis, Integrated Assessment Models) to assess large-scale mitigation measures.	*What is the economy-wide effects of a shift to 100% renewable electricity production in France?*
Anticipatory LCA (NLCA)	A future-focused tool incorporating prospective models, decision theory, and diverse social perspectives.	*What are the future environmental burdens associated with an emerging technology for extreme-case scenarios?*
Prospective LCA (PLCA)	Estimates future life-cycle environmental impacts using scenario analysis.	*What is the impacts of future buildings when accounting for the decarbonisation of electricity?*
Scenario-based LCA (SLCA)	Uses scenarios for life-cycle, scenario, and valuation modeling to improve environmental performance.	*What is the best scenario for improving the life-cycle performance of a single house in France?*

Beyond these two approaches, the LCA community has developed a diverse array of methodologies outside ISO and national standards, often referred to as an *'alphabet soup'* of LCA (Guinée et al., 2018). In particular, Guinée et al. (2018) propose a classification for explorative LCA methods, which focuses on future-oriented assessments. Table 2.2 outlines the main concepts behind the LCA method defined by Guinée et al. (2018), including typical questions.

Except for ALCA, all methods described aim to model the environmental effects of scenario-based changes, assessing the implications for future systems over varying timeframes. This perspective transcends the traditional dichotomy between ALCA and CLCA, allowing practitioners to select the methodology that best suits their needs for evaluating the consequences of modifications to current or future systems. In practice, LCA practitioners use methods that often blur the lines between these different LCA categories. For example Maes et al. (2023) combines a consequential approach with a prospective perspective, specifically applied to the electricity sector.

While this typology focuses on future-oriented approaches, the combination of LCA with other methods has also emerged. Notably, LCA has been associated with absolute environmental sustainability assessments (AESA). This includes the development of LCIA methods based on environmental carrying capacities (Bjørn et al., 2015) and, subsequently, methods grounded in the Planetary Boundaries framework, known as PB-LCA (Ryberg et al., 2018).

Prospective LCA

Expanding the application of LCA to include guidance at macro level offers invaluable insights for understanding the environmental impacts of long-term changes, particularly in climate change mitigation efforts. Although traditional product-level consequential LCAs are effective in estimating indirect effects of changes, Guinée et al. (2011) note that *'It may be more realistic to start thinking how more realistic, macroscopic scenarios for land use, water, resources and materials, and energy (top-down) such as drafted by the IPCC [...] can be transposed to microscopic LCA scenarios'*. This is increasingly relevant as systems evolve through technological advancements and efficiency gains, necessitating an understanding of both current and future impacts of low-carbon technologies on upstream energy generation and economic activities (Gibon et al., 2015). Thus, merging detailed LCA methods with broad scenarios presents a pragmatic path towards sustainable decision-making and long-term sustainability.

In LCA, variations in the model, input parameters, or external conditions are frequently described as scenarios thus blurring its meaning. Guidance on future-oriented LCA came from early studies and the efforts of the Society of Environmental Toxicology and Chemistry (SETAC). Notably, Fukushima and Hirao (2002) propose a first scenario-based LCA framework and Pesonen et al. (2000) define scenario in the context of LCA as *'a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future'*. In this definition, scenarios encompass potential future situations, with each scenario potentially comprising one or more product alternatives for examination within the LCA framework. The frame of a scenario is included in the first step (goal and scope definition) and incorporates features like system boundary, technology levels, temporal or geographical aspects. The modelling of a scenario is incorporated within both the LCI and the LCIA phases. Pesonen et al. (2000) distinguish two basics approaches to scenario development in the LCA context:

- ***'what-if'* scenarios**. They are quantified, the topic is relatively simple and familiar to the modeler, and the objective is to investigate consequences of discrete assumptions and uncertainties. An example could relate to the assessment of using triple-glazed window instead of conventional window. Bisinella et al. (2021) notes that it can be misleading and lead to confusion as it is not aligned with the use of *'what-if'* by the foresight community, e.g. the definition given by Börjeson et al. (2006).

- ***'cornerstone'* scenarios**. They have a more exploratory purpose, and are appropriate for new and complex fields, where the purpose is to gain knowledge and strategic information. An illustrative case might be the evaluation of adopting large-scale fungal insulation in building renovations.

They also distinguished **technology** scenarios, typically established in the LCI (for example, using traditional Portland cement versus alternative low-carbon cements in concrete production) , and **environmental**, and **valuation** scenarios, defined in the LCIA, which refer to characterisation and weighting respectively. The characterisation step in LCIA involves quantifying and converting different environmental emissions and resource extractions into common impact indicators based on their potential environmental impacts. Weighting is a step that may follow characterisation, where different environmental impact categories are assigned relative importance or weights based on value choices. This process is more subjective and reflects societal, cultural, or individual preferences regarding the relative significance of different environmental impacts.

Since the first guidance, the evolution of LCA towards integrating scenarios stands as a crucial advancement over the last years. Indeed, the combined application of LCA and future-oriented studies has seen an exponential increase in interest, as half of the articles in this field were published after 2017, with the field of energy for large scale study being the most represented (Bisinella et al., 2021). Several recent literature review have been proposed such as Bisinella et al. (2021) and Arvidsson et al. (2023), while Thonemann et al. (2020), van der Giesen et al. (2020) and Moni et al. (2020) focusing on emerging technologies. However, the absence of formal guidance within ISO standard frameworks and the multiplication of studies have led to a proliferation of diverse practices, methods, terminologies, and concepts that lead to confusions. The first example is the use of the term 'scenario', which has been inconsistently applied, sometimes referring to technology alternatives or as a method to address uncertainty. Moreover, it is often not clear whether the foreground, the background or both are affected, and if the scenarios affect the present or a future point in time. Bisinella et al. (2021) propose a shared definition of scenario between the LCA and future studies communities defined as *'a set of aspects describing a specific situation at a specified time'*. When the time frame reveals a future state, the scenario becomes a future scenario. In this case, any element in the LCA framework affected by future states should be communicated in a transparent fashion. The second example is the variety of terminologies used in the context of future-oriented LCA. In particular, how prospective and ex-ante LCA differ or are related lead to confusion inside the community, as in some cases, different terms refer to similar approaches, and in others, the same term is interpreted differently by different research groups (Bergerson et al., 2020). For example, the definition of prospective LCA used by Arvidsson et al. (2018) is aligned with the definition of ex-ante LCA used by Cucurachi et al. (2018). Arguably, the temporal positioning and technological maturity, often given in the reference to their Technology Readiness Level (TRL) are two key aspects that shape the terminology (Arvidsson et al., 2023), while the level of the maturity of the market in which the technology could be deployed also be included (Bergerson et al., 2020). In their review, Arvidsson et al. (2023) recommend to use the term prospective LCA and to keep others aspects (such as the TRL) for the goal and scope of the study.

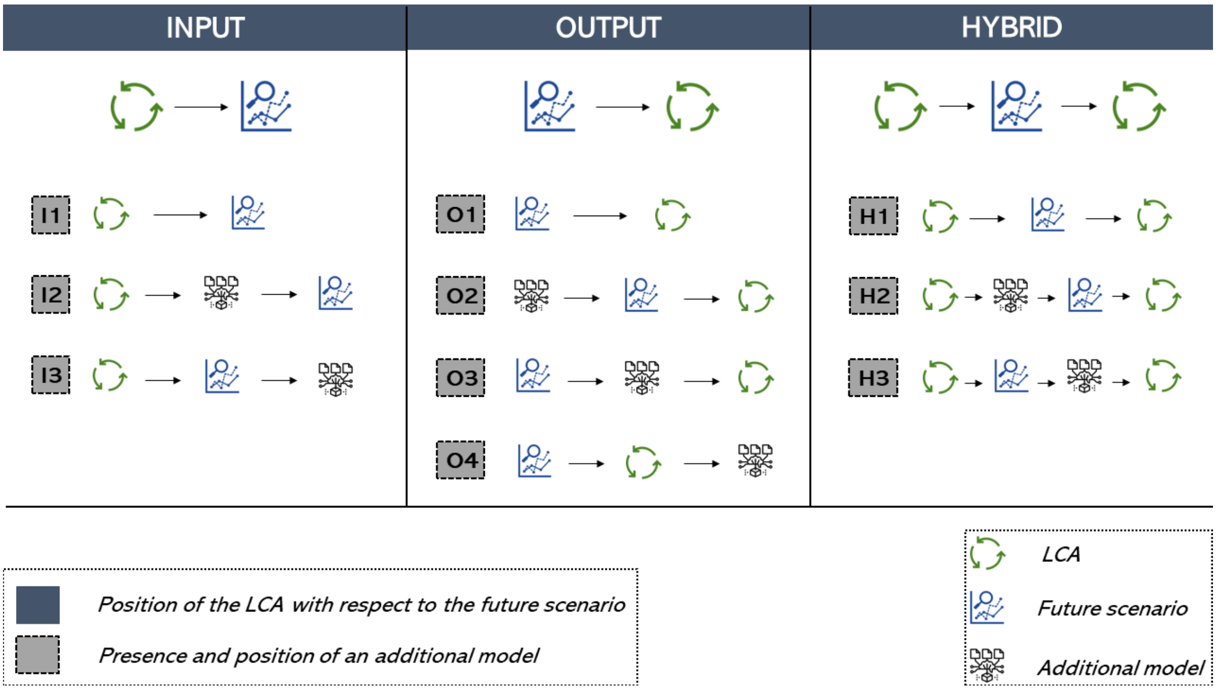


Figure 2.4: Approaches for future-oriented scenario LCA (adapted from Bisinella et al. (2021))

Bisinella et al. (2021) provide an insightful analysis based on an extensive review of the literature on the integration of future studies and LCA methodologies. They observe that many studies fail to acknowledge or reference methodologies from future studies, leading to a gap in the comprehensive application of scenarios within the LCA framework. Specifically, a significant portion of these studies does not clearly define the type of scenario employed, even though 51% could be categorised as explorative and 42% as predictive. Additionally, there is a notable deficiency in the application of sensitivity and uncertainty analysis methods, which are rarely included. Based on these findings, they propose a structured framework to clarify how future studies and LCA methodologies can be coherently integrated. This framework outlines three principal approaches for incorporating future scenarios into LCA: input, output, and hybrid. The framework is illustrated in Figure 2.4.

As observed in the Figure, the classification depends on how LCA is positioned relative to the future scenarios, guiding the application of scenarios within the LCA process. Within each type (e.g. input, output, hybrid), specific subtypes (e.g., I1-I2-I3 for input, O1-O2-O3-O4 for output, and H1-H2-H3 for hybrid) are identified, based on the incorporation and role of additional models or databases. Among these, subtypes O1, O3, and H1 emerge as the most prevalent in the literature, accounting for 39%, 18%, and 16% of the articles reviewed, respectively.

A critical element in future-oriented LCA is maintaining consistency when applying changes to both the foreground system and the background system. Mendoza Beltran et al. (2018) emphasise the risk of temporal mismatches between these systems, which could lead to misleading outcomes and inappropriate recommendations for stakeholders. Methodologically, incorporating scenarios in prospective LCA necessitates modelers to consult additional, exogenous databases beyond traditional LCA resources. This approach aims to capture the evolution of future socio-economic and technological landscapes, thereby embracing uncertainties and enhancing temporal coherence in the LCA exercise.

The application of IAMs for scenario generation offers comprehensive global economic sector coverage, although challenges persist in aligning regional and sectoral specifics between IAMs and LCI databases, as well as extending environmental indicators beyond the typically emphasized climate metrics (Sacchi et al., 2022). This methodology has been successfully implemented across various domains, including battery and electric vehicles (Cox et al., 2018), mobility (Mendoza Beltran et al., 2018), building impacts (Zhang et al., 2024) and metal supplies (Harpprecht et al., 2021). However, oftentimes, only selected aspects (e.g., electricity) of the LCI database are modified. For a more accurate depiction of the future, ideally, comprehensive changes across all relevant aspects should be considered, accompanied by uncertainty and sensitivity analyses for both foreground and background systems (Mendoza Beltran et al., 2018).

The advent of prospective LCI databases marks a significant step forward in consistently representing future technologies and supply chains. These databases are created by blending existing LCI databases such as ecoinvent (Wernet et al., 2016) with scenario data from IAMs and additional sources. Typically, modifications to these databases cover three main aspects: the introduction of new technologies, the regionalisation of new or existing technologies, alterations to the market composition of existing technologies and changes in system efficiency (Sacchi et al., 2022). Given the number of processes potentially affected, manual updates are impractical. The THEMIS framework have introduced matrix multiplication method for updating the 2.2 ecoinvent version with IEA scenarios (Gibon et al., 2015). Recently, tools built on the Brightway2 suite (Mutel, 2017a) like wurst (Mutel, 2017b) and premise (Sacchi et al., 2022), enable modifications to the LCI database using information from two IAMs, namely IMAGE (van Vuuren et al., 2021) and REMIND (Baumstark et al., 2021). While these tools have undoubtedly improved the creation of prospective LCI databases, challenges persist in ensuring reproducibility and facilitating sharing among LCA practitioners, the IAM community, and public and private organizations. Initiatives like Futura (Joyce and Björklund, 2022) offer a solution by sharing a 'recipe file' that documents the changes made to the original database. Similarly, the unfold Python package (Sacchi, 2023b) employs data packages for this purpose. To accommodate the potential variety of background databases, the superstructure approach (Steubing and de Koning, 2021) simplifies the integration of different background databases within the Activity Browser interface (Steubing et al., 2020).

Temporal issues in LCA

The standard LCA methodology has traditionally been applied in a static manner. Temporal considerations are typically not modelled during the LCI stage. Subsequently environmental impacts are treated as occurring at a singular aggregated point in time (Beloin-Saint-Pierre et al., 2020). This approach overlooks the temporal dynamics of systems and environmental impacts, a limitation acknowledged within the ISO framework and tackled by pioneering studies. Notably, Levasseur et al. (2010) have introduced dynamic LCI considering the temporal profile of emissions as well as time-dependant characterisation factor.

Lueddeckens et al. (2020) provide a comprehensive review of temporal issues in LCA, identifying six main categories namely time horizon, discounting, temporal resolution of the inventory, time-

Table 2.3: Glossary of terms relative to temporal issues in LCA inspired from (Beloin-Saint-Pierre et al., 2020)

Term	Description
Time Horizon	*'Relative temporal scope over which environmental impacts are summed up to provide LCA results.'*
Dynamic LCI	*'LCI that is calculated from supply and value chains where dynamic of systems or temporal differentiation is considered, resulting in temporal distributions to describe elementary flows.'*
Dynamic LCIA	*'Characterisation models of environmental mechanisms that account for the dynamic of ecosphere systems and can therefore use temporal information of DLCIs.'*
Dynamic LCA	*'LCA studies where relevant dynamic of systems and/or temporal differentiation of flows are explicitly defined and considered.'*
Discounting	Changing value or importance of environmental impacts over time.
Dynamic weighting	Changing significance assigned to different environmental impact categories over time.
Dynamic normalisation	Updating the reference values against which LCA results are compared, reflecting changes in the broader environmental or societal context.

dependent characterisation factor, dynamic weighting and time-dependent normalisation. Table 2.3 provides a glossary of terms relative to temporal issues in LCA.

The most important part of a dynamic LCA includes identifying time-dependent environmental impacts, selecting an appropriate temporal resolution, and compiling a LCI that accurately reflects time-specific data. These steps are crucial for capturing the dynamic interplay between a system and its environmental impacts over time, providing a more accurate representation of reality. Dynamic characterisation in LCA specifically refers to the process of assessing the environmental impact of an inventory item (such as 1t of CO_2) using characterisation factors that take into account changes over time in how that emission affects the environment. This approach is based on the understanding that the environmental impact of a given emission can vary due to changes in environmental conditions, background concentrations, or the relative sensitivity of the environment and human health to that emission over time. For example, the impact of CO_2 emissions on global warming might be modeled differently if the capacity of ecosystems to absorb CO_2 changes over time, or if background levels of CO_2 and other GHG vary, altering the overall contribution to climate change.

Addressing temporal issues in LCA adds complexity but significantly enhances the assessment's accuracy and relevance. By incorporating temporal considerations, LCA practitioners can better understand the environmental impacts of systems over time. The consensus within the research community highlights the enhancement of LCA methodologies through the inclusion of dynamic LCI data and time-dependent characterisation factor. Overlooking these temporal dimensions is acknowledged as a simplification that may occasionally result in bias decisions (Lueddeckens et al., 2020).

The significance of temporal dynamics is especially pronounced for long-lived assets like buildings. Negishi et al. (2018) highlights various time-sensitive and dynamic factors that influence these assets, including: a) the performance degradation of construction products over time, along with their replacement and the adoption of new technologies; b) similar degradation in energy equipment and the introduction of novel technologies for harnessing renewable resources; c) variations in occupant behaviour, such as changes in occupancy typology and thermal comfort preferences; d) shifts in the energy mix; e) advancements in end-of-life technologies, including the options for material disposal versus reuse and recycling; and f) the balance of carbon uptake and emissions, particularly in the context of biogenic carbon.

Building LCA

LCA is increasingly recognised in the building and construction industry as one of the main tools to provide a holistic accounting of environmental impacts. A prominent example is LCA's mandatory incorporation into France's Environmental Regulation (RE2020), which mandates the calculation of both operational and embodied environmental impacts for new construction projects. This integration testifies the growing importance of LCA in guiding sustainable construction practices and policy-making. This sub-section looks at building LCA from a micro-perspective, looking at LCA for construction products and individual buildings. Meso and macro analysis of building stocks are covered in Section 2.2.

To conduct a building LCA, data on construction products and equipment are essential. At the product level, Environmental Product Declarations (EPDs), guided by EN-15804 and ISO14025, offer vital environmental profiles for construction products, streamlining data collection and potentially overcoming barriers to the widespread adoption of LCA (Fnais et al., 2022). In France, the INIES database[6] serves as the national reference for building product EPDs.

Despite their utility, notable challenges have emerged, including the differences in environmental emission coefficients between EPDs and LCI databases (Lasvaux et al., 2015), as well as concerns regarding transparency and comparability (Moré et al., 2022). Furthermore, while 75% of data originate from process-based methodologies (Chae et al., 2023), Crawford et al. (2022) advocate for hybrid approaches (detailed in Section 2.1.5) with Australia's EPiC database, which provides hybrid coefficients for nearly 300 construction materials.

At the core of building LCA is the European Standard EN-15978, which offers a standardised methodology for the calculation of building LCA, delineating the life cycle into five distinct stages: Product, Construction, Use, End-of-life, and Benefits beyond the system boundary. Figure 6.3a illustrates these four distinct stages along with their sub-phases (e.g A1-A3, A4-A5, B1-B5, B6-B7, C1-C4 and D), and in relation to the life-cycle philosophy considered, e.g. from cradle to gate to cradle to cradle.

This standard clarifies the categorisation of operational and embodied impacts, facilitating a comprehensive analysis of a building's environmental footprint. Operational impacts typically fall under the Use stage (B6-B7), while embodied impacts encompass all other stages, where upfront impacts

[6] https://www.inies.fr/

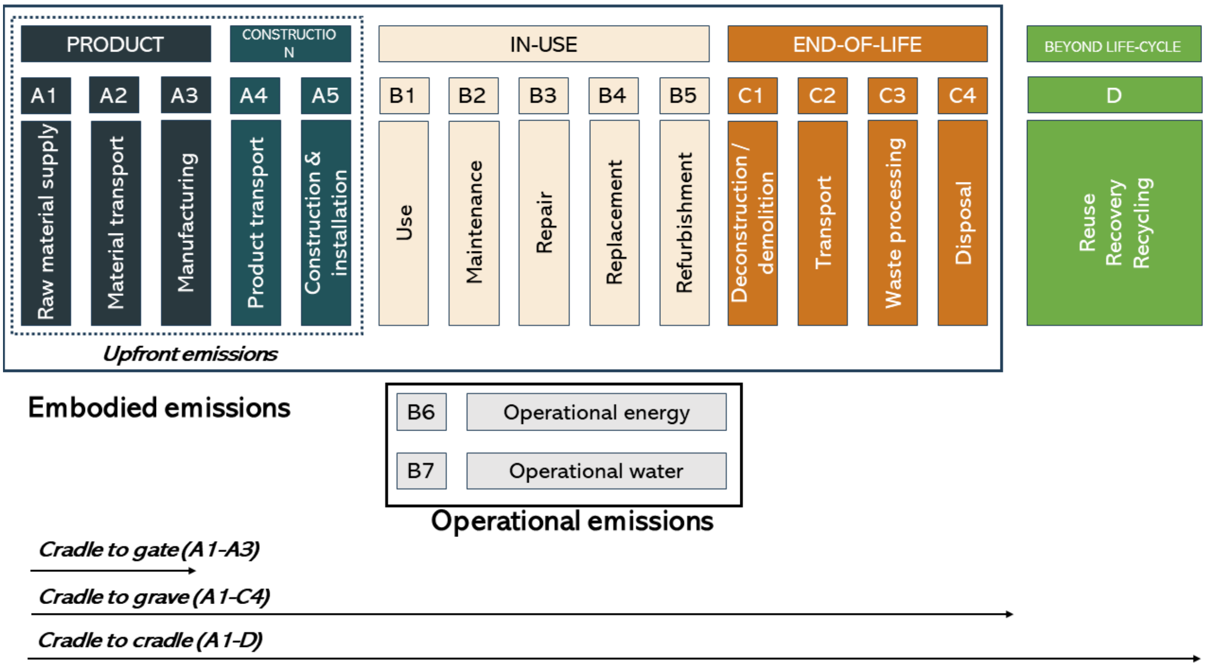


Figure 2.5: EN-15978 modules and stages framed in the operational/embodied framework

cover product and construction stages. Research compiling hundreds of building LCA case studies highlights the increasing significance of embodied emissions, especially in new, energy-efficient buildings (Röck et al., 2018). It should be noted that the EN-15978 also stands for assessing the environmental impacts of building renovations.

Fnais et al. (2022) review current research, challenges, and future directions in building LCA. They particularly emphasise the need for greater integration with Building Information Modeling (BIM) alongside optimisation and machine learning techniques to manage uncertainties. The use of dynamic, regionalised, and temporally-explicit LCI data are notable challenges which can help improve building LCA's precision and consistency. The need to integrate LCA during the design phase is also critical for minimising embodied impacts.

2.1.4 Input-Output Analysis (IOA)

This section presents an overview of Input-Output Analysis (IOA), focusing particularly on its Multi-Regional variant. The application of IOA in forward-looking studies is also discussed.

Introduction

Input-Output Analysis (IOA) is a methodology that examines the interconnections and interdependencies of sectors within an economy, showing how outputs from one sector are inputs to other sectors. It is a well-established and extensively studied methodology, with Miller and Blair (2009) being widely recognised as a reference manual in the literature. Developed by economist Wassily Leontief in the 1930s, IOA was initially intended for economic production planning (Leontief, 1936). In the 1970s, the methodology evolves to include environmental and social assessments through satellite accounts, leading to the development of Environmentally-Extended Input-Output Tables (EE-IOT) (Leontief, 1970). This adaptation provides a comprehensive framework for understanding the environmental impacts of various production and consumption patterns.

IOA is not without limitations, which are well identified in literature. These includes:

- **Aggregation issues**: IOA often requires the aggregation of different industries and products into broader categories, which can mask the nuances and specificities of individual industries. This aggregation may lead to oversimplifications, affecting the precision of the analysis, especially in diverse and complex economies. For example, aggregating all agricultural commodities into a single 'Agriculture' sector can result in significant errors. Besides, in the context of EE-IOA, monetary IOT and satellite accounts may use different classifications systems which causes problems in their integration. Lenzen (2011) demonstrates that disaggregating monetary IOT is superior to aggregating environmental data in broad sectors in the context of determining multipliers.
- **Static nature**: Traditional IOA models are static and do not easily account for changes over time, such as technological advancements, shifts in consumer behavior, or policy interventions. This limitation makes it difficult to use IOA alone for forecasting or assessing dynamic economic processes.
- **Proportional assumptions**: A common assumption is that the input structure (i.e., the proportion of various inputs used) for a given sector is uniform across all outputs of that sector. For instance, if a sector produces multiple products, it is assumed that the proportion of raw materials, labor, and other inputs used to produce each product is the same.
- **Data quality and availability**: the accuracy of IOA depends heavily on the quality and availability of the underlying economic and environmental data. In some cases, especially for smaller or less-developed regions, data might be outdated, incomplete, or not detailed enough.

Computational structure of IOA

The foundational elements of Input-Output Tables (IOTs) are the Supply and Use Tables (SUTs), which meticulously detail the production and consumption patterns of products across various industries. The Supply Table catalogues the output from different industries alongside imports, whereas the Use Table delineates the distribution of these outputs across sectors and their ultimate consumption. Transitioning from SUTs to IOTs involves two principal methodologies (Eurostat, 2008):

- The commodity technology model assumes that products from an industry have uniform input structures, regardless of their usage.
- The industry technology model suggests that each industry produces a distinct product.

Environmental Extended Input-Output Analysis (EE-IOA) employs a series of matrices, detailed in Table 2.4, to model the economic and environmental interactions within an economy:

Table 2.4: Description of matrices in Input-Output Analysis

Notation	Description
x	Total output vector indicating the total production of each sector.
y	Final demand vector showing the demand for goods and services by external consumers.
Z	Inter-industry flow matrix showing how each sector's output is used as inputs by other sectors.
A	Technical coefficients matrix, derived from Z, representing the input required from each sector to produce one unit of output.
B	Environmental extension matrix indicating direct environmental impacts per unit of output from each sector.
F	Environmental footprint matrix that quantifies the total, direct and indirect, environmental impact associated with the final demand.
V	Value-added matrix representing the additional value created at each stage of production in each sector (e.g. capital, labor, taxes).

In IOA, these matrices are pivotal for conducting consumption-based impact accounting through the Leontief production framework and its extensions to environmental footprint assessments, embodied in the following equations:

$$x = Zx + y \tag{2.3}$$

This foundational IOA equation delineates that an economy's production (x) fulfills two primary roles: supplying inter-industry consumption (Zx) and meeting final consumption (y). Here, x and y are vectors, while Z is the inter-industry flow matrix, mapping out the utilisation of outputs as inputs across sectors. The Z matrix is then transformed into the Leontief inverse $(I-A)^{-1}$, where I denotes the identity matrix and A the technical coefficients matrix. The equation is then transformed to:

$$x = (I-A)^{-1}y \tag{2.4}$$

Where x calculates the total (direct and indirect) inputs required to satisfy a unit of final demand (y).

Finally, the equation that extends the model for environmental analysis by calculating the direct and indirect environmental impacts of production to meet final demand (y) is the following :

$$F = B(I-A)^{-1}y \tag{2.5}$$

Where F represents the environmental footprint matrix, which quantifies the total environmental impact associated with the final demand y. B is the satellite matrix, indicating direct environmental burdens or impacts per unit of output from each sector (such as CO_2 emissions per unit of output).

Environmentally-Extended Multi-Regional Input-Output (EE-MRIO)

Multi-Regional Input-Output Tables (MRIOT) expands the conventional input-output analysis framework to encompass multiple regions or countries, enhancing the capacity to analyze global trade impacts and inter-regional dependencies. Unlike standard IOA, which typically focuses on a single region, MRIOA integrates international trade by specifying the geographic origins of economic activities. This allows for a more comprehensive understanding of global supply chains and their environmental implications.

The transformation of the Z and Y matrices in MRIOT to include sub-matrices reflects this expanded scope. This refinement enables a detailed assessment of the origins and destinations of products and services across global networks. In a MRIOT, the Z matrix described in Table 2.4 contains sub matrices and is noted:

$$\mathbf{Z} = \begin{pmatrix} Z_{11} & Z_{12} & \cdots & Z_{1r} \\ Z_{21} & Z_{22} & \cdots & Z_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{r1} & Z_{r2} & \cdots & Z_{rr} \end{pmatrix} \tag{2.6}$$

Where each sub-matrix $Z_{i,i}$ represents the domestic interactions for each industry while off diagonal matrices $Z_{i,j}$ describe the international trade from region i to region j for each industry.

Similarly, the y vector described in Table 2.4 is transformed into a matrix and is noted:

$$\mathbf{Y} = \begin{pmatrix} Y_{11} & Y_{12} & \cdots & Y_{1r} \\ Y_{21} & Y_{22} & \cdots & Y_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{r1} & Y_{r2} & \cdots & Y_{rr} \end{pmatrix} \tag{2.7}$$

Where $Y_{i,i}$ represents the final demand satisfied by domestic production and $Y_{i,j}$ the direct imports from country i to satisfy final demand in country j.

The wider availability of economic and environmental data as well as the computational progress have enabled the development of multiple MRIO databases that bring more details (Wiedmann, 2009). The development of MRIO databases has enabled its growing use in environmental studies, particularly in calculating various environmental footprints like carbon, water, and resource use (Malik et al., 2019). It has proven instrumental in tracing the origins of emissions or resource use across global supply chains, offering insights into the environmental pressures of energy use, greenhouse gas emissions, material use, water use, and land use. This approach has facilitated the assessment of both absolute and relative decoupling of these environmental indicators from economic growth and population, as well as the dynamics of consumption, trade, and environmental impacts over time (Wood et al., 2018b).

Several MRIO databases have been developed, each with unique features and scopes. These databases include the World Input-Output Database (WIOD) (Timmer et al., 2015), EORA (Lenzen and Rueda-

Cantuche, 2012), Global Trade Analysis Project (GTAP) (Aguiar et al., 2019), and Exiobase 3 (Stadler et al., 2018a), among others. Table 2.5 offers a comparison of these databases in relation to key indicators such as sectoral and geographical resolution, temporal coverage and environmental extensions.

Table 2.5: Comparison of the main MRIO databases

Database	Developing team/project	Details
WIOD	Consortium led by University of Groningen	56 sectors; 43 countries + RoW; Annually (1995-2014); Focus on manufacturing and business services sectors
EORA	University of Sydney	Up to 400 sectors (by country); 187 countries; Annually (1990-2014); 35 environmental indicators; Social accounts
GTAP	Center for Global Trade Analysis, Purdue University	57 sectors; 140 countries; Periodic updates; CO2 emissions and labor skill categories
Exiobase 3	Developed under the EXIOPOL, CREEA, and DESIRE projects	200 sectors; 44 countries + 5 RoW; Annually (2000-2013); Detailed in agriculture, forestry, mining, and energy

In terms of environmental extensions, Exiobase stands as particularly consistent (Malliet, 2020), and is used in several EU countries for official consumption-based accounts (Haut conseil pour le climat, 2020). While giving powerful information for policy-making, MRIO inherits from uncertainties from single region IO and introduces new ones that are detailed below:

- **Regional disaggregation**: This difficulty arises from the varying levels of economic development, industrial structures, and data availability across regions, potentially leading to inaccuracies in regional analysis.
- **Exchange rate fluctuations**: Exchange rates significantly impact the valuation of international trade in MRIO. Variability in currency values can skew import and export valuations, leading to discrepancies when comparing data over time or between countries. Adjustments, such as using a standard currency or purchasing power parity, are often necessary to normalise these fluctuations.
- **Trade flow matrices**: Accurately representing and recording trade flows between sectors and regions is crucial yet challenging. Discrepancies in trade data recording, classification standards, and data collection time lags can affect the precision of the results.
- **Allocation principles**: Notably, the choice for emission allocation between the residence principle, used in the System of National Accounts (SNA) and territorial principles, used in national emission inventory impacts MRIO results. The residence principle, which accounts for activ-

ities undertaken by a country's residents regardless of location, contrasts with the territorial principle that focuses on activities within a country's borders, irrespective of who conducts them. This choice affects how emissions are allocated within the emissions vector. The **territory principle**, used in UNFCCC greenhouse gas inventories, allocates emissions to the geographical location where they occur. This is appropriate for tracking emissions relative to national commitments and targets under international agreements. The **residence principle**, often used in MRIOA, allocates economic activity and emissions to the entities (individuals or corporations) responsible for them, regardless of where the emissions physically occur. This is useful for understanding the environmental impacts of consumption patterns, especially in a globalised economy where production and consumption can occur in different regions. The residence principle is recommended for consistency in consumption accounts (Owen et al., 2016).

- **Harmonisation of satellite accounts**: Harmonising satellite accounts shows that carbon footprint results for major economies disagree by less than 10% between MRIO models (Moran and Wood, 2014). However, differences in domestic emission inventories and consumption estimates are primary causes of variation.

Key areas of future research include the development of city and subnational MRIO databases, which can offer more localised insights into consumption impacts. An example is given by Wiedmann et al. (2016) with the concept of 'City Carbon Maps' for the city of Melbourne in Australia. Additionally, the integration of social indicators into MRIO databases opens new avenues for analysing supply-chain effects on employment, inequality, poverty, occupational health and safety, labor, and gender equity (Malik et al., 2019).

A significant challenge in applying IOA to LCI (see Section 2.1.5) is the scarcity of sector-specific environmental data in many countries. Available emission inventory databases, while useful, often differ in detail, base year, and industry classification, complicating the construction of comprehensive sectoral environmental datasets (Lenzen, 2011).

Prospective studies in IOA

In the realm of IOA, prospective studies or scenario-based analyses necessitate methodologies that extend beyond the inherently static nature of traditional IOA, as discussed in Section 2.1.3. Scenarios in IOA are typically implemented by simulating an exogenous shock, affecting various matrices such as the technical coefficients matrix (A), final demand (Y), or environmental stressors (B). Tools like the MARIO module facilitate transparent simulations of these scenarios (Tahavori et al., 2023). Examples of transformation include for instance, incorporating changes in energy use, investment structures for energy technologies, or variations in household expenditure patterns (Wiebe et al., 2018).

Effective exploration of future implications requires coupling IOA with forward-looking models like IAMs (detailed in Section 2.1.2). The integration of IAMs with IOA, including hybrid methods that combine IOA and LCA, offers a comprehensive approach, merging the strengths of both methodologies. IAMs provide a forward-looking perspective, often with a focus on technological transformations, but they typically lack a life-cycle perspective and the detailed analysis of supply chains beyond energy systems. Conversely, IOA comprehensively captures environmental and economic dimensions of global supply chains but falls short in dynamic assessments and fails to account for technological advancements.

Lefèvre (2023) reviews the integration of IOA (including hybrid methods with an IOA focus) and IAMs, highlighting that this field is still in its nascent stages. The majority of studies use a soft-linking approach in a unidirectional manner. One common application is integrating IAM results into IO models for prospective analysis. Examples include Wiebe et al. (2018), who applied IEA ETP 2°C and 6°C scenarios to modify the Exiobase 3 database, focusing on the energy sector. They implemented changes to energy use coefficients, investment structures for energy technologies, and household expenditure structures. Similarly, De Koning et al. (2016) implemented BAU, technological, and 2°C scenarios, including behavioral changes, in the Exiobase 2000 version. In the context of hybrid methods, studies like Hertwich et al. (2015) investigate the life-cycle environmental impacts of deploying low-carbon energy sources, incorporating energy technology developments. These studies extensively use the THEMIS model (Gibon et al., 2015), which represents a state-of-the-art integration of hybrid analysis and prospective models.

The less common approach involves applying IO results to IAMs, such as including life-cycle emission coefficients within IAMs (Pehl et al., 2017) or questioning the robustness of IAMs' optimal solutions when incorporating indirect emission factors (McDowall et al., 2018).

For future research directions, Lefèvre (2023) suggests focusing on the energy-industry nexus, integrating a broader range of environmental indicators aligned with the Sustainable Development Goals (SDGs), and incorporating social aspects related to justice. Additionally, the coupling makes possible to explore post-growth scenarios by including additional demand-side solutions in IAMs.

2.1.5 Hybrid LCA-IOA

This section explores the parallels and distinctions between IOA and LCA, leading to the development of hybrid methodologies that integrate the advantages of both frameworks.

Introduction

Both IOA and LCA are essential tools for evaluating environmental impacts. LCA focuses on the impacts associated with specific products or services with its bottom-up approach. In contrast, IOA offers a broader perspective, encompassing entire economies through its top-down approach. They both share a common goal of understanding the total inputs required to produce a specific output including both direct and indirect contributions.

Hybrid methods emerge as a state-of-the-art solution to address the limitations of both IOA and LCA, as their strengths and weaknesses appear complementary (Suh and Huppes, 2005). In particular, they address the already mentioned issues related to sector aggregation in IOA and truncation errors in LCA, that are often due to data limitations or complexity, and which can lead to incomplete assessments of environmental impacts and potentially misleading results. In particular, *upstream* truncations involves omitting certain stages or processes at the beginning of a system's supply chain due to constraints like time, budget, or data availability (e.g. extraction or initial processing stages of raw materials), *downstream* truncations occurs when intermediate manufacturing processes are not included in the analysis and *sideways* truncation happens when certain processes are excluded from analysis due to their perceived minor contribution, lack of data, or unawareness of their importance.

Table 2.6 offers a comparison of process-based, IO-based and hybrid LCI, detailed their advantages and disadvantages.

Table 2.6: Comparison of LCI methods

Method	Pros	Cons
Process-based LCI	Detailed and specific to the studied system. High accuracy for direct emissions and resource use. Specific to processes or materials.	Time-consuming. High potential for truncation error. Requires detailed process data.
IO-based LCI	Covers entire economy, minimising truncation error. Efficient for capturing indirect effects. Useful for large-scale and sectoral assessments.	Less detailed for specific products. Potential for aggregation error.
Hybrid LCI	Combines the strengths of both process-based and IO-based approaches. Improves accuracy for both direct and indirect emissions.	More complex and resource-intensive to conduct. Requires expertise in both process-based and IO-based methods. Potential issues with double-counting

Hybrid methods aims to combine both IOA and LCA's strength, offering the comprehensive economic scope of IOA with the detailed product-specific analysis of LCA. By leveraging the strengths of both IOA and LCA, hybrid methods provide a more complete picture of environmental impacts. On one hand, hybrid models can disaggregate broad economic sectors into more specific categories, enhancing the precision of impact assessments. On the other hand, by incorporating broader economic data from IOA, hybrid methods can fill the gaps left by LCA's truncation issues, providing a more holistic view of environmental impacts. Notable limitations of hybrids methods are the complexity of such approaches, as well as potential issues with remaining truncations (Agez et al., 2021) and double-counting (Agez et al., 2020).

One notable limitation of IOA is its focus on the pre-consumer stages of a product's life cycle, leaving subsequent stages beyond its analytical boundary. Additionally, the data underpinning IO-based LCI often predates that of process-based approaches, owing to the extended timeline required to publish IO tables from industry surveys (Suh and Huppes, 2005).

Hybrid LCA seeks to overcome the constraints of sector-specific data scarcity and the temporal lag in IO table publication, merging process-based and IO-based LCA frameworks into a cohesive model. This model captures the microstructure of product systems alongside the macroeconomic environment, effectively bridging the gap between detailed process interdependencies and the broader economic interactions.

Reconciling LCA and IOA computational structure

Both LCA and IOA share a common mathematical foundation in linear algebra that facilitates the development of hybrid models combining the detailed process analysis of LCA with the economic breadth of IOA. Heijungs et al. (2022) outlines how both process-based LCA and IO-based LCA use matrix computations to assess environmental impacts, but they apply different foundational matrices due to their distinct approaches to modelling the economy and environmental interactions.

Table 2.7 provides a comparison between the different elements of both LCA and IOA already presented respectively in Table 2.1 and Table 2.4.

Table 2.7: Comparison between LCA and IOA frameworks adapted from Heijungs and Suh (2002)

Element	Description for LCA	Element	Description for IOA
A (technology matrix)	Commodity x process matrix (usually not square), representing direct inputs required for one unit of output in each process. Inputs are < 0, outputs are > 0	A (technical coefficient matrix)	Square matrix, (industry x industry or product x product), representing direct inputs required per unit of output. Only positive signs.
B (intervention matrix)	Matrix linking processes to emissions or resource extractions, quantifying environmental interventions per unit of process output.	B (satellite matrix)	Accounts for environmental or social externalities not priced in the market, linked to economic sectors, quantifying interventions per unit of economic activity.
f (functional unit)	Vector of final demand ($n \times 1$), defining the scope of the product system under study in terms of the output function.	y (final demand)	Vector of final consumption by households, government, and exports, driving the demand for industry outputs.
$A^{-1}f$ (life cycle inventory)	Calculation of total inputs and emissions across the life cycle for a given functional unit, based on the technology matrix inverse.	x (total production)	Vector of total output by each sector needed to meet final demand, calculated using the Leontief inverse.
A^{-1}	Technology matrix inverse, used to calculate direct and indirect inputs per unit of process output.	$(I - A)^{-1}$	Leontief inverse, the matrix used to calculate total (direct and indirect) inputs required per unit of final demand.

A notable analogy exists between LCA's technology matrix and IOA's transaction matrix (Heijungs and Suh, 2002). In LCA, the technology matrix aligns commodities (rows) with processes (columns). It details the inputs and outputs for each process in terms of product flows like fuel or electricity. This matrix captures both inputs and outputs, with outputs distinguished by negative signs. Conversely, the transaction matrix in IOA records the inputs in terms of outputs from other processes. This matrix is process-oriented, with each column representing a process's inputs only, simplifying the outputs as a single aggregated output per process. A key difference lies in the structural configuration of the matrices: the square nature of the A matrix in IOA eliminates the need for further allocation steps required in LCA to convert a rectangular matrix into a square one. Also, the A matrix in LCA does not deal with annual transaction records, and is more focused on physical flows (Suh, 2004).

Furthermore, the Leontief inverse in IOA and the inverse of the technology matrix in LCA serve analogous roles but offer different perspectives: the former provides an economy-wide view, while the latter focuses on specific product supply chains. The concept of the functional unit in LCA is akin to the final demand vector in IOA, where the LCA's functional unit is represented as a zero vector except at one position, signifying the product of interest. Similarly, the LCI in LCA parallels the total production vector in IOA.

Typologies of hybrid methods

Despite being used for several decades, there is lack of consistent terminology to describe hybrid LCI methods which complicates the understanding of these methods and their applicability in life-cycle studies. Conventional terms like 'process-based' and 'input-output-based' to define hybrid methods can be misleading, as they are not precise enough to fully capture the essence of the hybridisation method employed.

Suh and Huppes (2005) provides a comprehensive comparison of different hybrid LCI methods including tiered hybrid analysis, IO-based hybrid analysis, and integrated hybrid analysis. Crawford et al. (2018) proposes an updated typology by placing them in the spectrum between process-based and IO-based which are seen as two extremes in hybrid methods. Figure 2.6 proposes a visualisation of the four described methods. Table 2.8 summarises the key elements of each technique displayed in Figure 2.6, along with their advantages and disadvantages. Crawford et al. (2018) points a lack of clarity in how hybrid methods are described in studies, making them hard to reproduce. Additionally, there is a general lack of awareness about the potential benefits of using hybrid methods over conventional approaches. The lack of tools or software for hybrid LCI methods poses additional barriers for non specialists.

Capital formation in IOA and LCA

Capital goods are goods used during the production of goods and services that outlives the production process, such as factories, machineries or buildings. They play a pivotal role in production processes and significantly impact the environment. In national accounts, the treatment of capital goods involves key concepts like Gross Fixed Capital Formation (GFCF), Consumption of Fixed Capital (CFC), and Gross Capital Stock (GCS). GFCF refers to the value of a producer's new acquisitions of fixed assets, CFC represents the value reduction in fixed assets used in production, and GCS indicates the value of all fixed assets still in use at current prices, regardless of the assets' age (Eurostat, 2008). In short, the GFCF contains the new additions to the capital stock that will be used in the production of future goods and services, while the CFC describes the depreciation of the capital stock

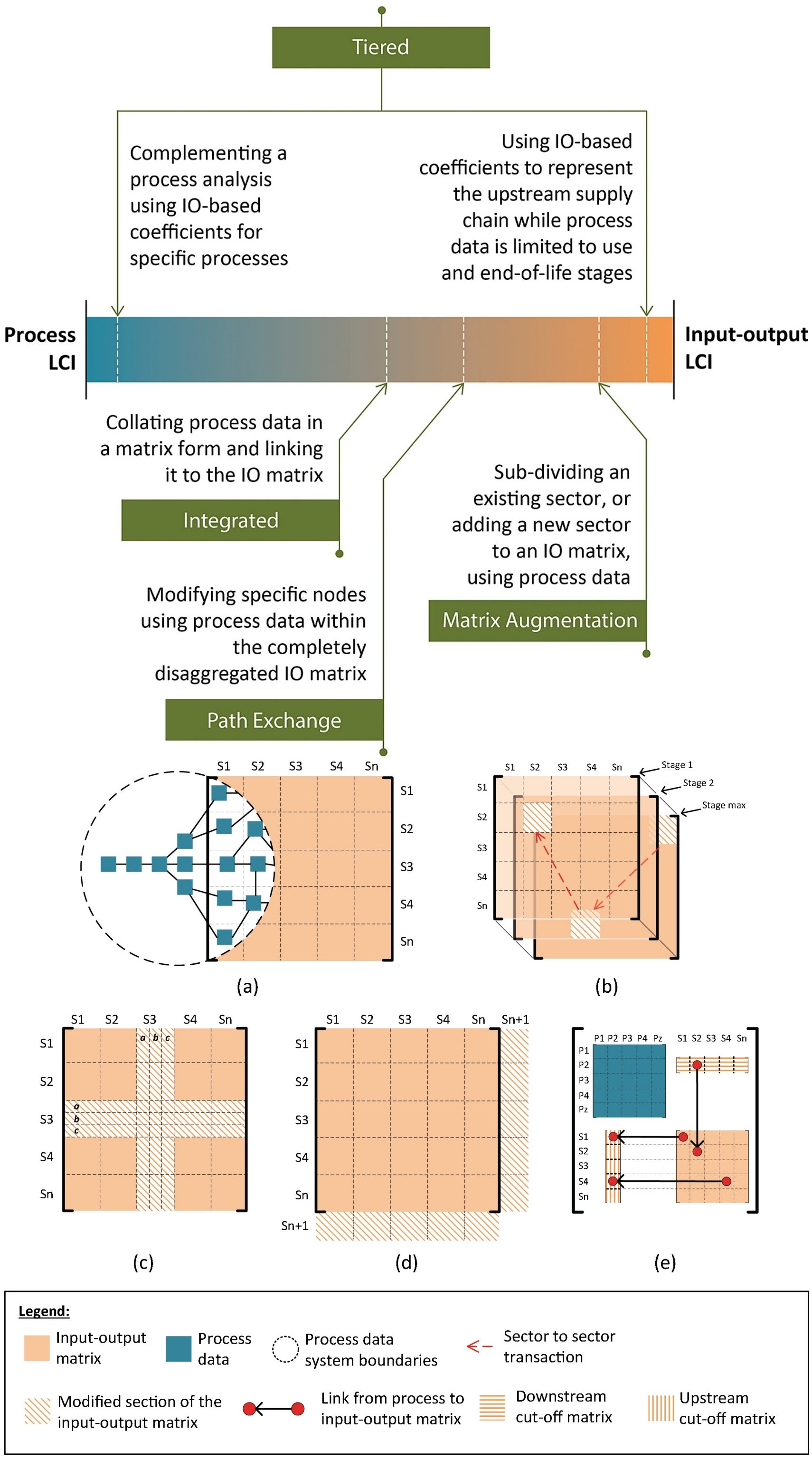


Figure 2.6: Hybrid LCI methods from Crawford et al. (2018)
. Notations: (a) Tiered, (b) Path Exchange, (c) Matrix Augmentation - sector disaggregation, (d) Matrix augmentation - new sector, (e) Integrated

Table 2.8: Summary of hybrid LCI methods described in Crawford et al. (2018)

Method	Description	Pros	Cons
Tiered Hybrid	Integrates process and input-output data, using process data for specific analyses and input-output data for broader economic impacts.	Flexible system boundaries, reduces truncation error.	Potential for double counting, subjective boundary definitions.
Path Exchange Hybrid	Disaggregates the input-output matrix for customisation of the supply chain, modifying specific nodes with process data.	Enables detailed supply chain customisation.	Complex and time-consuming.
Matrix Augmentation	Modifies the input-output matrix by adding new sectors or disaggregating existing ones for specific product/service analysis.	Resolves aggregation error, precise assessment.	Potential reverberation issues, assumes similar output structure for new sectors.
Integrated Hybrid	Combines process and input-output data within a single matrix, linking detailed process data with broader economic sectors.	Comprehensive analysis, detailed integration.	Computational complexity, potential for double counting.

currently in use (Agez et al., 2021). In national accounts, both CFC and GFCF are aggregated by product type without stating the destination sector, and the statistics about which sectors use which capital stock is inexistent.

Capital goods play a crucial role in production processes and have significant environmental impacts. In 2015, GFCF was comparable to the direct emissions from industry globally (Hertwich and Wood, 2018) and is a more important final-demand category driver of emissions than household and government consumption (Hertwich, 2021). In the context of a transition towards more renewables integration, which are known to be more capital intensive (Hertwich et al., 2015), the integration of capital formation and its dynamics in prospective environmental assessments is particularly important (Andrieu et al., 2023).

Yet, the environmental impacts of capital goods, which often last several years, are accounted for differently in IOA and LCA. In process-based LCA, capital inputs are included within unit process inventories, with their impacts allocated over the total output they help produce during their lifetime. In contrast, IOA treats capital goods separately from the manufacture of products/services. Indeed, the GFCF is reported in a separate final demand category, while the CFC is reported in the value added matrix. Consequently, even though capital goods are essential to production processes akin to intermediate goods, they are not allocated to the products/services using these capital goods (Agez et al., 2021). This discrepancy may lead to underestimations of impacts in the footprint calculations of products involved in supply chains heavily reliant on significant capital goods (Steubing and de Koning, 2021). This allocation also contrasts with a life-cycle perspective, wherein the impacts of production are encompassed within the final footprint of the sector or products (Södersten et al., 2018a).

Recent developments in MRIOA have addressed this by endogenising (e.g. integrating) capital transactions in the Exiobase database (Södersten et al., 2018a). This approach allocates emissions from capital goods to final consumption, revealing that incorporating capital goods significantly increases the carbon footprint of final consumption, as seen in several countries, and amplifies current patterns of bilaterally traded emissions (Södersten et al., 2018b). In practice, the endogenisation of capital goods lies in the integration of a capital matrix (K) alongside the traditional transaction matrix (A), linking capital formation emissions directly to production. Environmental impacts due to capital formation are thus connected to the production of products in IO by adding A and K.

2.2 Life-cycle modelling of building stocks

This section delves into building stock modelling techniques with an emphasis on bottom-up methodologies. It examines the challenges involved in accurately representing buildings across diverse scales and outlines approaches for linking these approaches with the previously described environmental assessment methods in order to calculate both operational and embodied impacts. Additionally, it discusses the significance of spatial and temporal dynamics within the context of the life-cycle modelling of building stocks.

2.2.1 Introduction

Building Stock Models (BSMs) provide a method for evaluating the environmental impacts associated with building inventories. They also facilitate the identification of opportunities for mitigation by considering the demands for energy and materials alongside technological solutions at the stock level (Nägeli et al., 2018). They have emerged as pivotal tools for assessing the environmental impacts of buildings and devising mitigation strategies to understand policy implications (Sandberg et al., 2021). When used in static analysis, the term 'building stock' refers to the existing buildings in the stock at a particular point in time, while flows correspond to the addition (e.g. new construction), modification (e.g. renovation) or removal (e.g. demolition) of buildings within the stock. In dynamic analysis, the building stock encompasses not only the existing buildings but also includes the new construction and renovation flows, as they are accounted in the stock in subsequent years (Lanau et al., 2019).

Comprehensive reviews, such as Mastrucci et al. (2017) and Röck et al. (2021), have explored BSMs in conjunction with LCA, predominantly focusing on residential buildings at multiple scales. Urban studies, which in addition to building stocks often include mobility, have been reviewed by Lotteau et al. (2015) and Mirabella et al. (2019). In the realm of building stock energy models and Urban Building Energy Models (UBEM), notable recent reviews include Langevin et al. (2020) and Johari et al. (2020). While the number of studies is rising, research is still needed to provide high quality information at large scale (Stephan, 2022).

Mastrucci et al. (2017) delineate three critical components essential for the environmental analysis of building stocks: building stock aggregation, energy modeling, and LCA. Building stock aggregation encompasses the delineation of the buildings or archetypes under study, their categorisation, and the extrapolation of their results. Röck et al. (2021) structure their review around 22 studies, selected for their environmental modeling of building stocks and the examination of spatio-temporal dynamics pertinent to future development. They identify six primary modules integral to this analysis:

1. **Building stock characterisation** involves defining representative buildings or archetypes, and, when necessary, data processing for a building-by-building aggregation approach.
2. **Building stock aggregation** aggregates information from materials and energy modeling, scaling up to the building stock level.
3. **Material modelling** focuses on modeling building components and materials.
4. **Energy modelling** helps to determines the operational energy demand.
5. **Life-cycle impact assessment** quantifies environmental impacts using characterisation factors.
6. **Visualisation and reporting** it enhances understanding and communication of findings.

The next section will focus on building stock characterisation and aggregation, material and energy modelling. It will also address the spatial and temporal dynamics of building stocks, which are particularly important in the context of prospective studies.

2.2.2 Methods for building stock characterisation and aggregation

The process of building stock aggregation emerges as a critical approach for evaluating the environmental impacts of buildings at broader scale, transitioning from the granularity of individual buildings to the broad scope of urban, regional, national and even transnational building stocks. It answers to the question: *how to describe the entire building stock under study?*

This process is generally categorised into top-down and bottom-up approaches. Top-down methods leverage macro-economic or other aggregated statistics for a broad-strokes view of building stocks. Bottom-up approaches delve into the specifics of individual stock components, later extrapolating these detailed analyses to represent larger stocks. They provide a more detailed and localised understanding of energy and material usage (Müller et al., 2014). Within the bottom-up paradigm, two primary methodologies stand out: the archetypes approach and the building-by-building approach. Table 2.9 describes the main characteristics, strengths and limits of both approaches.

The choice of aggregation approach for building stock modelling is significantly influenced by the size of the stock. According to Röck et al. (2021), the archetype approach currently predominates, with larger stocks tending to utilise fewer archetypes relative to the number of buildings. This raises questions about the methods used to define archetypes and whether they are sufficiently detailed to capture the stock's heterogeneity. Building-by-building approaches are typically applied at smaller scales. However, the increasing availability of granular data, such as building geometry data, could

Table 2.9: Comparison of archetype and building-by-building approaches for building stock aggregation

	Archetype approach	Building-by-building approach
Description	Classifies the building stock into a set of representative archetypes based on common characteristics like age, size, and house type.	Analyses either each building individually or a representative sample of them, and aggregates the results to represent the entire stock.
Strengths	• Simplifies the analysis of diverse building stocks. • Facilitates scenario planning and estimation of environmental impacts for large populations. • Minimises data requirement.	• Provides detailed, building-specific insights. • Captures the variability within the stock more accurately. • Enables precise environmental performance assessments.
Limits	• Potential over-simplification. • Might not capture the full diversity and variability of the building stock. • Relies on assumptions for archetype classification.	• Data-intensive and potentially impractical for large stocks. • Challenges in scaling and aggregating results. • Requires extensive databases and can be time-consuming.

facilitate the application of this approach at larger scales. The sample approach described by Swan and Ugursal (2009) also enables to reduce the number of building into consideration by taking a representative sample of the building stock, and latter up-scaling the results to the entire stock. In both the archetype and building-by-building approaches, the balance between capturing heterogeneity and the manageability of conducting LCA calculations is also a critical consideration in determining the number of buildings to include in the analysis.

Johari et al. (2020) highlight three methods for classifying buildings into sub-groups which can be applied for both archetypes and building-by-building approaches:

1. **Deterministic classification** involves categorising buildings based on specific and known parameters. Construction year and building type are the most commonly used characteristics, either individually or in combination, with size and climate characteristics also being crucial factors (Röck et al., 2021).

2. **Probabilistic classification** groups buildings based on energy demand data, which may be more relevant for Urban Building Energy Models (UBEM) rather than comprehensive life-cycle modelling of building stock.

3. **Clustering** employs unsupervised data-mining techniques to reveal hidden structures within datasets. This approach doesn't group buildings into predefined categories but clusters them based on similarities identified by the algorithm.

Deterministic classification, despite its simplicity and widespread use, has been criticised for potentially failing to capture the diversity within a building stock, such as variations in heating systems or key materials. The subjective nature of this classification can introduce bias (Borges et al., 2022), making it a starting point or suitable for broad-scale studies, but less reliable for detailed analysis. Probabilistic classification and clustering offer improved capture of building diversity, with clustering particularly effective at managing multiple variables (Verellen and Allacker, 2020). In the context of renovation policies, clustering has been used to prioritise buildings for energy consumption and/or GHGE reduction. For example, Geyer et al. (2017) developed clusters based on initial and post-renovation potentials to identify high-priority buildings for renovation in Switzerland. Similarly, Verellen (2022) proposed a method to identify clusters of buildings with similar renovation potentials within specific geographical areas (e.g., districts), incorporating both building parameters and occupant behaviours. Lastly, Gomes et al. (2022) tested different clustering algorithms (namely K-Means, K-Medoids and Hierarchical clustering) on a group of 300 buildings. A concise overview of these algorithms, including their advantages and limitations, is presented in Table 2.10. For further insights into these and additional clustering methods, the documentation of *scikit-learn* [7] offers comprehensive descriptions and visualisations of various clustering techniques.

2.2.3 Energy modelling

The objective of the energy modelling phase is to estimate the energy demand of building stocks. The larger scope include energy demand for heating, domestic hot water, cooling, ventilation, lighting and other appliances. The energy demands for these services serve as crucial inputs that would be later derived into operational impacts. Given the detailed level of analysis required, a bottom-up approach to energy modeling is predominantly adopted in LCAs of building stocks (Mastrucci et al., 2017).

Numerous bottom-up energy building models exist and have been classified. Notably the typology defined by Swan and Ugursal (2009) is often used and is presented in Table 2.11. Engineering-based methods are capable of modeling new technologies and energy savings predictions. However, they require detailed input data and rely on assumptions that may not reflect reality, notably concerning occupant behaviors. Statistical techniques can better reflects real condition with available consumption data. They are however limited in modelling the impacts of the introduction of new technologies.

[7] https://scikit-learn.org/stable/modules/clustering.html

Table 2.10: Comparison of K-Means, K-Medoids and Hierarchical Clustering algorithms

Algorithm	Description	Strengths	Limitations
K-Means	Partitions datasets into K clusters by minimising the variance within each cluster.	• Efficient for large datasets. • Easy to implement.	• Requires specifying K. • Sensitive to initial centroids.
K-Medoids	Similar to K-Means but uses actual data points as cluster centers, enhancing robustness to outliers.	• Robust to noise and outliers.	• Computationally more expensive than K-Means. • Still requires specifying K.
Hierarchical	Builds clusters step by step, either by merging smaller clusters into larger ones or splitting larger clusters into smaller ones.	• Does not require specifying K. • Dendrogram provides insightful visual representation.	• Computationally intensive for large datasets. • Sensitive to noise and outliers.

Langevin et al. (2020) introduces a new classification framework for building stock energy models, organised into four main quadrants based on their design approach (top-down or bottom-up) and transparency (black-box or white-box):

1. **Top-down/Black-box (Q1)**: Models in this quadrant use sector-wide historical variables, such as demographics or economic indicators, to estimate building stock energy without detailed end-use energy attribution. They are split into econometric models, which forecast outcomes based on economic indicators, and technological models, which consider technological characteristics of the building stock.

2. **Top-down/White-box (Q2)**: This category includes models that represent physical causality at an aggregate level. An example is system dynamics, which models aggregate-level building and technology stocks and flows with feedback loops.

3. **Bottom-up/Black-box (Q3)**: These models attribute building energy use to specific end-uses based on historical information, assuming model prediction space mirrors the training space. Classical statistical techniques and machine learning fall under this quadrant, offering predictive accuracy from large datasets.

Table 2.11: Typology of bottom-up energy modelling according to Swan and Ugursal (2009)

Approach type	Subtype	Description
Engineering Methods	Distributions	Uses probabilistic models to represent the variability of parameters affecting energy consumption.
	Archetypes	Develops detailed models based on representative building types to estimate energy use.
	Samples	Involves the analysis of detailed energy use data from a sample of buildings to extrapolate findings to a larger population.
Statistical Techniques	Regression Analysis	Uses historical data to establish relationships between dwelling characteristics and energy consumption.
	Conditional Demand Analysis	Focuses on the demand for energy based on the presence and characteristics of specific appliances and systems within homes.
	Neural Networks	Employs machine learning to model complex, non-linear relationships between inputs (e.g., household characteristics) and energy consumption.

4. **Bottom-up/White-box (Q4)**: Encompasses models that simulate the physical relationships of processes at the building or end-use level, including physics-simulation models and agent-based models (ABMs). These models are recognized for their detailed simulation capabilities, supported by advances in computing.

2.2.4 Material inventory of building stocks

The increasing significance of embodied emissions in the whole-life carbon footprint of buildings underscores the necessity for meticulous accounting, modelling, and representing material stocks. Precise material stock modelling is crucial for evaluating environmental impacts of the different building elements and facilitating strategies for urban mining and the circular economy.

The modelling material stock can be approached from two directions: top-down and bottom-up. Top-down approaches offer a broad perspective, aggregating material stocks through the analysis of annual net additions, relying on data related to construction and demolition activities. Conversely, bottom-up approaches dissect the stock in a more granular manner, categorising the stock element by element, and applying Material Intensity Coefficients (MIC) for a detailed analysis of both the quantity and quality of materials involved (Lanau et al., 2019). By coupling MICs with data from

Geographic Information Systems (GIS), it is possible to spatially map material stocks in buildings (Augiseau and Barles, 2017) and have estimates of materials stocks and impacts, even at large scales (e.g. cities, regions, countries). Several studies have developed MICs for buildings and infrastructure in countries (e.g. Haberl et al. (2021) in Austria and Germany), cities (e.g. Kleemann et al. (2017) in Vienna, Augiseau and Kim (2021) in Paris, Mao et al. (2020) in Beijing and Lanau and Liu (2020) in Odense). The emergence of open databases that aggregate this information is a significant advancement in the understanding of material stocks (Heeren and Fishman, 2019).

The quest for applications at finer scales has highlighted the limitations of MICs, particularly their failure to fully capture the diversity and nuances of material stocks. Criticisms have been leveled at MICs for their lack of consideration for the geometric and constructional complexities of buildings, which can introduce significant uncertainties in the outcomes (Stephan and Athanassiadis, 2018). Moreover, for applications such as circular economy and urban mining, MICs fall short in providing the requisite level of detail to accurately identify available materials (Tirado et al., 2021). An emerging solution involves the integration of geometrical data with expert insights to meticulously reconstitute a building's material composition, an approach often described as creating 'material passports' (Lanau et al., 2019). These detailed material profiles, when further associated with environmental impact data, can enable a thorough assessment of environmental impacts. Illustrative of this innovative approach are the efforts in Melbourne, as documented by Stephan and Athanassiadis (2018), where building footprints and assemblies for 48 defined archetypes (characterised by land use, building age, and height) were combined. This methodology was further refined in the 'Nested Phoenix' tool, detailed by Stephan et al. (2022). Similarly, the 'macro component' approach, as implemented in the *Ile-de-France* region by Tirado et al. (2021) exemplifies another practical application. This method decomposes buildings into their primary components—such as floors, walls, roofs, and windows—and calculates the material composition for each based on the archetype's characteristics and supplementary data, including energy performance certificates (EPC). Tirado et al. (2021) defines a 'macro component' as a collective of components and assemblies, allowing for the proportional estimation of each component's quantity within a building. Stephan et al. (2022) discusses 'construction assemblies'—comprising elements like outer walls, roofs, windows, and internal walls—made from various materials, and the 'bill of quantities' or material inventory generated through the integration of construction assemblies with GIS data, offering a more granular and precise perspective on building material stocks. While these advanced approaches offer greater accuracy and detail, they require a significant collection of data, including GIS data, environmental data, and, notably, databases of construction assemblies, which are often compiled on a project basis and are scarce.

2.2.5 Spatial and temporal dimensions

Spatio-temporal dynamics answer the question of *'where and when material stocks cause flows and in what volume'* and *'how much flow will occur'* (Tanikawa et al., 2015). These dynamics are essential for understanding the distribution of building materials over time and across different locations.

Röck et al. (2021) underscore the importance of spatialising results for decision-making. The use of GIS offers a promising avenue for addressing the spatial analysis challenges associated with large-scale LCA by identifying reduction hotspots and support urban planning decisions. Understanding the location of materials, identifying buildings requiring renovation, and pinpointing energy-intensive areas are vital queries that digital models integrated with GIS can address, adding a spatial dimension to environmental assessments (Tanikawa et al., 2015).

The time-related concept of static and dynamic models refers to the approach used to model a system over time, although it can also refer to the accounting of environmental impacts over time in the LCIA (described in Section 2.1.3). Static models provide a snapshot of the state of the system at a specific point in time, or compare the current state with a hypothetical future state. On the other hand, dynamic models consider the evolution of the system over time, using scenarios to project potential changes. Although most of the studies adopt static approaches (Lanau et al., 2019), dynamic models offer a nuanced view of the system's interaction within broader contexts, significantly enhancing our understanding of complex dynamics. They are particularly suitable to assess the effectiveness of mitigation strategies on future environmental impacts (Lanau et al., 2021). Dynamic perspectives are frequently incorporated via dynamic Material Flow Analysis (MFA), which offers a structured evaluation of flows and stock within a defined spatio-temporal system (Brunner and Rechberger, 2004). This method effectively connects stock and flows by considering the removal of materials from stocks at the end of their life-cycle, along with incorporating probability functions for renovation and demolition activities (Müller, 2005). Additionally, it can be aligned with optimisation strategies, such as identifying and prioritising the renovation of the most energy-inefficient houses (Pauliuk et al., 2013a).

Dynamic MFA is further divided between activity-driven approaches and stock-driven approaches. The former relies on exogenous stock-level activities rates (e.g. construction/demolition/renovation rates), mainly from historical data. The second focus on the concept of service-demand provision in which the stock is considered as the drivers of the flows (Augiseau and Barles, 2017). It considers the changing needs and preferences of the population in terms of building size, type and functionality as the main driver of the stock (Lauinger et al., 2021). By analysing the stock-flow-service nexus, it is possible to obtain a more holistic understanding of the building stock role in providing essential services to society (Haberl et al., 2017). It regards the demand for end products not as an end it itself, but as a mean to acquire and maintain a stock in use that fulfils the changing needs for services.

2.3 Summary of methods and their applications to building stocks

This Chapter proposes an in-depth literature review which delineates the current state-of-the-art, identifying both the strengths and gaps within environmental assessment methods, building stock modelling and their integration.

First, this review highlighted several key insights relative to environmental assessment methods:

- **Emission accounting** methods follow well-defined guidelines for production-based accounting (PBA) at national level (e.g. through IPCC guidelines) and for Non-State Actors (e.g. through GHG Protocol, ISO14064/14067/14068). While the literature clearly identifies their strength and weaknesses, alternative approaches like consumption-based accounting (CBA) lack universally accepted guidelines, affecting comparability between countries. Traditional emission accounting methods also often fail to provide detailed insights into cross-sectoral and cross-border activities, limiting their ability to pinpoint supply-chain hotspots.

- **Input-Output Analysis (IOA)**, and in particular its Environmental-Extended Multi-Regional (EE-MRIO) variant is well-suited to identify supply-chain environmental impacts, offering insights into cross-sectoral and international impacts. In the context of the building activities, aggregation issues can be problematic, making it more suitable for macro-scale studies. As a static method, IOA needs to be integrated with prospective tools for forward-looking analysis.
- **Life-Cycle Assessment (LCA)** is a standardised methodology which is widely used in the context of building environmental assessments. Despite its wide application, LCA has notable and well-identified limitations, especially concerning its time dimension, which impacts its utility as an emissions accounting tool. A diverse array of approaches have flourished in the LCA community, facilitated by its integration with prospective and integrated tools and models. This coupling has paved the way for its application in broader macro-scale and prospective studies offering the possibility to expand its scientific and policy relevance.
- **Hybrid-LCA** represents a state-of-the-art solution to couple the strength of IOA and LCA (e.g. completeness and accuracy respectively) while aiming to mitigate their limitations (e.g. aggregation and truncation respectively). However, it remains complex and largely within the purview of experts, with data availability being a significant constraint.
- **Prospective studies** and in particular scenario analysis is sometimes being called a '*very fuzzy multi-field*' (Börjeson et al., 2006), due to its lack of consistency, with no standardisation or guidelines receiving unanimous approval. Despite this, certain scenario typologies provide a framework for understanding the objectives of different scenarios, facilitating clearer aims in prospective studies. The integration of the prospective field, which is diverse and multi-disciplinary, with the industrial ecology community would benefit from increased cohesion to enhance the depth and breadth of forward-looking environmental assessments.

Secondly, the review concentrates on building stock modelling (BSM), a field experiencing significant evolution due to the growing availability of data. This expansion is matched by the development of increasingly sophisticated methods. Moreover, there's a notable trend towards enhanced coupling and integration with the environmental assessment methods outlined earlier. The advancements within this field specifically cover the following areas: :

- **Building stock characterisation and aggregation** leans towards a more data-driven, building-by-building approaches as the number of databases and information of building stock are growing. Yet, the archetype approach still remains predominant.
- **Material inventory** has traditionally relied on Material Intensity Coefficients (MICs) for its execution. However, increasingly advanced methods are emerging, which combine geometrical data with material passports to refine the modelling of building components and equipment further. This approach opens new avenues for enhancing circular economy studies by offer-

ing more detailed insights into stocks and flows, thereby increasing its utility for policymakers and construction industry stakeholders. Nonetheless, the accessibility of detailed construction assemblies data often remains limited to specific projects or locations, hindering broader adoption within the field.

- **Spatial and temporal dynamics** integrate building stock modelling (BSM) techniques and environmental assessment methods, in particular LCA, scenario analysis and Material Flow Analysis. This coupling broadens the range of impacts considered, offering a more holistic view and facilitating forward-looking studies that leverage the precision of BSM approaches.

Table 2.12 provides a summary of the key characteristics of the methods discussed in this chapter. It begins by identifying the actors or disciplines involved in the production and utilisation of these methods, along with the scopes of their application. The table also details the extent of standardisation or available guidelines, reflecting the methods' maturity and the scientific community's consensus on their applicability. Finally, aspects of transparency and data quality are highlighted, shedding light on the potential for integration with other approaches, tools, and methods.

Table 2.12: Summary of environmental assessments and building stock modelling methods

	Actors	Scope	Standardisation / Guidelines	Maturity	Transparency
National emission accounting	Statistical agencies	National, top-down	IPCC guidelines used in the UNFCCC framework for production-based accounting. Non-standardised for other approaches	Well mature and used	Wide availability for production-based accounting, more scattered for consumption-based accounting
NSA's emission accounting	Consultancy firms, non-profit organisations	Cities, companies	Standardised through GHG Protocol and ISO 14064/14067/14068	Well mature and used, although data can be old and non-actualised	Variable
Prospective studies	Governmental agencies, non-profit organisations	From economy-wide or sectoral studies to organisa-tional level	Non-standardised, non widely recognised guidelines	Very diverse, as the field is non-organised	Dependent on the actors
Life-Cycle Assessment (LCA)	Consultancy firms, industrial ecology researchers	From micro to macro scale	Standardised through ISO 14040-044 for attributional and consequential LCA. Non-standardised for other LCA approaches.	Attributional LCA is well mature and used in legislation. Forward-looking LCA approaches are more recents and under development.	Dependent on studies, which can share their underlying data (e.g. life-cycle inventory). Most life-cycle inventory data are not free (e.g. ecoinvent).
Input-Output Analysis (IOA)	Statistical agencies, industrial ecology researchers, economists	National, top-down	Eurostat guidelines are applied for monetary Input-Output Tables. Satellite accounts depend follow well-established guidelines.	Well-mature and used	Dependent on the databases, as they are not always free
Hybrid-LCA	Industrial ecology researchers	From micro to macro scale	Non-standardised	Reserved for LCA/IOA experts	Data availability issues for most regions.
BSM	Building activities researchers	From meso scale to macro scale	Non-standardised	Data-expertise and/or building or architecture expertise required	Dependent on data availability of the specific location studied

3

State of the art of climate change and decarbonisation scenarios

Contents

This chapter presents an in-depth overview of the scenarios underpinning this thesis. Initially, it delves into the evolution of prospective studies, with a particular emphasis on the development of environmental and sustainability scenarios post-1970s. A comprehensive section is dedicated to climate change scenarios, focusing notably on the IPCC scenario families and the IEA's scenarios that are extensively referenced in Chapter 5 and 7. The chapter also reviews literature on building activities, encompassing both global studies and more granular studies. and introduces scenarios specific to the French context, highlighting scenarios from ADEME and RTE which play a crucial role in Chapter 6. For convenience, Table 3.4 summarises these different scenarios, serving as recap and aiding in navigation of the content. Lastly, different framing of decarbonisation solutions used by the scientific community are presented.

3.1 Introduction

The field of future studies, rich in history and methodologies, spans from early visions of ideal societies like Thomas Moore's 'Utopia' to mathematical advancements in statistics that have shaped modern predictive techniques (Bell, 2017). In the post-World War II era, future studies evolved into a distinct discipline. In the United States, Herman Kahn introduced the term 'scenario' in the context of military and strategic planning in the RAND Corporation, further popularised the concept in the social and political arena as the director of the Hudston Institute (Kahn, 1962). In France, Gaston Berger created and popularised the concept of *'prospective'* (Berger, 1964). In the corporate realm, companies like Shell pioneered the use of future studies in strategic planning, in order to analyse decisions and investments in a systemic way along with their long-term implications (Wack, 1985). This practice has since become increasingly prevalent in organisational and company strategy (The Shift Project, 2019a). Notably, the STEEP (Social, Technological, Economic, Environmental, Political) framework, which categorises external macro domains affecting organisations enables to examine factors influencing strategic decision-making.

This period also saw a shift from the 1950s and 1960s' trend stationary to the dynamic crises of the 1970s, which challenged the assumptions of continuous economic growth and predictability. The 1970s witnessed a surge in interest regarding the use of scenario to study the environmental impacts of globalisation. These studies were focused on the exploration of long-term sustainability of natural resources and the impacts of energy use in various environmental indicators such as GHGE (Leontief, 1977). A landmark development was the Club of Rome's World3 model, which used systems dynamics to explore human societal development across five domains: population, agriculture, natural resources, industry, and pollution. The resulting 'Limits to Growth' report (Meadows et al., 1972) outlined twelve scenarios extending to 2100, with most suggesting a pattern of 'overshoot and collapse.' The report posited that stabilising population and industrial capital could prevent such outcomes. A recent comparison of the 30's year update with empirical data have reaffirmed the model's relevance and prescience in understanding global dynamics (Herrington, 2021).

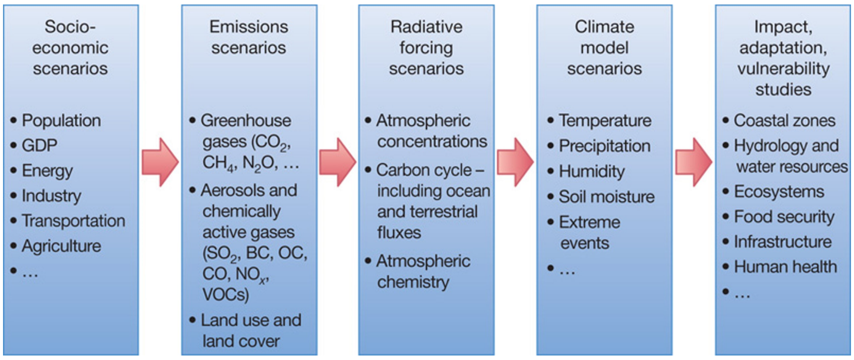
3.2 Panorama of scenarios

3.2.1 Climate change scenarios

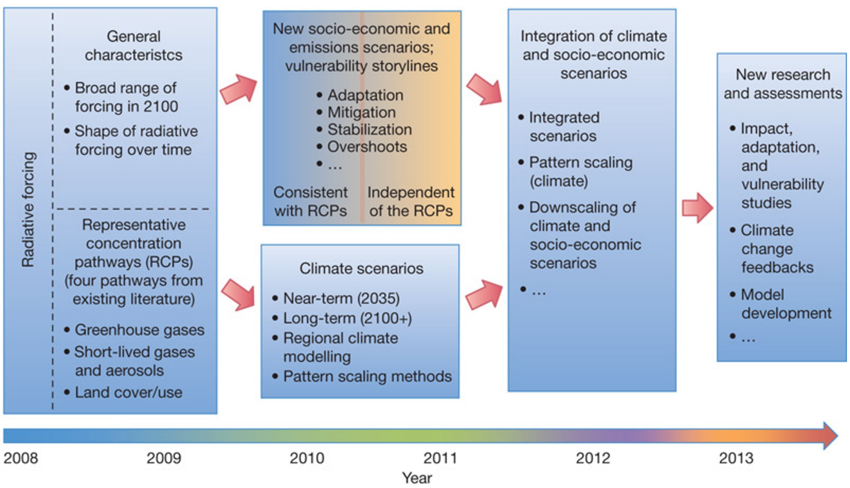
Future scenarios are increasingly vital in strategic decision-making, especially in addressing global environmental challenges like climate change (Swart et al., 2004). When applied in this context, scenarios help to evaluate uncertainties about the response of the Earth system to human substances affecting the radiation balance, the impacts of future climates, and the implications of different mitigation and adaptation policies (Moss et al., 2010). They are essential for comprehending and responding to climate change as they encompass various dimensions, including energy use, land management, socio-economic factors, and institutional aspects (Guivarch et al., 2022). They serve to explore the causal chain from socio-economic developments to energy and land-use to GHGE to changes in atmospheric concentration to changes in global mean temperatures and finally impacts on socio-economic conditions, closing the loop of analysis across different research communities (O'Neill et al., 2020).

In particular, emissions scenarios are descriptions of future substances that affect the planet radiation balance (e.g. GHG and aerosols). In addition to information on land-use, they are an input to climate models, that are the main tools to simulate the physics of the carbon sinks (e.g. atmosphere, land and oceans). Emissions scenarios are produced with Integrated Assessment Models (IAMs) that produce among other things energy and GHGE outputs with inputs such as population growth, GDP and sets of technologies. As every type of scenarios, they are not forecasts or predictions, but exploration of possible evolution of GHGE based on expert judgments and their illustration in IAMS.

Climate change scenarios are closely linked to the Intergovernmental Panel on Climate Change (IPCC), its assessment reports (ARs) and organisation into three Working Groups (WGs) which deals respectively with (1) the physical scientific aspects of the climate system and climate change, (2) the impacts, adaptation strategies, and vulnerabilities associated with climate change and (3) the strategies and policies relative to climate change mitigation and their broader socio-economic and environmental impacts. For this reason, it is important to understand how the scenario framework have evolved over time. Figure 3.1 from Moss et al. (2010) illustrates this change.



(a) Sequential approach



(b) Parallel process

Figure 3.1: The new climate change scenario framework from Moss et al. (2010)

In early assessment reports (ARs), the IPCC commissioned and approved several sets of emissions scenarios produced by a small amounts of models. These model-based scenarios were solely focused on hypothesis on future increases of GHGE. The Special Report on Emission Scenarios (SRES) were later developed, with a more open process. They incorporated socio-economic and energy drivers and featured four scenario families of population, economic growth and greenhouse gas emissions (Intergovernmental Panel on Climate Change, 2000). This so-called 'sequential approach' (illustrated in Figure 3.1a) was however time consuming and did not facilitate a fast integration across scales and disciplines. Moreover, there was interests in the exploration of additional mitigation scenarios, more than the 'no climate' scenarios, as well as overshoot scenarios, where radiation forcing peaks and then targets to reach a target. What's more, the already visible impacts of climate change has increased in interested in climate adaptation, with a need for more detailed spatial and temporal resolution, as well as socioeconomic scenarios that would make possible the assessment of climate vulnerability.

Against these issues and challenges, the scientific community developed a so-called 'parallel process' (illustrated in Figure 3.1b) with a new scenario framework (Moss et al., 2010). This started with the creation of the Representative Concentration Pathways (RCPs), detailing five emissions and atmospheric composition pathways with different radiative forcing levels by 2100 (2.6, 4.5, 6.0 and 8.5W/ m^2) (van Vuuren et al., 2011), which were the central scenarios in AR5. Purposefully, RCPs do not include any socioeconomic narratives. In the same time, the Shared Socio-economic Pathways (SSPs)[1] , five narratives based on a detailed description of future socioeconomic trends, were developed, providing visions of the world where mitigation and adaptation policy range from low to high in the absence of climate policy (O'Neill et al., 2017b). SSP1 ('Sustainability') and SSP5 ('Fossil-fuel Development') are optimistic in terms of human development indicators such as education and health, yet differ a lot in what drives these trends. SSP1 assumes a shift towards sustainable practice while SP5 assumes this development will be fossil-based and energy-intensive. SSP3 ('Regional Rivalry') and SSP4 ('Inequality') are pessimistic in terms of human development with bad ecocomic and social indicators coupled with fast-growing population and increasing inequalities. SPP2 ('Middle of the Road') assumes continuation of historical patterns by the end of the century (Riahi et al., 2017).

The integration of SSPs and their radiative forcing outcomes (e.g. RCPs) form a scenario matrix representing possible integrated scenarios (van Vuuren et al., 2012) (Van Vuuren and Carter, 2014). They are often referred as 'SSP*x*-*y*' where *x* is the SSP scenario (from 1 to 5) and *y* represents the forcing pathway by the end of the century (similar to RCPs). SSPs scenarios are assessed by Integrated Assessment Models (IAMs). Modelers assess baseline scenarios (e.g. without additional policies) as well as mitigation scenarios which explore additional mitigation and adaptation policies. For this, they used Shared Policy Assumptions (SPA) (Kriegler et al., 2014) around how quickly international collaboration on climate policy could occur within each SSP, as well as respecting limitations imposed by the underlying assumptions around population growth, economic activity and technological development in each pathway.

[1]Carbon Brief offers a detailed explanation of SSPs https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/

A large amount of IAMs have quantified SSP scenarios. Six IAMs were chosen and a single 'marker' scenarios were chosen to be used in climate models (O'Neill et al., 2016). Figure 3.2

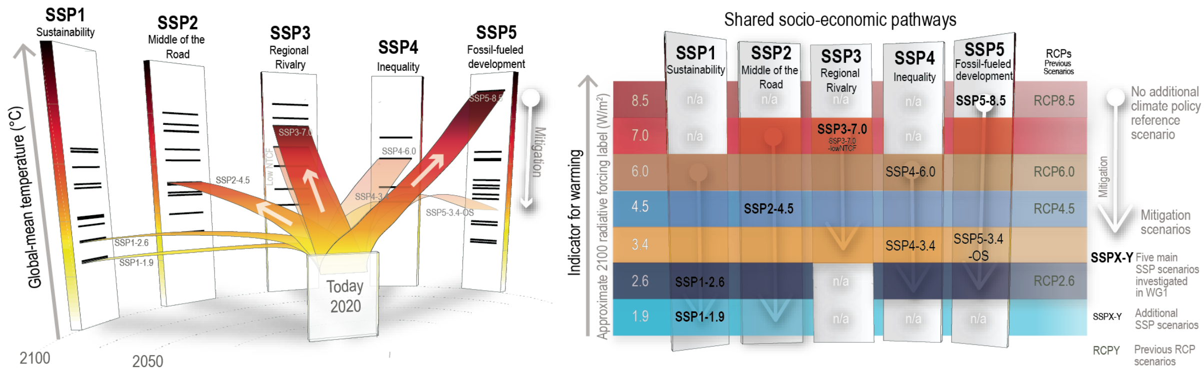


Figure 3.2: The scenario matrix and the SSPx-y chosen in AR6 (Chen et al., 2021)

The matrix at the right of Figure 3.2 shows the SSPs scenarios in the x axis along with their radiative forcing in the y axis. The original RCPs scenarios are shown at the right, and the combination of SSPs and RCPs are present in the matrix, with arrow indicating the possible radiative forcing from a single SSP from baseline to mitigation scenarios (where no solution is found from IAMs, the matrix indicates 'n/a'). Five SSPx-y scenarios are assessed by WGI in climate models represented in the left of Figure 3.2. They were chosen to fill the gaps of RCPs scenarios, notably to provide additionnal 'no policy' scenarios (with SSP3-7.0) and scenario that reach the 1.5°C goal of the Paris Agreement (with SSP1-1.9).

While WGI assesses a selected number of scenario, IAMs can potentially produce thousands of scenarios. For this reason, WGIII also introduced climate categories (C1 to C8) based on projected global warming by the end of the century, with seven Illustrative Pathways (IPs). They are illustrated in Figure 3.3.

Among the Illustrative Pathways (IPs), two reference pathways ('CurPol' and 'ModAct') illustrate high emissions that would arise from current policies and five illustrative mitigation pathways (IMPs) illustrate mitigation policies with different focus, for example renewables (IMP-Ren), carbon dioxide removal (IMD-Neg), low-demand and efficient resource-use (IMP-LD). Other IMPs illustrate the gradual strengthening of current policies in the (IMP-GS) as well as with sustainable development goals (IMP-SD). Carbon Brief proposes an interactive tool that enables to navigate through the different climate categories, illustrative pathways and illustrative mitigation pathways. [2] Additionally, the IPCC scenario database hosted by the International Institute for Applied Systems Analysis (IIASA) compiles a large number of scenarios from different IAMs.

3.2.2 IEA scenarios

Founded in response to the 1973 oil crisis, the IEA was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to help its member countries

[2]Available at https://interactive.carbonbrief.org/one-point-five-pathways/index.html

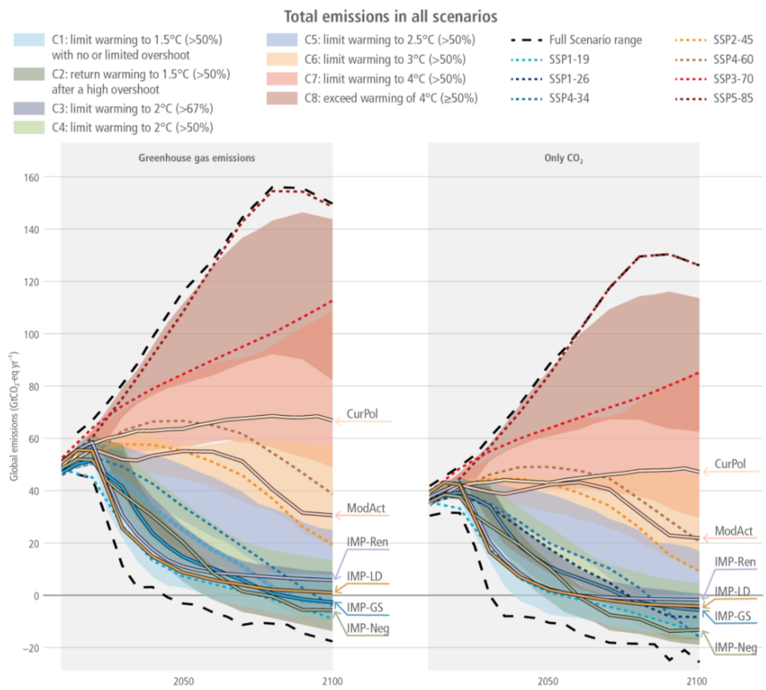


Figure 3.3: Climate categories and illustrative pathways from WGIII (Riahi et al., 2022)

coordinate a collective response to major disruptions in oil supply. Over the years, the IEA's role has expanded beyond oil market analysis to encompass a broader energy mandate, including energy security, economic development and environmental issues. The analysis of decarbonisation scenarios began in 2006 with the ETP Accelerated Technology (ACT) Scenarios, which aimed to mitigate emissions growth by reducing emissions to 2005 levels by 2050. This effort was advanced with the ETP BLUE Map Scenario in 2008, targeting a 50% cut in CO2 emissions by 2050, and was further refined into the 2°C Scenario (2DS).

In terms of modelling capabilities, the IEA introduced the World Energy Model (WEM) in 1993, a comprehensive simulation framework designed to mirror the dynamics of energy markets. A decade on, the Energy Technology Perspectives (ETP) model was introduced. This model, rich in technological detail and employing a bottom-up approach, was developed to complement the WEM. In 2021, both models were integrated in the Global Energy and Climate (GEC) model (IEA, 2023b), now the cornerstone for generating detailed, long-term scenarios on a sectoral and regional basis across IEA publications. The GEC Model synergises the analytical strengths of the WEM and ETP models into a comprehensive bottom-up, partial-optimisation modelling framework. This framework offers deep insights into energy markets, technological trends, policy impacts, and investment requirements crucial for meeting climate objectives. It spans the entire energy system, including demand, transformation, and supply, underpinned by a partial equilibrium approach that enables to calculate sectoral and cross-sectoral energy and emission balances. It traces the flow of primary energy through the supply chain to meet the final service demand by end-users, employing a dynamic, soft-linking method across various supply, transformation, and demand modules.

The IEA's key publications include the World Energy Outlook (WEO) (IEA, 2023c) and Energy Technology Perspectives (ETP) (IEA, 2023a). The WEO is the IEA's flagship publication, released annually to provide analysis and insights into the trends, opportunities, and challenges facing the global energy markets. It examines the future of energy supply and demand based on different policy and technological scenarios, assessing their implications for energy security, environmental outcomes, and economic development. The WEO scenarios are instrumental in understanding potential pathways for the energy sector, influencing policymakers, industry leaders, and financial institutions worldwide. The ETP complements the WEO by focusing on the technology side of energy transitions. It analyses energy technologies and their potential to enhance energy efficiency, reduce emissions, and support sustainable energy systems. The ETP examines various technology-driven scenarios, highlighting innovation gaps and investment needs to achieve global energy and climate goals.

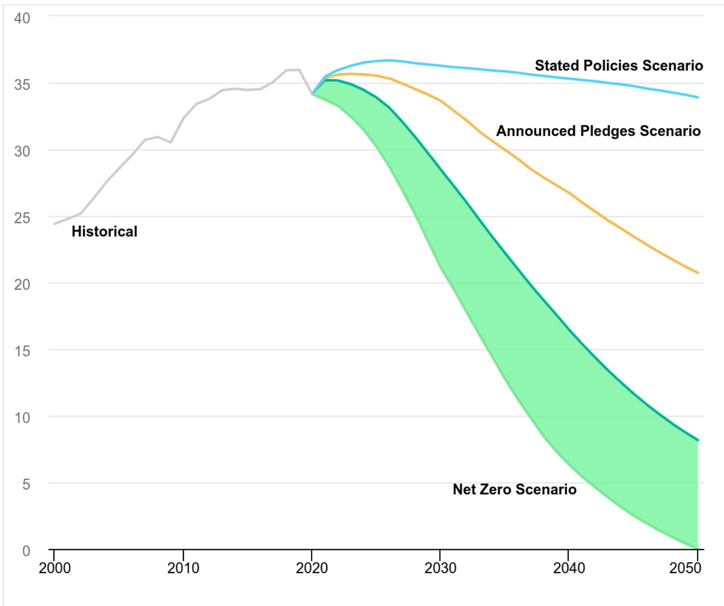
The WEO and ETP, along with their associated reports, delve into the nuances of three main scenarios. Table 3.1 provides a summary of their key objectives, while Figure 3.4 displays their CO_2 emissions and temperature outcomes (computed through the MAGICC climate emulator) by the end of the century.

The Net Zero Emissions by 2050 Scenario (NZE Scenario) is prescriptive, designed with the goal of following an emissions trajectory that keeps the global temperature rise by 2100 under 1.5°C (with a minimum 50% likelihood), aiming for minimal overshoot. This scenario also targets universal access to modern energy services by 2030 and significant improvements in air quality, delineating a roadmap to achieve these objectives. Conversely, the Announced Pledges Scenario (APS) and the Stated Policies Scenario (STEPS) are exploratory. They establish initial conditions based on current policies and targets to observe their future implications, reflecting market dynamics and technological advancements in their energy system models. In addition to these three scenarios, the IEA developed the Sustainable Development Scenario (SDS) to envision a future energy system aligned with global energy-related sustainable development goals, which is not included in the WEO2023.

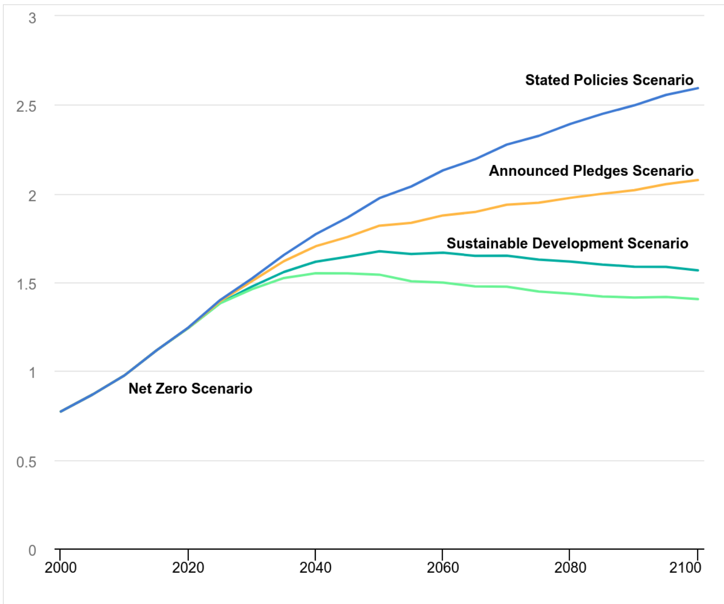
3.2.3 Building activities scenarios

In the IPCC's building chapter (Cabeza et al., 2022), four scenarios based on four models are assessed to project future building sector trends and impacts:

1. **IEA's Net Zero Emission by 2050 Scenario (NZE)**
2. **IEA's Sustainable Development Scenario (SDS)**
3. **IMAGE-Lifestyle-Renewable (LiRE) Scenario**: Based on the SSP2 baseline, this scenario incorporates lifestyle changes to reduce environmental impacts, modeling a shift towards renewable energy adoption. It reaches a RCP 2.6.
4. **Resource Efficiency and Climate Change-Low Energy Demand (RECC-LED) scenario**: Unique for being produced by a bottom-up model, the ODYM-RECC model (Pauliuk et al., 2021), this scenario focuses on the energy and material flows within the residential building stock using a



(a) CO_2 emissions by 2100 in $GtCO_2$



(b) Temperature outcome by 2100 in °C

Figure 3.4: CO_2 emissions and temperature outcomes of the four IEA scenarios

Table 3.1: Comparison of IEA scenarios in the WEO 2023

Aspect	Net Zero Emissions by 2050 Scenario	Announced Pledges Scenario	Stated Policies Scenario
Scenario type	Normative	Exploratory	Exploratory
Definition	A pathway for the global energy sector to achieve net-zero CO2 emissions by 2050, focusing on reductions within the energy sector itself. Ensures universal access to electricity and clean cooking by 2030.	Assumes all climate commitments by governments and industries worldwide as of August 2023, including Nationally Determined Contributions and net zero targets, will be met in full and on time.	Reflects energy-related policies in place or under development as of August 2023, considering planned capacities for clean energy technologies.
Objectives	To delineate the necessary sector-wide actions and timelines for achieving net-zero energy-related CO2 emissions by 2050 and other sustainable development goals, like universal energy access.	To evaluate how current pledges align with the target of limiting global warming to 1.5°C, identifying the ämbition gap"between this scenario and the NZE Scenario, and assessing progress towards universal energy access.	To serve as a benchmark for the impact and limitations of recent energy and climate policies, highlighting the ïmplementation gapnneeded to meet announced decarbonisation targets.

stock-driven approach. It builds on the principles of the Low Energy Demand (LED) scenario (Grubler et al., 2018).

The analysis includes variables such as per *capita* floor area, final energy demand by energy carrier and end-use, and both operational and embodied greenhouse gas emissions (GHGE), with the latter being exclusive to the RECC model. Results are presented by decade for nine geographical regions. The attribution of changes in energy and GHGE is assessed using the Log Mean Divisia Decomposition Analysis (LMDI) method (Ang, 2005) and the Sufficiency-Efficiency-Renewables (SER) framework (Saheb, 2021). The ODYM-RECC model is the only bottom-up model under study. Using it in combination with the SSP1-2 and LED scenarios, Pauliuk et al. (2021) and Fishman et al. (2021) focus on residential buildings with an emphasis on material efficiency strategies,

Apart from the four scenarios assessed in the IPCC's chapter, notable other global studies have focused on material requirements from buildings using SSP scenarios. For example, using the IMAGE's

SSP2 scenario as baseline, Deetman et al. (2020) uses a dynamic stock model and a building material database from Marinova et al. (2020) to study the annual demand for construction materials (e.g. concrete, steel, aluminium, copper, wood and glass) and the availability of waste materials for residential and service sector buildings. Similarly, Le Boulzec et al. (2023) use a stock-flow model in combination with multiple SSPs-RCPs combination, as well as IEA's scenario, that are used to emphasise the energy-material nexus, thus accounting for potential changes in the embodied energy of building infrastructures. These two studies however do not estimate the GHGE from stock and flows. In terms of energy and operational GHGE, Mastrucci et al. (2021) uses the MESSAGEix-Buildings model (Huppmann et al., 2019) to estimate the energy and operational GHGE from space heating and cooling across SSPs1-3.

Due to their large coverage, global studies tend to lack granularity compared to smaller scales studies, especially on the building stock characteristics. The scale of the studies often differ from geographical scales (e.g. continents, countries, cities, portfolio), as well as stock-level activities (e.g. renovation, new construction, demolition) and scopes of emissions (operational, embodied or whole-life) or other environmental impacts considered (Röck et al., 2021). Multiple national scenarios are available for example in the USA (Berrill et al., 2022) (Arehart et al., 2022), Switzerland (Heeren and Hellweg, 2019), Sweden (Österbring et al., 2019) (Peñaloza et al., 2018), Australia (Stephan and Athanassiadis, 2017), Luxembourg (Mastrucci et al., 2020b) and Norway (Pauliuk et al., 2013b).

At EU level, Ramboll et al. (2023) uses building archetypes and stock-level activities to scale up the emission for the entire European building stock. They design three scenarios (BAU, "Tech" and "Life") with the help of the EU Calc tool [3] which provides prospective carbon intensity factors for space heating as well as decarbonisation scenarios for construction materials. With a baseline of 1360 $MtCO_2eq$, among which 79% are operational GHGE and 21% embodied GHGE, the BAU scenario reaches 920 $MtCO_2eq$ while the Tech scenarios reaches 438 $MtCO_2eq$ and the Life scenario reaches 344$MtCO_2eq$ in 2050.

3.2.4 French scenarios

In 2022, in the context of the presidential election and to inform the French Strategy for Energy-Climate and its components (including the SNBC), various governmental agencies, institutions, and NGOs have proposed decarbonisation scenarios with a goal of reaching net-zero emissions by 2050. Among these, ADEME's comprehensive economy-wide scenarios and RTE's focused projections on the electricity sector have emerged as flagship scenarios. Other notable studies include the négaWatt scenario (négawatt and Solagro, 2021) which promotes the Sufficiency-Efficiency-Renewable framework (Saheb, 2021). Their analysis emphasises the demand-side mitigation levers, and integrate detailed resources on the emissions and material footprints of the French economy. Other examples include the work from the Shift Project who crafted a low-carbon plan for the French economy, including detailed resources on the residential sector (The Shift Project, 2021).

When focusing on the building activities, the need for a massive renovation wave is well documented in every scenarios that achieve carbon neutrality by 2050 (ADEME et al., 2022). Nonetheless, be-

[3] Available at http://tool.european-calculator.eu/intro

cause of their reliance on the national GHGE inventory format, they do not represent building activities in a holistic way and mostly focus on direct operational emissions. Scenarios that aim to fulfill the SNBC's goals envision that buildings exclusively uses low-carbon energy carriers. For individual buildings, the primary focus is on heat pumps, with limited use of biomass due to resource constraints. Collective dwellings are expected to connect to renewable energy-powered district heating systems where feasible, or use heat pumps otherwise. In the SNBC scenario, it is anticipated that 85% of new dwellings will switch to electricity, with the remaining 15% adopting biomass or district heating. For existing dwellings, the projected shift is 80% towards electricity and 20% towards a combination of biomass, district heating, and gas (DGEC, 2021).

ADEME scenarios

ADEME's 'Transitions 2050' presents four consistent scenarios offering a path to achieve a state of net-zero emissions by 2050 e.g. *Frugal generation (S1)*, *Regional cooperation (S2)*, *Green technologies (S3)*, *Restoration gamble (S4)* (ADEME, 2021a). Although based on the same macroeconomic, demographic and climate change scenarios, they differentiate themselves by the emphasis they make on the different levers among sufficiency, efficiency, decarbonisation and carbon sinks to reach a state of net-zero by 2050 (Gaspard et al., 2023). In addition to the main report, 17 supplementary reports have been developed to explore various sector-specific or detailed environmental, social, and economic considerations. Notably, one report is dedicated to new construction (ADEME, 2022), with a special focus on S2 and S3 scenarios. Further enriching this comprehensive analysis, an updated synthesis (ADEME, 2024a) and executive summary (ADEME, 2024b) have been released in March 2024.

The four scenarios were designed through a process that combined narratives with quantitative analysis across various economic and social sectors with the use of sectoral models. In summary the key features of each scenarios are the following:

1. **S1**: significant societal changes lead to increased sufficiency. Only natural sinks capture the unabated emissions.
2. **S2**: society embarks towards a mix of efficiency and sufficiency.
3. **S3**: society puts its faith in technological progress to answer environmental challenges, without significant changes in the way of life.
4. **S4**: society gambles on technological progress, heavily relying on carbon capture and storage and negative emissions.

These scenarios present a diverse range of approaches to technological advancement and societal transformation, both recognised as significant challenges. Given the substantial socio-technical changes required across all scenarios, ADEME emphasises the critical need for immediate action. Figure 3.5 depicts the four distinct scenarios, providing key insights into how each scenario envisions changes in lifestyles (food consumption, housing, mobility), macro economics, technical and industrial metrics. The scenarios comprehensively cover sectors including construction, transporta-

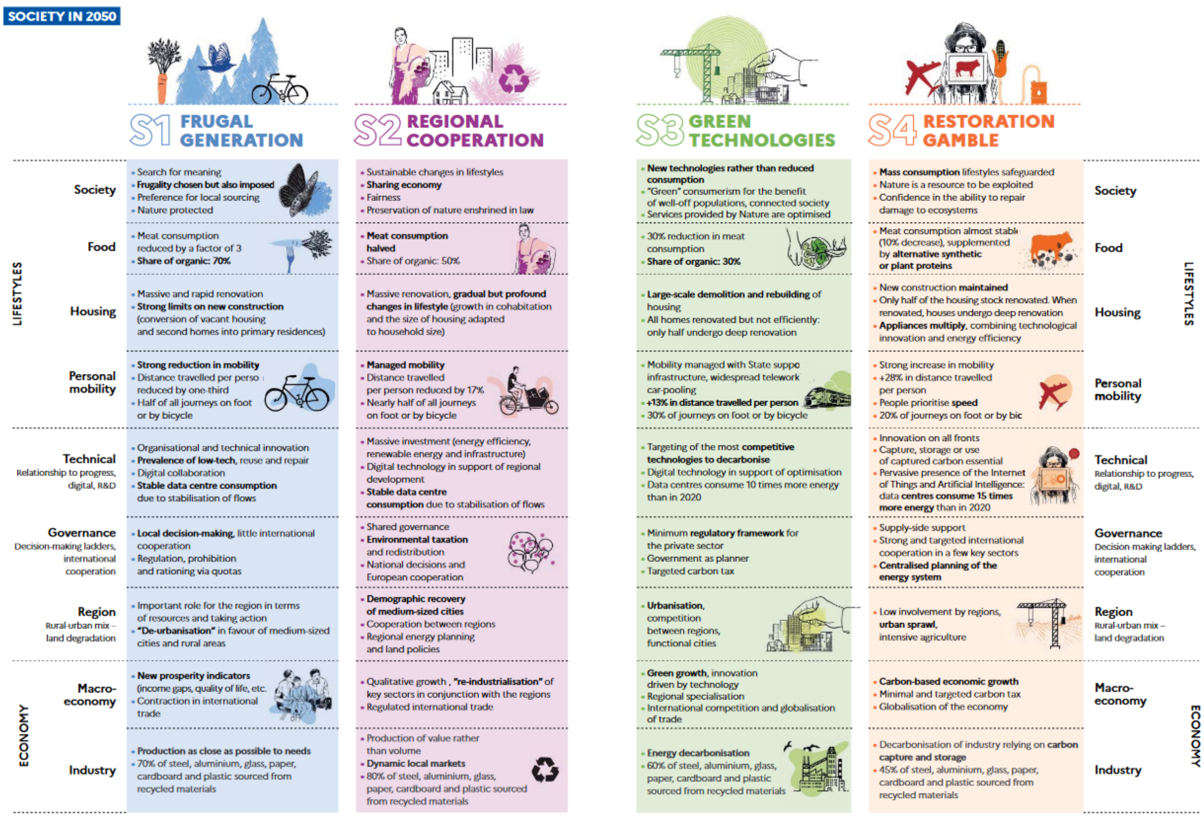


Figure 3.5: The four ADEME's 'Transition(s) 2050' scenarios (ADEME, 2021a)

tion (passenger and freight), food, agriculture, forestry, industry, waste management, and energy services (fossil fuels, bio-energy, gas, hydrogen, heat, and electricity). Key parameters studied include energy demand, water consumption for irrigation, building materials, agricultural inputs, land use, waste generation and management, energy production, energy mix composition, imports and exports, and the balance of greenhouse gases and carbon sinks.

While the variables in the different scenarios show considerable variations, a consistent theme across all scenarios is the reduction of energy demand, which ranges from 23% to 55% compared to 2015 levels, and the substantial increase in renewable energy penetration, accounting for 70% to 88% of the gross final energy demand. Table 3.2 outlines the key features of each scenarios, providing a clear comparison of their distinct characteristics with a focus on the variables relevant to the building activities.

In addition, to these key features, the full report details the following metrics for the four scenarios:

- Number of main residence per type of heating generator (by decade)
- Energy consumption by usage and energy carrier for residential and tertiary buildings (by decade)
- Energy consumption of seven industries for fulfilling the building needs (in 2050)
- Energy consumption of construction works (by decade)

Table 3.2: ADEME's scenarios main features and distinctions relative to building activities

Scenario name	Residential stock dynamics	Energy consumption and GHGE in 2050	Material consumption in Mt (2015-2050)
S1	• 111,000 new dwellings/year, 64,000 demolished dwellings/year (2015-2050 average) • 100% of 2015 dwellings renovated in 2050 (79% BBC)	• 228 TWh (residential), 146 TWh (tertiary) • 3.3 $MtCO_2eq$ (residential & tertiary, scope 1&2) • 4.2 MtCO2eq sequestred in wood products	• 525 (new construction, residential), 122 (new construction, tertiary) • 74 (BBC renovation, residential)
S2	• 149,000 new dwellings/year, 91,000 demolished dwellings/year (2015-2050 average) • 100% of 2015 dwellings renovated in 2050 (81% BBC)	• 247 TWh (residential), 149 TWh (tertiary) • 3.7 $MtCO_2eq$ (residential & tertiary, scope 1&2) • 4.8 MtCO2eq sequestred in wood products	• 671 (new construction, residential), 114 (new construction, tertiary) • 75 (BBC renovation, residential)
S3	• 348,000 new dwellings/year, 169,000 demolished dwellings/year (2015-2050 average) • 99% of 2015 dwellings renovated in 2050 (22% BBC)	• 312 TWh (residential), 207 TWh (tertiary) • 3.9 $MtCO_2eq$ (residential & tertiary, scope 1&2), 3.5 MtCO2eq sequestred in wood products	• 1,289 (new construction, residential), 131 (new construction, tertiary) • 18 (BBC renovation, residential)
S4	• 282,000 new dwellings/year, 91,000 demolished dwellings/year (2015-2050 average) • 99% of 2015 dwellings renovated in 2050 (41% BBC)	• 356 TWh (residential), 254 TWh (tertiary) • 17.1 $MtCO_2eq$ (residential & tertiary, scope 1&2) • 3.4 MtCO2eq sequestred in wood products	• 1,144 (new construction, residential), 160 (new construction, tertiary) • 32 (BBC renovation, residential)

- Consumption of 21 types of materials for new construction and BBC renovation (cumulated 2015-2050)
- Waste production by stock-level activities (in 2050).

Lastly, a data portal [4] enables to download these key metrics.

RTE scenarios

Taking a focus on the electricity sector, RTE's 'Futurs Énergétiques 2050' provides an in-depth exploration of France's potential energy futures, focusing on the transformation of electricity production and consumption (RTE, 2021). The study introduces three primary consumption trajectories: one follow the SNBC hypothesis, a trajectory emphasising enhanced sufficiency adoption measures, and another is centered on profound re-industrialisation. These are further expanded with four variants examining the impacts of varying degrees of electrification, energy efficiency, and the generation of decarbonised hydrogen. The baseline electricity consumption reaches 645 TWh in 2050 (against 530 TWh in 2019), with a range extending from 555 TWh in scenarios prioritising sufficiency, to as high as 754 TWh in scenarios heavily reliant on hydrogen (RTE, 2022a). In terms of electricity production, the study evaluates six distinct scenarios, each reflecting varying degrees of dependency on nuclear power, alongside similar projections for hydropower, marine, and bio-energies. Despite the apparent contrasts between these production patterns, scenarios focusing mainly or solely on renewable ("M" scenarios) and those proposing a diverse mix of renewable and new nuclear reactors ("N" scenarios), the study highlights their similarities, notably their high share of renewable energy and the predominance of investments costs over operating costs (RTE, 2022c).

The study underscores that all scenarios necessitate re imagining a power system vastly different from today's. Whether completely renewable or a combination of renewables and nuclear, the future system will operate on principles distinct from those France has known for the past three decades. This transformation will be propelled by technological advancements reducing unit consumption, proactive public policies like building renovations, and the electrification of various end-uses, thereby enhancing overall energy efficiency. Furthermore, the anticipated increase in electricity demand, substituting fossil fuel energy, requires the French power system to be capable of accommodating this surge, even with substantial gains in energy efficiency and sufficiency. Maintaining a sizeable nuclear fleet would contribute significantly to decarbonisation but alone is insufficient for achieving carbon neutrality. Consequently, the development of considerable renewable energy capacity is deemed essential, irrespective of the scenario. The study also points out that achieving a 100% renewable energy scenario would necessitate broad acceptance of renewable energies and a rapid increase in their development. It emphasizes the importance of starting now to adapt the power system to potential climate change effects, such as changes in water resources, heat waves, and wind patterns. Despite the life-cycle carbon footprint of infrastructure, electricity in France is projected to remain largely decarbonised, significantly contributing to carbon neutrality by replacing fossil fuel energy. The electrification of end-uses alone is expected to reduce France's emissions by 35% by

[4] https://data-transitions2050.ademe.fr/

2050. The study also notes potential tensions around the supply of certain metals, crucial in the energy transition, and stresses the need for strategic planning in this area.

The scenarios are analysed across four critical dimensions: technical, economic, environmental, and societal. Technically, it examines the entire energy system, incorporating aspects like low-carbon hydrogen production and sector coupling, and aligns with IPCC's RCP scenarios while considering climate resilience. Economically, the study compares the comprehensive costs of various scenarios, factoring in all components of the electrical system. Environmentally, it extends beyond greenhouse gas emissions to address broader impacts such as mineral resource consumption, land use, and air pollution. Societally, the study explores the effects of these energy scenarios on French lifestyles, focusing on their acceptability, energy sufficiency, and the need for flexibility.

Table 3.3 summarises the main philosophy and metrics from the six production scenario, with GHGE referring to the baseline scenario.

An interactive website [5] enables to navigate through the different production and consumption scenarios, as well as the main results (production capacity, energy production, costs, GHGE, resource consumption...).

[5] https://rte-futursenergetiques2050.com

Table 3.3: RTE's scenario main features and metrics

Production scenario	**Key features**	**Share of production technologies and life-cycle GHGE in 2050**
M0	Fast decommissioning of existing nuclear reactors. Maximum deployment rate of RES.	• 100% RES • 12.1 MtCO2eq
M1	Fast and distributed development of RES, in particular solar	• 87% RES / 13% nuclear • 11.4 MtCO2eq
M23	Fast development of all RES, notably large onshore and offshore wind farms. Economic and geographic optimisation to target highest efficiency	• 87% RES / 13% nuclear • 10.4 MtCO2eq
N1	New nuclear reactors program, developed in pairs on existing sites every 5 years starting in 2035. Robust RES development.	• 74% RES / 26% nuclear • 9 MtCO2eq
N2	Launch of a programme calling for the faster development of new reactors (a pair every three years) from 2035 with a gradual ramp-up. RES development continues but at a slower pace.	• 64% RES / 36% nuclear • 9 MtCO2eq
N3	Existing nuclear power plants in service are kept for as long as possible along with fast development of new nuclear (EPR2 and SMR).	• 50% RES / 50% nuclear • 8.4 MtCO2eq

3.3 Framing of decarbonisation solutions

The landscape of decarbonisation solutions in the building sector is diverse and can be categorised through various frameworks. They provide a structured way to address different aspects of GHGE reduction and highlight the importance of considering a range of strategies that address the different stages of buildings life-cycle. Inside each category, specific carbon reduction solutions can then be detailed. Among them the Demand-side/Supply-side (Creutzig et al., 2018) (Creutzig et al., 2021), Sufficiency/Efficiency/Renewable (Saheb, 2021), and Avoid/Improve/Shift (Creutzig et al., 2022) frameworks offer structured approaches to understanding and addressing the complex challenge of reducing GHGE within the building activities supply chain.

The first one distinguishes between two primary strategies for decarbonisation. *Supply-side* measures involve transitioning to low-carbon energy sources and materials while *demand-side* measures focus on reducing energy consumption through building design, technology enhancements as well as behavioral changes. It is well designed for holistic approaches and often used in energy system optimisation models. The second one, inspired by Negawatt's motto (négaWatt, 2022) categorizes solutions based on three approaches. *Sufficiency* emphasizes reducing demand by designing buildings that inherently require less energy. *Efficiency* focuses on optimizing energy use within buildings through improved systems and technologies. *Renewable* advocates for the adoption of low-carbon energy sources. The last one, endorsed by the IPCC (Cabeza et al., 2022), the UNEP (UNEP, 2023) and EU studies (Ramboll et al., 2023), emphasises three key strategies. *Avoid* involves make the best-use of the existing stock in order to avoid production of materials and design buildings with low-energy demand. *Shift* entails transitioning to low-carbon energy sources and materials, reducing both operational and embodied emissions. *Improve* centers on enhancing the energy efficiency of existing buildings through upgrades and retrofits, and improving conventional materials and use them only when necessary. *Avoid* solutions can be limited by social factors, *Shift* solutions are often limited by resource availability and *Improve* solutions are limited by innovation and access to market.

3.4 Summary of scenarios assessed

This Chapter presents an in-depth literature review of comprehensive scenarios from the IPCC and IEA, along with a focus on national scenarios by ADEME and RTE. Table 3.4 summarises the key characteristics of the scenarios discussed in this chapter. It starts by listing the various scenarios from these entities, followed by their geographical scales and specific sectoral focuses. The Table then assesses data availability and quality, and includes links to the relevant data portals for convenience.

Table 3.4: Summary of scenarios assessed in the Chapter

	IPCC	IEA	ADEME	RTE
Key scenarios and/or scenarios frameworks	• SSPx-RCPx • C1-C8 categories • Illustrative Mitigation Pathways (IMPs)	• Stated Policies Scenario (SPS) • Announced Pledges Scenario (APS) • Net Zero Scenario (NZS)	• S1 • S2 • S3 • S4	• M0 • M1 • M23 • N1 • N2 • N3
Geographical scale	World, with different geographical regions depending on models	World, with 15+ geographical regions	France	France
Focus	Climate change and socio-economic projections	Energy and industrial sectors	All macro-economic sectors in the main report, separate focus in 17 dedicated reports	Electricity sector
Data availability and quality	AR6 database offering IAMs input and output data	Free data do not offer full access to datasets	Data portal giving access to variables for specific years (2015 and 2050), by decades or cumulated (2015-2050)	Interactive website offering vast array of data by decades
Data portals	https://data.ene.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces	https://www.iea.org/data-and-statistics/data-sets?filter=scenarios	https://data-transitions2050.ademe.fr/datasets?topics=rdBL564dt8E4m7XCs4sx4	https://rte-futursenergetiques2050.com/

4

Linking state of the art to applied methods

Contents

This chapter serves as a bridge between the state-of-the-art methods for environmental assessment and building stock modelling (Chapter 2) and existing scenarios (Chapter 3) and the subsequent chapters that will present their practical application, justifying their relevance and and their contributions towards achieving the research objectives outlined in Chapter 1. Specifically, it details the application of emissions accounting methods and Input-Output Analysis, along with IEA's scenarios as foundational elements for the analysis in Chapter 5. Furthermore, it discusses how Life-Cycle Assessment and building stock modelling methods, coupled with scenarios specific to the French context and from Integrated Assessment Models, underpin the studies presented respectively in Chapter 6 and Chapter 7.

4.1 Connecting theory to applied methods developed in the doctoral thesis

In the next three chapters, various methods and scenarios respectively presented in Chapter 2 and 3 are combined. They represent the core methodological bone of the doctoral thesis. They are applied to different scopes that are linked to the three research questions outlined in Chapter 1. Table 4.1 illustrates them for the different chapters, along with their precised scopes.

Table 4.1: Summary of the next chapters methodologies

	Chapter 5	Chapter 6	Chapter 7
Objective	Representing the Whole-Life-Carbon of the building activities at national level, Expanding existing sectoral carbon budgets, Creation of an holistic carbon budget	Exploring how residential activities can meet or deviate from the carbon budgets, leveraging stock-level activities dynamics as well as current and future performance levels for both operational and embodied emissions	Exploring the current and future embodied performance of new building typologies through integration of Integrated Assessment Models scenarios, Assessing their comparison with future target values
Scope	Building activities	Residential activities	New residential construction activities
Modelling approach	Top-down	Comparison top-down / bottom-up	Bottom-up
Methods	Input-Output Analysis; Life-Cycle Assessment; Scenario analysis	Building-by-building energy simulation; Demand-driven construction; Bottom-up dynamics; Building LCA; Scenario analysis	Building stock aggregation; Clustering; Association rule mining; Building LCA; Prospective LCA
Scenarios	SNBC; IEA	ADEME; RTE	Integrated Assessment Models scenarios from IMAGE and REMIND

Chapter 5, which focuses on the building activities in their entirety, provides a framework for integrating elements of process-based LCA (through the coupling of energy carriers statistics and life-cycle emission factors) with input-output based LCA (by using the Exiobase database). The objective of this integration is to form a robust and holistic accounting framework at national level that leverages the strengths of both life-cycle inventory approaches, thus addressing system boundaries issues, truncation errors and minimising aggregation error that have been documented in Chapter 2. This methodology adopts a top-down approach, focusing on quantifying emissions in an inventory fashion, rather than using building stock modelling techniques like archetype or building-by-building modelling. Instead, it details all building activities-related emissions and identify hotspots in terms of energy carriers and upstream sectors. To project Whole-Life-Carbon budgets, national scenarios from the Low-Carbon National Strategy (SNBC) and international scenarios from the IEA are used respectively for operational and embodied emissions.

Chapter 6 adopts a bottom-up approach to model several decarbonisation pathways and assess their compatibility with the top-down carbon budgets established in Chapter 5. This requires detailed data to characterise the current building stock, such as energy consumption, energy carriers used, renovation potential, and materiality, which are readily available only for the residential sector through comprehensive databases like the French Building National Database (BDNB). For this reason, this chapter narrows its scope to residential activities compared to the previous one that encompasses all building activities. It proposes a dynamic modelling of the residential building stock from 2020 to 2050. It integrates detailed energy results from the BDNB, derived from a national-level building-by-building energy simulation conducted using a bottom-up engineering-based energy model. These results are aggregated into a matrix that tracks the surface area per energy performance label before and after renovation, detailed by the energy carriers used. This matrix is central to the dynamic modelling of renovations and demolitions, transitioning from a pure building-by-building approach to a hybrid approach where surface areas are tracked based on their potential post-renovation and the ambition of the scenarios regarding the number of renovation and demolition operations per year. For new constructions, the analysis adopts a demand-driven approach, influenced by population growth and per *capita* square meter requirements. The embodied emissions of new constructions, renovations, and demolitions are assessed using statistical analysis from a building LCA database that incorporates process-based Environmental Product Declarations (EPDs). French scenarios from RTE (for electricity), INSEE (for population), and ADEME (for various variables, including gas and district heating networks).

Chapter 7 applies a prospective LCA methodology to a national building LCA database to evaluate how the future embodied performance of various building typologies might align with future target values established in Chapter 6. This analysis specifically focuses on new residential buildings, given that comprehensive databases are currently available predominantly for new construction. Initially, the chapter details a method to select archetype buildings that are representative in terms of geometry and materiality characteristics. This method leverages building stock characterisation methods described in Chapter 2, traditionally used in building stock databases, and adapts them for use in a building LCA database. The process begins with a stratification approach based on building type and main structural material. It then employs association rule mining and clustering to refine the selection of representative typologies. Subsequently, three distinct building typologies of individual housing are characterized using prospective LCA methods. This includes the use of the *premise* package to incorporate scenarios from two Integrated Assessment Models, enhancing the analysis with forward-looking environmental impact assessments.

To sum up, Figure 4.1 provides a visual representation of the scopes of the different Chapters, e.g. from all building activities to new residential construction buildings, as well as their main methodological approach, from top-down to bottom-up.

Figure 4.1: Visual representation of the scope and methodological approaches developed in Chapters 5, 6 and 7

5

Integrating consumption-based metrics into sectoral carbon budgets to enhance sustainability monitoring of building activities

Contents

This chapter introduces the first journal article of the PhD thesis. The paper has been published in 'Sustainability' and can be found at https://doi.org/10.3390/su16166762. It is reproduced here as it is, while formatting might change. Please refer to Appendix 9.4 for the Supporting Information accompanying this publication.

CONTRIBUTIONS

- **Marin Pellan** - Conceptualisation, Data analysis, Formal analysis, Investigation, Methodology, Writing - original draft
- **Denise Almeida** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Mathilde Louërat** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Guillaume Habert** - Conceptualisation, Supervision, Validation, Writing - review & editing

5.1 Highlights

- New methodology to represent WLC at national level.
- In 2019, French building stock emits 162MtCO_2eq: 64% operational emissions, 20% abroad.
- WLC budgets merge 2019 data with 2050 national targets and global scenarios.
- By 2040, embodied emissions might be the predominant scope.
- Climate policies need to address broader emissions for buildings.

5.2 Abstract

Climate policies such as sectoral carbon budgets use national greenhouse gases emissions inventories to track the decarbonisation of sectors. While they provide an important compass to guide climate action, the accounting framework in which they are embedded lack flexibility for activities that are international and at the crossroads of different sectors. The building activities, as being largely linked with important upstream emitters such as energy production or industrial activities, which can take place outside of national borders, are such an example. As legislation increasingly addresses the whole life carbon emissions of buildings, it is vital to develop cross-sectoral accounting methods that effectively measure and monitor the overall impact of buildings. Such methods are essential for creating sound and holistic decarbonisation pathways that align with sustainability policies. This article aims to provide a consistent approach for depicting the life-cycle emissions of buildings at the national level, using France as a case study. By integrating the different emission scopes with decarbonisation pathways, this approach also enables the creation of comprehensive whole-life carbon budgets. Results show that the French building stock footprint reaches 162 MtCO_2eq in 2019, with 64% attributed to operational emissions, primarily from fossil fuel combustion, and the remainder to embodied emissions, mainly from upstream industrial and energy sectors. Overall, 20% of emissions happen outside of national borders. Under various global decarbonisation pathways, the significance of embodied emissions is projected to increase, potentially comprising 78% of life-cycle emissions by 2050 under current policies.This underscores the necessity for climate policies to address emissions beyond territorial and operational boundaries.

Keywords: *climate change; sustainability monitoring; emissions accounting; carbon budgets; climate policies; whole-life carbon; cross-sectoral approach*

5.3 Introduction

Human activities are warming the Earth at an alarming rate that is unprecedented in the last 2000 years. The last decade saw the higher global net anthropogenic greenhouse gases emissions (GHGE) in human history (Dhakal et al., 2022). In order to reduce the risks and impacts of climate change, the next decades are critical in order to pursue the well below 2°C objective of the Paris Agreements (United Nations, 2015). The 1992 Rio Conference is one of the first responses from the international community to address climate change. It marks the creation of the United Nations Framework

Convention on Climate Change (UNFCCC) whose primary objective is to stabilise *"greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"* (UNFCCC, 1992).

5.3.1 GHGE accounting systems

In 1997, the Kyoto Protocol operationalises the UNFCCC by establishing legally binding emissions reduction targets for Annex-I countries. Article 5 also introduces an emission accounting system which includes rules for measuring, reporting, and verifying emissions (UNFCCC, 1998). It follows a production-based accounting (PBA) system which is framed by the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2006). In this framework, GHGE emissions are attributed to the sectors and regions where they physically occur. One of the main limits of a PBA system is that it does not identify the (potentially) increasing imported emissions that are due to globalisation. In parallel, other accounting systems have been developed (Steininger et al., 2015), the most widely used being the consumption-based accounting (CBA) system (Hertwich and Wood, 2018), where impacts are attributed to the region where the final demand occurs and to the sector at the end of the supply chain (Cabernard et al., 2019). As a result, in most developed countries, using a CBA system reveal much larger GHGE and can change the repartition between sectors (Steininger et al., 2018).

Besides, another limitation concerning current accounting methods relates to the sectoral breakdown used in the UNFCCC process. The IPCC guidelines for national greenhouse gas emissions define four main sectors for reporting the GHGE namely (1) energy, (2) industrial processes and product use, (3) agriculture, forestry and other land use (AFOLU), and (4) waste, that can be further subdivided (for example, the energy sector is divided into mobile, stationary, including the emissions from housing heating, and fugitive emissions). In France, the SECTEN format used for the Low-Carbon National Strategy (SNBC) uses a slightly modified breakdown based on seven macroeconomic sectors namely: (a) industry, (b) residential and tertiary, (c) energy, (d) transport, (e) agriculture, (f) waste, (g) land-use, land-use change and forestry (LULUCF) (CITEPA, 2022b).

While they are straightforward for reporting purposes, these classifications do not enable to clearly point out and acknowledge high emitting activities for which emissions are split across different sectors and countries. With 37% of CO_2 emissions worldwide in 2021 (UNEP, 2022), the building and construction activities are such an example. Indeed, in PBA systems, buildings emissions are the ones associated with the combustion of fossil fuels (e.g. for heating, hot water or cooling) in the use stage, as they are the only type of emissions that physically occur within them. In the UNFCCC format, they appear within the Energy sector (under *Other sectors* that differentiates commercial, institutional and residential buildings) while the SECTEN format displays a separate *Residential and tertiary* sector which represents 17,9% of national emissions in 2021 (CITEPA, 2022b) .

5.3.2 Buildings in the need-activities-sectors framework

In building environmental assessments, emissions are analysed using life-cycle assessment (LCA) methods which aim to quantify the environmental impacts through the entire life-cycle of buildings, from the production of building materials to its end-of-life as well as the operation of the buildings. In France, it has been introduced in the new environmental regulation (RE2020) for new buildings, that integrates limit values for embodied and operational carbon emissions (Ministère de la Transition Ecologique, 2021).

If a life-cycle perspective would be transposed to a PBA system, buildings would be associated with emissions from multiple sectors, in particular, the industry sector (e.g. for the production of buildings materials and equipment) and the energy sector (e.g. for electricity and heat production). For this reason, the term *activities* might better suit and has been proposed in recent studies (Habert et al., 2020b) (Lützkendorf, 2021). Figure 5.1 illustrates this framework.

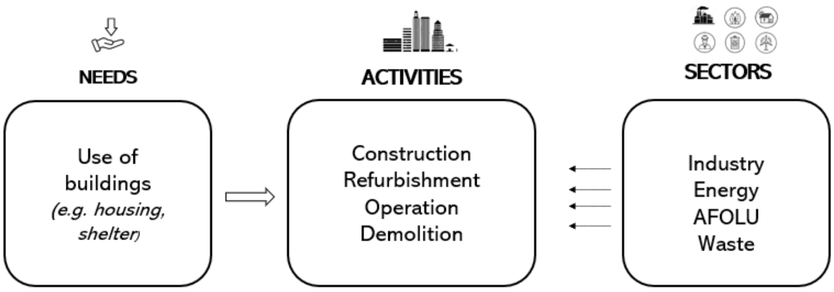


Figure 5.1: The needs-activities-sectors framework, as described by Habert et al. (2020b)

The building *activities* serves the *needs* of housing and shelter and contains multiple *activities* that are involved at different stages of a building life-cycle. To answer to these activities, several *economic sectors* are involved in the supply-chain. This framework acknowledges the significant influence that stakeholders from diverse sectors exert on the emissions associated with building activities. Given the limitations of the narrowly defined 'building' sector in national emission inventories, a comprehensive understanding of emissions and their potential for mitigation is essential.

The footprint of the construction and building activities has been investigated for various environmental impacts and at different geographical scopes. For GHGE, some studies handle global scale (Onat and Kucukvar, 2020) (Huang et al., 2018) (Hertwich and Wood, 2018) (Crawford, 2022) while others focus on national scale, for example in Ireland (Acquaye and Duffy, 2010) (O'Hegarty et al., 2022) in Australia (Yu et al., 2017) in Switzerland, (Frischknecht et al., 2020) and for India, Italy, South Africa and the UK (Pomponi and Stephan, 2021). Nevertheless, it is difficult to compare these results as the scope of what *building* or *construction* means is not homogeneous between studies. Most focus on the footprint of *construction* as an economic sector which includes buildings and infrastructure according to the Statistical Classification of Economic Activities (NACE) (Eurostat, 2008), also referred to as the *built environment*. As such, they target the emissions arising from the construction materials and equipment life-cycle, but omit to integrate emissions from the different energy carriers used during buildings use stage. (O'Hegarty et al., 2022) gather in a single methodology the whole-life carbon (WLC) emissions, but target all the built environment. They propose two methods for embodied GHGE accounting, the *sector summation method*, which uses floor area and average GHGE intensities and the *commodity accounting method*, which relies on various national and international statistics. However, they do not use Input-Output Analysis (IOA) which has been largely used to calculate footprint indicators (Minx et al., 2009) (Wiedmann et al., 2016) and to identify cross-sectoral impacts (Baynes and Wiedmann, 2012), not only for GHGE but also for water, resources or land-use changes. IOA has also played a significant role in quantifying imported emissions, a dimension typically absent from conventional sectoral carbon budgets. This approach offers additional consumption-based metrics that hold particular relevance in the context of construction activities, given the fragmentation of international supply chains for construction materials and equipment (Steininger et al., 2020).

5.3.3 The need for embodied GHGE budget

In recent years, there has been a notable shift in focus towards embodied GHGE which has been rising in relative and absolute terms, especially for new buildings (Röck et al., 2020). While they represent 25% of WLC emissions globally today, their share is expected to reach 49% by 2050 under a BAU scenario (UNEP, 2023). At the EU level, significant efforts have been deployed to represent WLC baselines and embodied GHGE pathway (Röck et al., 2022b). In their efforts to downscale WLC budgets for buildings in Switzerland and Denmark, (Priore et al., 2023) and (Horup et al., 2023) both use results from previous IOA studies to account for the baseline proportion of embodied GHGE and their imported share. However, they do not provide a detailed breakdown of the contributions from specific regions and sectors regarding these embodied emissions. Other studies have undertaken supply-chain decomposition, in particular (Pomponi and Stephan, 2021) and (Crawford, 2022) with the use of Structural Path Analysis (SPA). Nevertheless, they do not project emissions in the future with the combination of international sectoral scenarios.

5.3.4 Contribution of the paper

This article builds upon the need-activities-sectors framework and aims to reconcile the various methods of emissions accounting in order to prepare for appropriate carbon budgets for buildings (Habert et al., 2020b) (Pálenský and Lupíšek, 2019). It intends to clarify the different types of emissions that arise during buildings life-cycle and highlights the most important contributors in terms of energy carriers, upstream sectors and geographical regions. Through the integration of national operational GHGE scenario with scenarios for the decarbonisation of upstream sectors responsible for embodied emissions, this study tends to promote a more comprehensive approach to the decarbonisation of the building activities. Consequently, the goal is to better link climate policies and sectoral legislation and to propose additional consumption-based metrics for national building activities, which can help to reduce GHGE through the supply-chain (Wood et al., 2018a).

It raises two main questions:

- At national level, how to account for the life-cycle emissions of buildings as a cross-sectoral and cross-border activity?
- How to apply suitable decarbonisation pathways to the different scope of emissions identified, in particular embodied GHGE, to complement the coverage of existing sectoral budgets?

5.4 Materials and methods

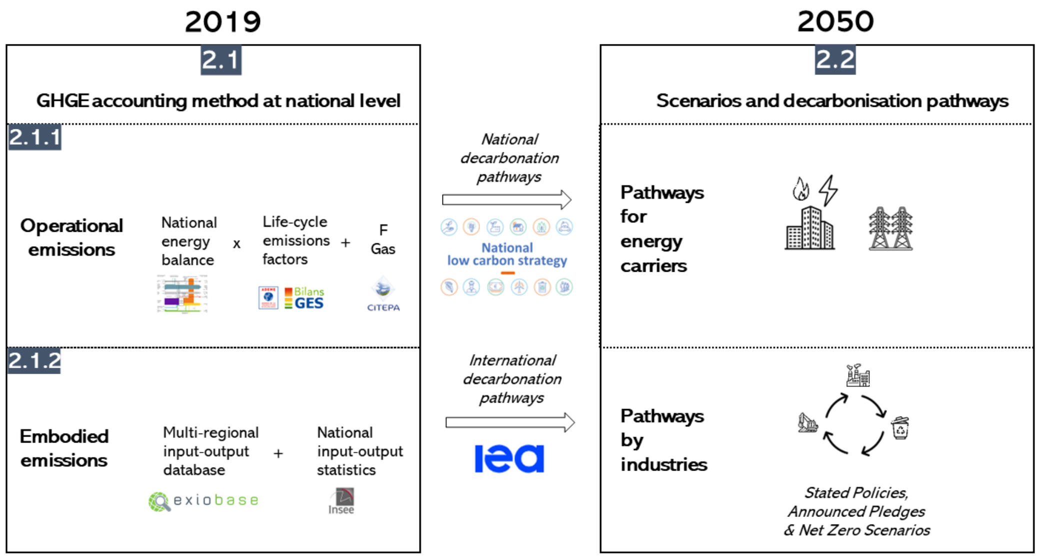
In France, there has been no precise quantification of the full scope of emissions that occur during buildings life-cycle. Yet, France is an interesting case as the Environmental Regulation (RE2020) for new buildings now integrates thresholds for embodied and operational carbon (Ministère de la Transition Ecologique, 2021), while the Law for Ecological Transition and Green Growth (LTECV) (Ministère de la Transition Écologique et Solidaire, 2015b) aims to achieve a level of energy performance in accordance with 'low-energy building' standard for the entire building stock by 2050. A deep understanding and follow-up of buildings GHGE are then essential to link buildings LCA with a more holistic vision at the building stock level. Expanding the scope of emissions considerations in climate policies, e.g. the SNBC, is also needed. This expansion is necessary because the latter focus on operational GHGE and do not explicitly provide pathways and reduction strategies for embodied GHGE, which is a rising concern at planetary (UNEP, 2023) and European level (Ramboll et al., 2023).

In order to answer these issues, the methodology developed in this article consists of two parts, displayed in Figure 5.2a. The system boundary of the study is displayed using the EN-15978 stages in Figure 5.2b, while delineating the life-cycle inventory methods applied for both operational and embodied GHGE.

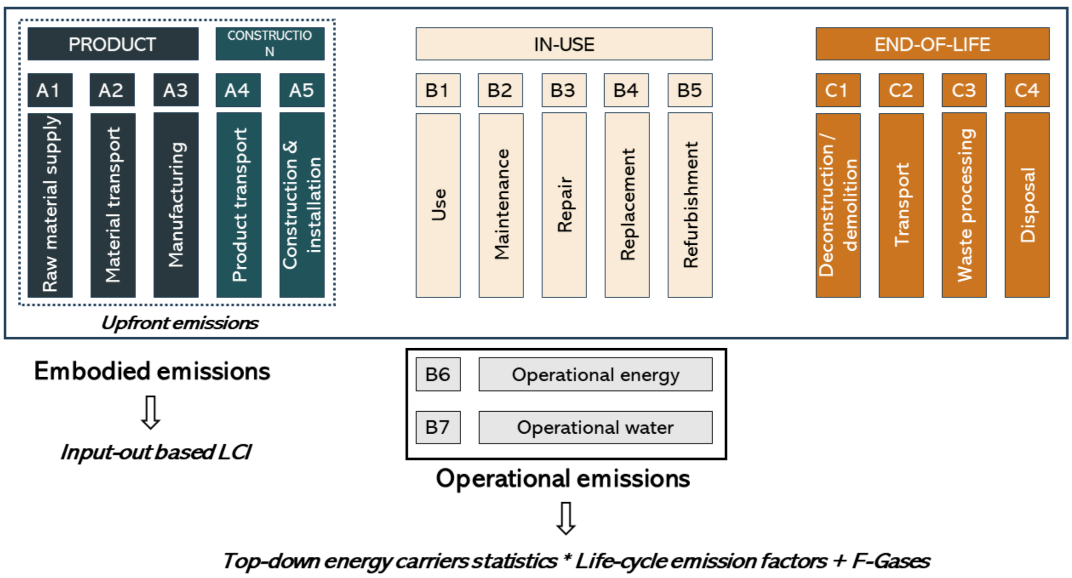
Firstly, the study introduces an accounting method for separately calculating distinct emission scopes at the national level, using 2019 as the reference year. This method also facilitates the quantification of imported emissions, which are traditionally absent from national statistics and climate policies for the building activities. Subsequently, the results are projected until 2050 using different decarbonisation pathways. National scenario for operational GHGE is combined with different scenarios that reflect decarbonisation pathways for the supply-chain sectors responsible for the embodied GHGE of the building activities.

5.4.1 System boundary

Regarding the system boundary, the study adopts a comprehensive cradle-to-grave analysis that covers all life-cycle stages. For operational GHGE, the method integrates a top-down statistical approach with elements of process-based LCA. This involves combing detailed information on energy carriers used in both residential and non-residential buildings with life-cycle emission factors. Conversely, the embodied GHGE calculation adopts an Input-Output Life-Cycle Inventory (IO-LCI) approach, leveraging the Exiobase database (Stadler et al., 2018b). The main advantage of this approach is the minimisation of truncation errors, which refers to the omission of relevant processes or sectors from the analysis, a significant concern in process-based LCA (Suh and Huppes, 2005). For macro-level analysis, IO-based LCI is often preferred to avoid issues with system boundary definitions (Onat and Kucukvar, 2020). One of the main disadvantages of the IO-LCI approach is the aggregation issue, referring to the consolidation of different industries into broader sectors, potentially masking the nuances and specificities of individual industries. Exiobase is chosen for its extensive coverage of products, facilitating an economy-wide view that minimises aggregation errors. Ultimately, the



(a) Methodology for GHGE accounting and decarbonisation pathways



(b) System boundary and LCI methods for operational and embodied emissions

Figure 5.2: Methodology and system boundary for GHGE accounting and decarbonisation pathways

study aggregates results for operational and embodied GHGE to represent whole-life cycle (WLC) emissions, thereby merging the accuracy of national energy use statistics with the comprehensive perspective of IO-LCI for embodied impacts.

5.4.2 GHGE accounting methods

At the building level, the EN15978 (AFNOR, 2012) provides a consistent and standardised methodology for LCA calculations. The four life-cycle stages (e.g. modules A-B-C-D) are often grouped into *operational* and *embodied* GHGE. The first ones refer to the B6-B7 stages and can be further decomposed in *direct* operational GHGE, which occur at buildings site (e.g. fossil fuels and biomass combustion, gas-leaks from heat pumps), and *indirect* operational GHGE, which are the results of electricity and district heating production. On the other hand, embodied GHGE are associated with the construction materials and equipment's life-cycle GHGE (Lützkendorf and Frischknecht, 2020).

Another standardised methodology for GHGE accounting is the scope 1-2-3 inherited from the GHG Protocol (GHG Protocol, 2011). While primarily designed for organizations, it has been used to classify building life-cycle GHGE (Onat et al., 2014) (Onat and Kucukvar, 2020). However, the two systems are not necessarily equivalent. Indeed, two types of emission factors (EF) can be used for energy carriers : direct emission factors (D-EF) - which calculate GHGE for the combustion process - and life-cycle emission factors (LC-EF) - which also include upstream processes, such as transport. When using LC-EF, the upstream part of the GHGE could hence be classified as a scope 3 instead of a scope 1 emission.

The relation between these two classifications and the sectoral approaches presented in the IPCC guidelines and French SECTEN format is shown in Table 5.1.

Table 5.1: Relation between GHGE accounting methods

	Direct operational GHGE	**Indirect operational GHGE**	**Embodied GHGE**
GHG Protocol	Scope 1	Scope 2	Scope 3
EN15978	B6-B7		A1-A5 B1-B5 C1-C4
IPCC	Residential (1.A.4.b), Commercial /institutional (1.A.4.a)	Public electricity, heat production (1.A.1.a)	All others
SECTEN	Residential Tertiary	Energy	Industry Transport Waste LULUCF Agriculture

When looking at national inventories, building activities GHGE are heterogeneous as they are cross-sectoral. Nevertheless, coupling standardised methodology at the building level with the national inventory process can close the gap between climate policies and building environmental assessment methods. Therefore, in this study the operational-embodied framework is transposed to the national level to depict the whole-life GHGE of the building activities.

The SECTEN format is not an official UNFCCC reporting format but it is used at national level for climate policies, e.g. the SNBC. It aims to be better understandable by economic stakeholders and is specific to the French context. It covers GHGE and air pollutants with annual time-series available from 1990. Inside each sectors, the source of GHG and air pollutants are reported by Selected Nomenclature for Air Pollutants (SNAP) code that correspond to a detailed level (CITEPA, 2022a).

Operational GHGE calculation

The calculation of operational GHGE starts from a detailed knowledge on the energy carriers used in buildings. At national level, the energy balance provides information on the extraction of energy from the environment to its transformation and consumption by the different economic sectors. In France, the energy balance is given by the Statistical Data and Studies Department (SDES) (SDES, 2021) which specifies energy flows for different sectors, including the *residential and tertiary* sectors. Additionally, the French electricity transmission system operator (RTE) offers granular data on electricity consumption by usage (e.g. heating, domestic hot water, air conditioning, lighting, other usages) (RTE, 2022a). The energy flows are then converted into GHGE by applying emission factors from the Base Carbone (ADEME, 2020). Operational GHGE also include fugitive fluorinated gases (F-gases) (used as refrigerant gas in heat pumps and air conditioning systems). These emissions are taken directly from the national GHGE inventory (CITEPA, 2022b).

Table 5.2 provide values for both direct emission factors (D-EF) and life-cycle emission factors (LC-EF).

Table 5.2: Emission factors of energy carriers in 2019 in kgCO_2eq/kWh taken from the Base Carbone (ADEME, 2020)

	D-EF	**LC-EF**
Biomass	0	0.0288
Geothermy	0	0.045
Solar thermal	0	0.055
Biogas	0.0428	0.044
Electricity (average)	0.0418	0.0607
Heat	0.107	0.132
Natural gas	0.204	0.227
LPG	0.233	0.272
Oil products	0.272	0.325
Coal	0.345	0.377

In the method, life cycle emission factors (LC-EF) are employed to include upstream emissions attributed to the entire life-cycle of energy infrastructure (e.g. extraction, production, transportation, and losses). Consequently, the utilisation of LC-EF leads to greater operational GHGE compared to studies that conventionally rely on D-EF (SDES, 2022). Compared to other countries, it should be noted that the French electricity emission factor is quite low, thanks to a large reliance on nuclear and hydropower production. The average emission factor is given in Table 5.2, with specific values for the different usages detailed in Annex 9.4.

To encapsulate the method in a formula, operational GHGE for a given year t can be calculated as follows:

$$\theta(t) = \sum_{k}^{n} (E_k(t) * f_k(t)) + \Gamma(t) \tag{5.1}$$

Where $E_k(t)$ represents the energy consumption of energy carrier k in kWh derived from the energy balance for the year t, $f_k(t)$ denotes the life-cycle emission factor of energy carrier k in $kgCO_2eq/kWh$ as sourced from the Base Carbone for the year t and $\Gamma(t)$ accounts for the F-Gases as reported in the national GHGE inventory, measured in $MtCO_2eq$ for the year t.

Embodied GHGE calculation at national level

Recently, embodied carbon is receiving growing attention (Röck et al., 2020) (Röck et al., 2022b) and numerous studies are trying to quantify the weight of supply-chain emissions. Embodied emissions are generally a blind spot of buildings policies (UNEP, 2022). At the building level, embodied GHGE are usually quantified using process-based LCA. However, at national level, the process becomes more challenging. Indeed, buildings LCA are only available for a couple of new buildings, with no equivalent for renovation and demolition projects. Another method would be to study the physical flows from sectors which produce the necessary inputs of the building activities. Alas, detailed material flow statistics on the supply and use of different construction materials and equipment are lacking (Heeren and Fishman, 2019) and it is thus difficult to assess the GHGE of selected materials at national level.

To overcome these limitations, this study follows a top-down approach for the embodied GHGE calculation. It is enabled by the use of Input-Output Analysis (IOA), which has been widely used to estimate scope 3 GHGE (Baynes and Wiedmann, 2012). IOA looks at how different sectors of the economy are interconnected through their production and consumption patterns. It dates back to the 1930's (Leontief, 1936) and it has been used in environmental assessments since the 1970's (Leontief, 1970), giving rise to Environmentally Extended Input-Output Tables (EE-IOT). If it is not adequate to study the GHGE impact of buildings use stage because of the lack of information on energy carriers used (de Koning et al., 2013), it is frequently used for macro-scale assessments (Hertwich and Wood, 2018), in particular with the use of Multi-Regional Input-Output (MRIO) databases which have been flourishing in the last decades. Among the different MRIO databases available, Exiobase (Stadler et al., 2018b) is used in this study thanks to its large sectoral decomposition (163 sectors, 200 products) and set of environmental extensions.

In IOA, direct and total impact multipliers (DIMs and TIMs) depict respectively the direct and total attribution of impacts from production to one unit of final demand (Wiedmann, 2017). TIMs are given by:

$$m = (F \cdot \hat{X}^{-1}) \cdot (I - A)^{-1} = f \cdot L \tag{5.2}$$

where F represents the total impact matrix, A is the inter-industry coefficients matrix, I is the identity matrix, X is the total output, f is a matrix of DIMs, and L is the Leontief Inverse.

In order to better understand the origins of GHGE along the supply chain, a diagonal matrix of DIMs is created and multiplied by the Leontief inverse (L). By multiplying it with the vector of final demand for the French *Construction* sector (y), the footprint is calculated:

$$FP_C = \hat{f} \cdot L \cdot y \tag{5.3}$$

where FP_C is the construction footprint. As such, it is possible to assess the contribution of the various sectors of the supply chain in the GHGE footprint of the *Construction* sector, and identify GHGE hotspots (Wiedmann, 2017).

However, this study focuses on buildings activities and not the all built environment. Thus, one last step concerns the subdivision of the *Construction* sector in order to remove the civil engineering GHGE (e.g. associated with infrastructure such as bridges). As Exiobase does not differentiate the subsectors inside the *Construction* sector, this study relies on a 139 symmetric IO table provided by the French statistical office (INSEE) to get additional information. It includes a subdivision of the NACE *Construction* sector in four subgroups namely *Development of building projects* (F41.a NACE code, 75$^{\text{th}}$ sector in the IOT), *Construction of residential and non-residential buildings* (F41.b NACE code, 76$^{\text{th}}$ sector in the IOT), *Civil engineering* (F42 NACE code, 77$^{\text{th}}$ sector in the IOT) and *Specialised construction activities* (F43 NACE code, 78$^{\text{th}}$ sector in the IOT). The Z transaction matrix describes the inter-sectoral exchanges in France, where rows represent the supplying sectors and columns depict demanding sectors:

$$Z = \begin{bmatrix} Z_{1,1} & Z_{1,2} & \cdots & Z_{1,139} \\ Z_{2,1} & Z_{2,2} & \cdots & Z_{2,139} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{139,1} & Z_{139,2} & \cdots & Z_{139,139} \end{bmatrix} \tag{5.4}$$

where each $Z_{i,i}$ (e.g. on the main diagonal) represents intra-sectoral exchanges and each $Z_{i,j}$ represents economic transactions from sector i to j.

The following equations are then employed to get the share of the *Civil engineering* subsector in the *Construction* sector in the Z matrix:

$$r = \frac{\sum_{k=1}^{139} Z_{k,77}}{\sum_{k=1}^{139} (Z_{k,75} + Z_{k,76} + Z_{k,77} + Z_{k,78})} \tag{5.5}$$

where r symbolises the ratio of the total economic transactions involving the *Civil engineering* subsector and all economic sectors to the sum of economic transactions involving the entire *Construction* sector (e.g. containing the four subsectors previously mentioned) and all economic sectors.

Subsequently, this ratio is used as a proxy to remove the *civil engineering* associated GHGE to finaly calculate the building activities footprint FP_B :

$$FP_B = \hat{f} \cdot L \cdot y \cdot (1 - r) \tag{5.6}$$

The decomposition of regions and sectors in Exiobase helps to provide a more comprehensive and accurate picture of the environmental impacts of upstream sectors across different geographical regions. Although it gives detailed information, aggregations can also be useful to better interpretate the results. In this study, aggregation is done using concordances matrices (detailed in Annex 9.4). In particular, the 44 regions x 200 products classification are linked with two formats:

- **A 3 regions x 8 sectors classification**. It enables to couple the results with the SECTEN format used by the SNBC. An additional *Services* sector and the intra-sectoral exchanges of the *Construction* sector replace the *Residential and tertiary*. France, the European Union and an aggregated Rest of the World (RoW) are represented in terms of geographical regions.
- **A 15 regions x 19 sectors classification**. It is inspired from the traditional aggregation in 17 sectors in IO tables, with additional custom sectors for which the IEA scenarios give detailed pathways by 2050.

5.4.3 Scenarios and WLC budgets

Complex and uncertain factors shape the decarbonisation of the economy in the next decades. In this context, scenario analysis is a useful tool to address alternative future pathways (Fishman et al., 2021). In the methodology, scenarios are used to understand the complex and interconnected factors that will shape the decarbonisation of buildings. They are not considered as forecasts, but rather taken as insights to quantify the possible evolution of the buildings GHGE in the next 30 years. It is then possible to identify over the years and in the different scenario the contribution of the different scopes of emissions, including the sectors involved in the building activities supply-chain, by assuming that the economic structure remains the same.

On one hand, operational GHGE are regulated by the Low Carbon National Strategy (SNBC), which is the national translation of the Paris agreement. It aims to reduce GHGE and monitor the transition to a low-carbon economy to reach a state of net-zero emissions by 2050. In Figure 5.3, historical GHGE are given from 1990 to 2021 along with the SNBC pathways by sectors used in the SECTEN format.

A sharp decline is planned for all sectors. What's more, carbon sinks need to increase in order to get to a balance state in 2050. In the study, direct operational GHGE follows the *Residential and tertiary* sectors pathway whereas indirect operational GHGE follows the *Energy* sector pathway. The two sectors have aggressive reduction pathways, with reduction are to happen quickly, e.g. in the next years, compared to sector like *Transport* where they are to happen in the next decades. Thus, only the *residential and tertiary* pathway for direct operational emissions and the *energy* pathway for indirect operational emissions are considered.

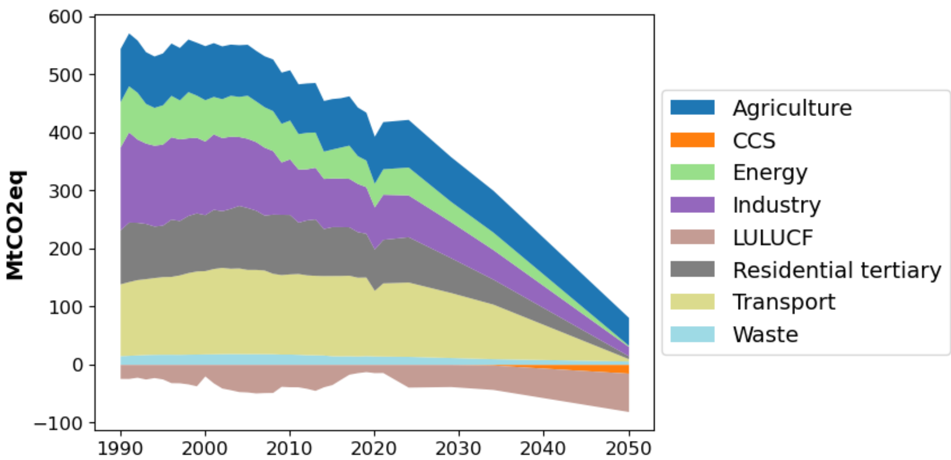


Figure 5.3: Historical GHGE from 1990 to 2021 and SNBC pathways by 2050

On the other hand, embodied GHGE happen in different geographical regions and are caused by multiple sectors. In that case, it is interesting to explore scenarios that display different pathways for regions and sectors. In the methodology, three IEA scenarios, displayed in Table 5.3, are used.

Table 5.3: IEA scenarios used for embodied carbon pathways.

	Scenario category	**Scenario type**
Net Zero 2050 (NZS)	Normative	Transforming
Announced Pledges Scenario (APS)	Predictive	What-if
Stated Policies Scenario (STEPS)	Predictive	Forecasts

The scenario typology described by Börjeson et al. (2006) is used to qualify the nature of each scenario. IEA scenarios are fully documented in the 2023 World Energy Outlooks (IEA, 2023c). The rationale behind each of them is the following:

- **Net Zero Emissions Scenario** : it reaches a state of net-zero emissions in 2050 globally. It is compatible with a 1.5°C temperature rise in 2100 with limited overshoot.
- **Announced Pledges Scenario (APS)** : it assumes that the policies and targets announced by countries will be implemented fully and on time, including their long term Nationally Determined Contributions (NDC) pledges. It is associated with a 1.7°C temperature rise in 2100.
- **Stated Policies Scenario (STEPS)** : it considers a wide range of policies and measures that are currently in place or under development in different countries. It is associated with a 2.4°C temperature rise in 2100.

In practice, the different scenario pathways (in % of reduction compared to 2019) are applied to the 2019 results for operational and embodied GHGE:

$$GWP(t) = GWP(2019) \cdot \alpha(t) \tag{5.7}$$

where $GWP(2019)$ is the calculated GHGE in 2019, $GWP(t)$ is the GHGE at year t and α is the annual reduction rate at year t.

The SNBC (used for operational GHGE pathways) provides annual reduction percentages up to 2050, while IEA scenarios (used for embodied GHGE pathways) only offer for 2030, 2035, 2040 and 2050. To address this gap, linear regression is employed to estimate values for the intervening years. The graphs are generated using the pyam package (Huppmann, Daniel et al., 2021).

To establish decarbonisation pathways for WLC assessment, the SNBC operational GHGE pathway is integrated with the pathways of embodied GHGE from the three IEA scenarios. This integration not only yields a more comprehensive and holistic idea of the future possible GHGE arising from the building activities, but it also enables to assess the distribution of the different scopes of emissions across scenarios.

5.5 Results

According to the method describe above, the GHGE of the French building activities can be estimated for year 2019. Then the decarbonisation pathways given by the SNBC and IEA can be applied to deduce WLC budgets for buildings by 2050.

5.5.1 GHGE accounting

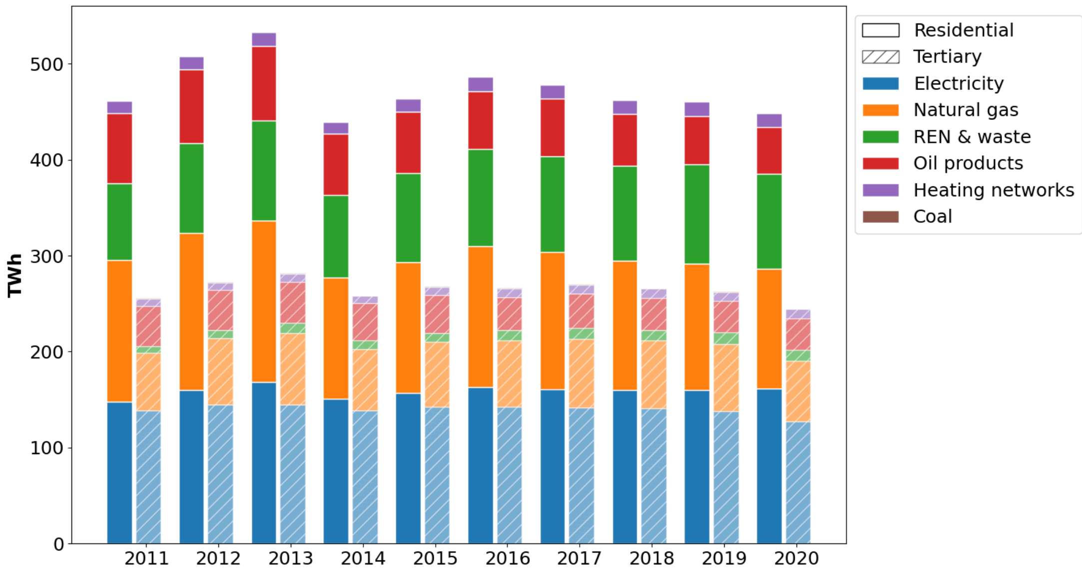
Operational GHGE

In 2019, the French building stock operational GHGE represent 104 $MtCO_2eq$ with 79% being direct operational (e.g. 83 $MtCO_2eq$) and 21% being indirect operational GHGE (e.g. 21 $MtCO_2eq$). The results differ compared to national statistics given by the SDES, which gives a value of 55 $MtCO_2$ for operational GHGE (SDES, 2022). The two main differences are the accounting of all GHGE and not just CO_2, and the use of LC-EF instead of D-EF. Indeed, using LC-EF add nearly 20% of the footprint.

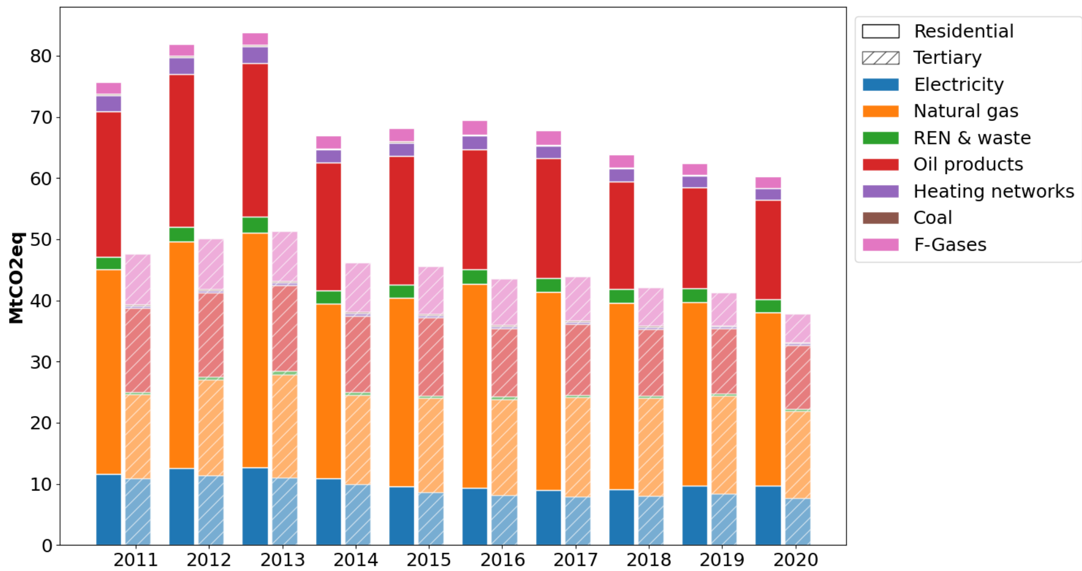
Figure 5.4 illustrates the relative importance of the different energy carriers in the total energy consumption 5.4a and operational GHGE 5.4b of residential and tertiary buildings from 2011 to 2020.

By juxtaposing the two sub-figures 5.4a and 5.4b, a comparative analysis of the impact of each energy carrier on energy consumption and the resultant operational GHGE can be conducted. For instance, in 2019, electricity accounted for 41% of the energy consumption but only 17% of the operational GHGE. This disparity can be attributed to the predominantly low-carbon sources used in French electricity production, such as nuclear and hydropower. A similar pattern is observable for the 'Renewable energy and waste' category, which constituted 15% of energy consumption (primarily in residential buildings) but only 2% of operational GHGE. In contrast, even though natural gas and oil products have modest proportions in energy consumption, at 24% and 12% respectively, they substantially influence operational GHGE. Natural gas contributes to 44%, and oil products to 26% of the total operational GHGE.

In terms of building types, residential buildings emerge as the dominant contributors both for energy consumption and operational GHGE. In 2019, they account for 64% of the energy consumption and



(a) Energy consumption per energy carriers in TWh



(b) Operational GHGE per energy carriers in MtCO2eq

Figure 5.4: Evolution of energy carriers use in residential and tertiary buildings

60% of operational GHGE, due to their reduced emission of F-Gases compared to tertiary buildings. When looking at trends from 2011, 2013 was the peak year. Then, a decrease is seen which can be partly explained by the 2012 Thermic Regulation (RT2012) and the climate severity index (CITEPA, 2022a). The share of the different energy carriers are quite stable between 2011 and 2020. For operational GHGE, the biggest differences are for natural gas, which rises from 38% to 44% while oil products decrease from 30% to 27%. F-gases has been fluctuating, reaching a peak in 2014 with 10.2 $MtCO_2eq$ and decreasing since then to reach 6.5 $MtCO_2eq$ in 2020.

Embodied GHG emissions

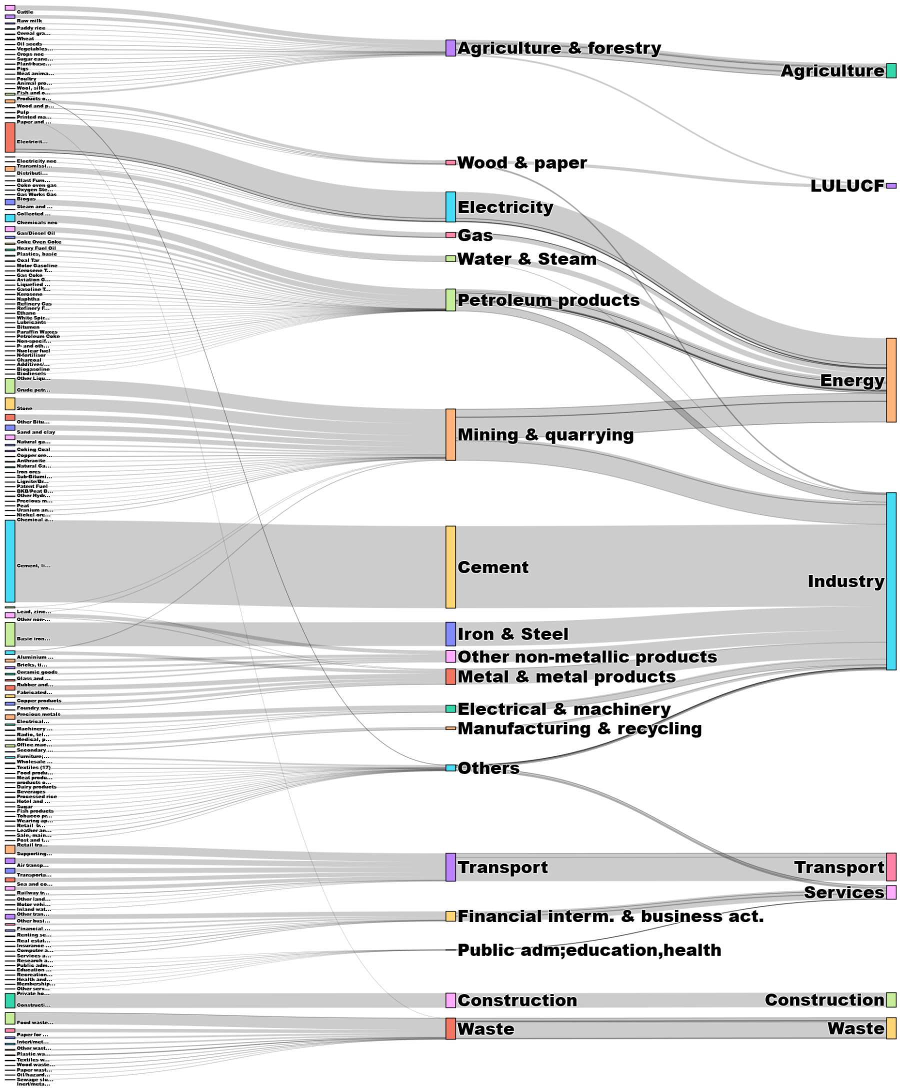
Embodied GHGE represent 57.9 $MtCO_2eq$ in 2019. After calculation (detailed in section 5.4.2), results are available in a 200 products x 44 regions format. This detailed disaggregation allows mapping the most impacting sectors and the regions where they occur. Results show that the GHGE footprint of the French construction sector is quite concentrated, with 20 combination of sector-region representing half of the impact. Table 5.4 displays the top ten combination of regions and sectors, representing their absolute and relative shares of the total embodied GHGE (in $MtCO_2eq$ and % respectively).

Table 5.4: Top ten couple of country-products contributors to embodied GHGE in 2019

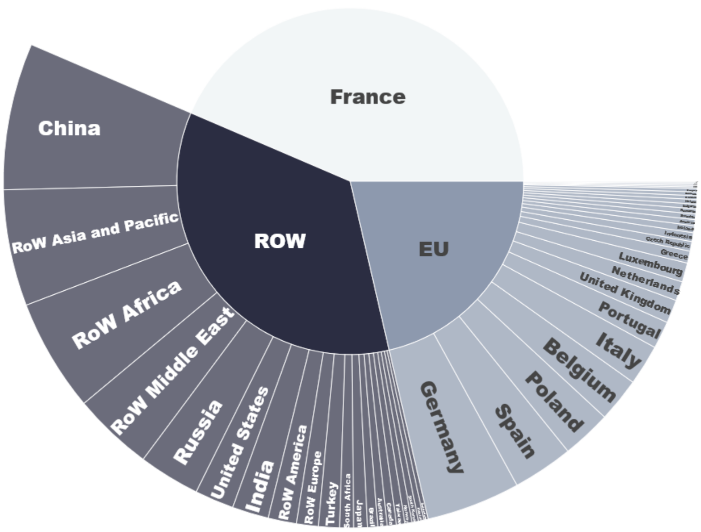
Region	**Sector**	**$MtCO_2eq$**	**%**
France	Cement, lime and plaster	9.14	15.8%
France	Construction work	2.14	3.7%
France	Stone	1.74	3%
France	Supporting and auxiliary transport services	1.14	2%
France	Waste for treatment: Landfill	1	1.7%
RoW Africa	Cement, lime and plaster	0.9	1.6%
China	Basic iron & steel	0.79	1.4%
China	Electricity by coal	0.77	1.3%
France	Basic iron & Steel	0.75	1.3%
France	Transportation services	0.64	1.1%

The French *Cement, lime and plaster* sector stands out as particularly impacting, with 15.8% of the GHGE footprint alone, when the second most impacting sector, the French *Construction* sector (e.g. representing the intra-sectoral exchanges) is far behind, representing 3.7% of the embodied GHGE.

Figure 5.5 allows to further analyse the global supply-chains emissions. The results and aggregation for sectors are illustrated with a Sankey diagram (5.5a) while the outcomes and aggregation for regions are presented through a sunburst plot (5.5b). In the analysis of sectoral distribution within a framework encompassing 200 sectors, the primary contributors identified are *Cement, lime and plaster*, *Basic iron & steel* and *Electricity by coal*. This finding aligns with previous research indicating that mineral production—especially cement—and metals such as steel are predominant factors in the construction footprint (C40 et al., 2019). Upon consolidating these 200 sectors into broader macro-sectors, the critical role of industry and upstream emissions related to energy becomes apparent, accounting for approximately 70% of the total embodied emissions. Additionally, emissions from transport and within the construction sector emerge as notably significant at the national scale. From a geographical perspective, with consideration to a division into 44 regions, the leading international sources of emissions are China, alongside the combined regions of Asia and Africa. When the data



(a) Sankey diagram aggregation from 200 products to 8 sectors



is further aggregated, it reveals that 42% of the footprint is located in France, with the European Union and the Rest of the World (RoW) responsible for 22% and 36% of the footprint respectively.

Whole-life GHGE

After aggregating operation and embodied GHGE, the whole-life GHGE of the French building stock emits 162 $MtCO_2eq$ in 2019. Operational emissions dominate the GHG footprint of buildings at national scale. However, embodied GHGE are already quite important, representing already one third of the footprint. As a whole, 20% of the French building stock GHGE are located outside of national borders.

5.5.2 Scenarios and WLC budgets

Operation GHGE budgets

Applying the SNBC pathways, the results show that operational GHGE should reach 6.6 $MtCO_2eq$ in order to be aligned with the SNBC, mainly represented by direct operational GHGE with 5.7 $MtCO_2eq$. It represents a 94% decrease from 2019 to 2050.

Embodied GHGE budgets

Embodied GHGE are located in various geographical regions and sectors displayed in Figure 5.5. The IEA scenarios give detailed pathways for these geographical regions and sectors, but not the pair of geographical region-sector (e.g. the Chinese cement sector). For this reason, the 2019 results are projected using sectoral pathways in Figure 5.6 for the Stated Policies, Announced Pledges and Net Zero scenarios. When applying sectoral pathways, there is a high discrepancy between the results because the scenarios do not follow the same objective as detailed in 5.4.3. In 2030, the embodied GHGE would reach 60 $MtCO_2eq$ under the STEPS, 52 $MtCO_2eq$ under the APS and 44 $MtCO_2eq$ under the NZS. The difference is bigger in 2050 with 56 $MtCO_2eq$ under the STEPS, 22 $MtCO_2eq$ under the APS and 2.2 $MtCO_2eq$ under the NZS.

The assignment of specific pathways to each sector is detailed in Annex 9.4. As they are applied to emissions from sectors within the *construction* supply-chain, the overall embodied pathway (e.g. the 'Total' black line in 5.6) is not necessarily equal to the GHGE pathway of each IEA scenario for the all economy. Indeed, the share of industry-related GHGE is substantial in the embodied GHGE of buildings, and such sectors typically have more modest decarbonisation pathways. For instance, the pathways for 'Cement' and 'Iron & Steel' are often less aggressive, mirroring the 'hard to abate' character of industrial sectors (Davis et al., 2018). Conversely, the 'Electricity & Heat' sector has always steep and rapid decarbonisation, even in the Stated Policies Scenario.

WLC emissions budgets

In order to provide WLC emission budgets, the SNBC scenario for operational GHGE is combined with the different decarbonisation pathways for embodied GHGE, resulting in the creation of three combined scenarios, displayed in Figure 5.7.

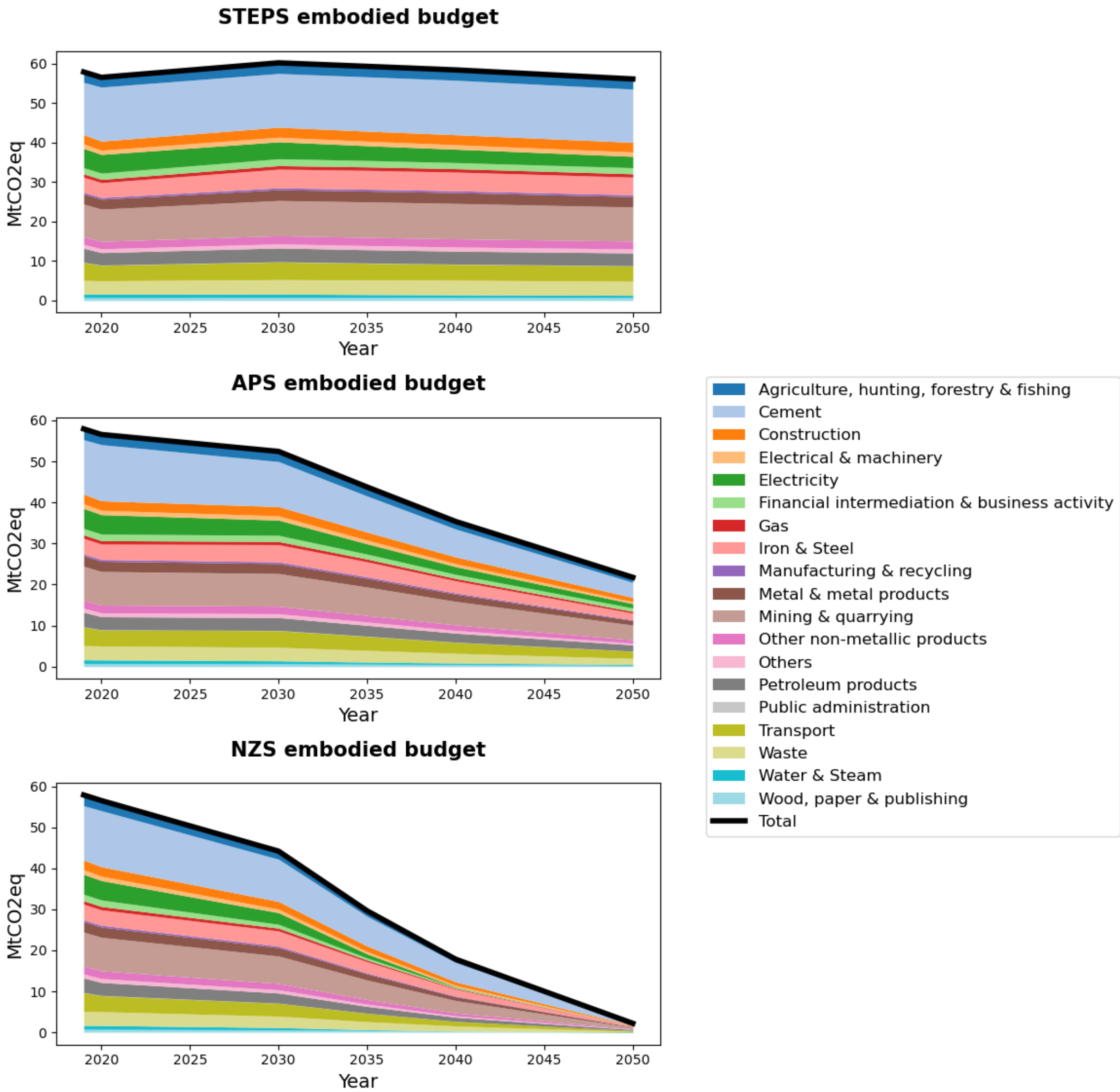


Figure 5.6: Embodied carbon pathways with IEA global sectoral scenarios

In 2030, the WLC emissions would reach 124 $MtCO_2eq$ under the SNBC-STEPS, 116 $MtCO_2eq$ under the SNBC-APS and 108 $MtCO_2eq$ under the SNBC-NZS. In 2050, the figures will decrease respectively to 62 $MtCO_2eq$, 28 $MtCO_2eq$ and 8 $MtCO_2eq$. Regarding the distribution of emission scopes, in both SNBC-STEPS and SNBC-APS scenarios, embodied GHGE are anticipated to approach operational levels by 2030 and reach respectively 90% and 78% of WLC emissions by 2050. Due to the rapid decarbonisation of all economic sectors in the NZS, these proportions differ significantly, with embodied GHGE accounting for 41% in 2030 and only 26% in 2050.

Considering that the Announced Pledges Scenario aligns with the policy targets of different countries, it may be the most logical scenario to couple with the SNBC, which represents France's long-term commitment to reach a state of net-zero emission.

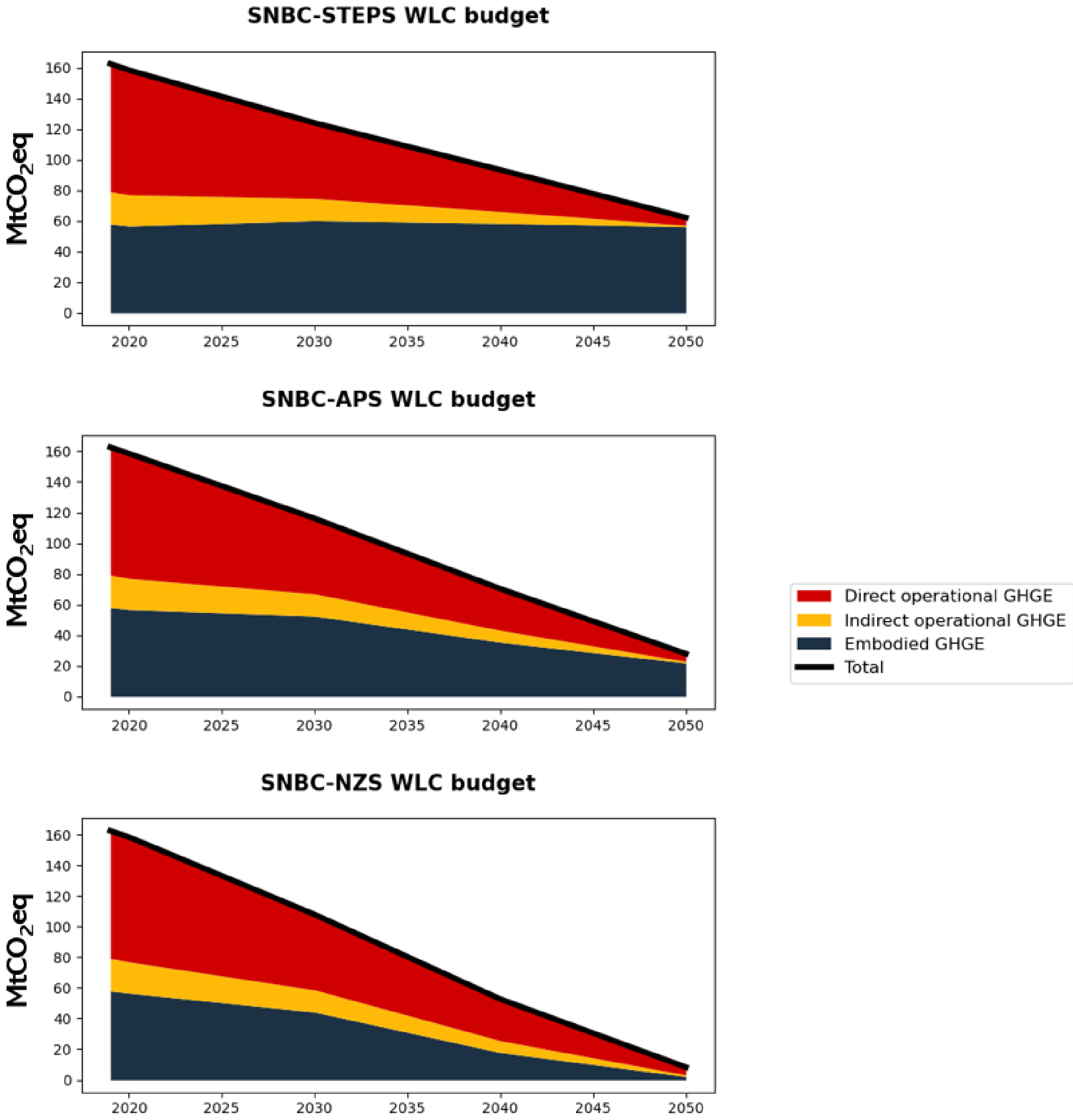


Figure 5.7: WLC pathways combining SNBC and IEA scenarios

5.6 Discussions

This study contributes to the body of work on the construction sector's carbon footprint and global supply chain analysis, discussed in Section 5.3.2. However, it is important to acknowledge the absence of a formal validation process, which constitutes a key limitation of this study. The results align well with findings from previous research, including (SDES, 2022) who highlight the predominant role of fossil fuel combustion in operational GHGE, (Huang et al., 2018) who emphasise the significant role of indirect emissions within the construction sector, (O'Hegarty et al., 2022) who report that one-third of whole-life carbon emissions in Ireland are embodied GHGE, and (**?**) who project that embodied emissions could constitute up to 75% of life-cycle GHGE in a Business-As-Usual scenario. However, this alignment with existing studies does not replace the need for rigorous validation. Validation could involve comparing these results with those obtained from other methodologies, such as bottom-up approaches, although such studies are rare at the national level. While incorporating quantitative indicators for measuring errors, such as sensitivity analysis within the MRIO framework, could also be beneficial, this process is complex and resource-intensive as it involves extensive computational work to evaluate the impact of each variable on the results. Additionally, the inherent challenges of sector aggregation, economic data discrepancies, and the assumptions about global supply chains add further layers of complexity to such an analysis (Crawford et al., 2018). Given these challenges, the scope of the current study was focused on establishing a robust methodological framework rather than extending into comprehensive validation. Future research could build on this foundation by developing and applying advanced validation techniques to address these challenges and enhance the robustness of the findings.

Despite this limitation, the study's findings remain valuable for informing policy decisions and advancing the understanding of whole-life carbon emissions in the construction sector by leveraging the strengths of various LCI methods to overcome the limitations inherent in each. It also addresses the noted scarcity of comprehensive macro-level studies, particularly those using MRIO databases for capturing both direct and indirect impacts, a gap especially pronounced in EU countries (Onat and Kucukvar, 2020), with no study specifically addressing France. This shortfall is particularly significant given France's advanced policy framework, exemplified by the SNBC and the RE2020. Indeed, this study adopts a more policy-oriented perspective, since its accounting methodology is designed to broaden the scope of existing sectoral carbon budgets. In the majority of studies that focus on establishing WLC budgets for national building activities (such as (Priore et al., 2023), (Horup et al., 2023) and (Horup et al., 2022)), the approach leans towards absolute sustainability. This involves an initial step to downscale the global remaining carbon budgets to national level, using different allocation principles. In this study, carbon budgets are conceived more as a policy target, defined by the SNBC and complemented by consumption-based metrics. As such, this approach does not address the issue of fairness, but can be seen as more relevant for defining environmental policies (Heijungs et al., 2014). Such analysis can also provide guidance in the context of international climate negotiation by highlighting the necessity of pursuing emissions reductions not only within the construction industry itself but also across its global supply chains, thereby identifying diverse opportunities for reduction.

In the WLC pathways, the share of embodied GHGE become more and more important, and should outpace operational GHGE in the next decades in the STEPS and APS. Indeed, when dealing with a large transformation of the building stock, either via retrofits or reconstruction, material-related impacts can become more important than energy-related impacts (de Oliveira Fernandes et al., 2021) (Verhagen et al., 2021). This finding is particularly true for France, where the indirect operational GHGE are relatively low, thanks to a low-carbon electricity mix. Worldwide, this assertion might not stand since indirect operational GHGE represent 57% of buildings life-cycle emissions in 2019 (**?**), thus it is likely that operational GHGE remain predominant. However, the importance of tackling embodied GHGE should be clearly acknowledged by building policies in order to avoid a displacement of GHGE from buildings to industrial sectors that produce construction materials and equipment. Using the suggested accounting framework sheds light on emission reduction potentials across the supply chain and the interconnection between industrial sectors and building demand. The cement and concrete value chain serves as a prime example, due to the significant role of the *'Cement, lime and plaster'* sector in embodied GHGE that illustrates the strong link between construction activities and these upstream industrial chains. Beyond the technical and upstream decarbonisation levers outlined in Appendix 9.4.5, the necessity of adopting a value chain reduction approach is underscored, proposing strategies from clinker production to structural applications in buildings (Habert et al., 2020a). This unified approach accentuates the intrinsic link between construction activities and the decarbonisation of cement and concrete, highlighting the vast potential for emission reduction through demand-side measures. Construction sector professionals are encouraged to demand the creation of lower CO_2 content in concrete, necessitating a concerted focus on emissions during the construction phase that involves a broad spectrum of stakeholders. By mandating progressive reductions in embodied emissions with limit values set for 2031, the new environmental regulation (RE2020) in France is a good example of such policies, even if it applies for new construction only. In terms of broader policy implications, the findings support the need for additional policies based on sufficiency measures, such as policies that encourage a reduction in floor area per *capita* and the optimisation of existing spaces by addressing vacant housing (Morfeldt et al., 2023).

Previous studies have attempted to apply scenarios to IO models by changing various parts of the IO system based on exogenous assumptions (De Koning et al., 2016) (Wiebe et al., 2018) (Donati et al., 2020). They have often focused on the electricity sector (Gibon et al., 2015) (Hertwich et al., 2015). In this study, the economic structure (e.g. inter-sectoral exchanges) is assumed to remain constant. Indeed, this study applies exogenous scenarios to IO results by using the IEA sectoral CO_2 pathways, similar to how operational results are combined with SNBC pathways. It is worth mentioning that IEA scenarios do not publicly provide prospective data on economic exchanges among sectors. Thus, if the approach is arguably less sophisticated, future studies would need to incorporate additional models to modify the economic structure. For the time being, the study is more concentrated on ongoing work at EU level focused on the creation of WLC and embodied carbon budgets for buildings (Röck et al., 2022b) (Ramboll et al., 2023), and represents a novel contribution by depicting budgets that depend on the decarbonisation of upstream sectors within the supply chain. However, this method would not be suitable to examine the effect of certain policies on the structural dependencies between economic sectors, such as circular economy measures or economic incentives, nor to address the effect on prices in the economy. These aspects are generally the focus of dynamic models, such as Computable General Equilibrium (CGE) models, while IO models are more conventionally regarded as accounting tools (Wiebe et al., 2018).

Additionally, while IOA offers a cross-sectoral and international vision of embodied GHGE, facilitating the minimisation of truncation errors, it does not come without limitations (Lenzen, 2008). In particular, the issues of sector aggregation and materials specific data are important when it comes to buildings (Teh et al., 2018). For example, the *construction* sector is aggregated in MRIO tables and its decomposition between *buildings* and *civil engineering* GHGE brings additional uncertainties. In this study, it is done through national statistics by using economic transactions as proxy. Matrix augmentation, which consists of sub-dividing an economic sector using process data, can be a more robust option (Crawford et al., 2018). It should be noted that this issue does not arise when the all built environment is considered.

Another major issue of IOA regarding embodied GHGE calculation is that it does not distinguish the building usages (e.g. residential and non-residential buildings) and typologies (e.g. new construction, renovation, demolition). However, the present work can serve as budget-based targets and be coupled with a LCA bottom-up building stock model, which aims to provide a holistic environmental assessment of the different building stages (Mastrucci et al., 2017). It would enable to model the transformation of the building stock through the years with respect to the top-down targets identified. Indeed, the idea of combining top-down and bottom-up modelling approaches for the building activities bring promising ideas (Hollberg et al., 2019). Yet, one of the challenges to be unravelled is the potential temporal mismatch between static LCA results and budget-based targets.

5.7 Conclusion

The development of sound GHGE accounting methods for cross-sectoral activities is urgent to better link climate policies such as sectoral carbon budgets with industrial and public policies. It can enhance the development of scalable carbon budgets that are needed to better shape stakeholders decarbonisation strategies. The article builds upon the needs-activities-sectors framework to present a methodology that enables to capture the whole-life GHGE of buildings at national level. It supplements the traditional sectoral approach of GHGE accounting by bringing a cross-sectoral and international perspective on national buildings activity. Alongside the GHGE of the different energy carriers used during buildings use stage, geographical and sectoral embodied GHGE hot spots are highlighted. This holistic approach better recognises the complexity of buildings GHGE and can help to activate decarbonisation levers along the supply-chain. The French case study shows that operational GHGE are dominant today with 66% of buildings GHG footprint, and are mainly caused by gas and oil combustion. Nevertheless, the weight of embodied GHGE is already significant today and is likely to become predominant in the next decades in almost every studied scenarios. Thus, the results show that strict limit on embodied GHGE should be enforce to better regulate the whole-life GHGE of buildings and avoid carbon leakages.

6

From limit values to carbon budgets: assessing comprehensive decarbonisation strategies

Contents

This chapter introduces the second journal article of the PhD thesis. The paper has been published in 'Building and Environment' and can be found at https://doi.org/10.1016/j.buildenv.2024.111505. It is reproduced here as it is, while formatting might change. Please refer to Appendix 9.5 for the 'Supporting Information' accompanying this publication.

CONTRIBUTIONS

- **Marin Pellan** - Conceptualisation, Data analysis, Formal analysis, Investigation, Methodology, Writing - original draft
- **Denise Almeida** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Mathilde Louërat** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Guillaume Habert** - Conceptualisation, Supervision, Validation, Writing - review & editing

6.1 Highlights

- New GHGE pathways methodology from open-source dwelling stock database.
- Comparison of WLC emissions with carbon budgets.
- Results highlight efficiency of fossil fuel reduction policies.
- Embodied GHGE become predominant in ambitious scenarios.
- Emphasis on stock efficiency, deep decarbonisation and sufficiency levers.

6.2 Abstract

Several countries are moving towards imposing mandatory limit values that consider the life-cycle greenhouse gases emissions (GHGE) of new construction projects. While they offer valuable guidance towards low-carbon practices, they may not be sufficient to ensure the building activities alignment with ambitious climate goals. To do so, it is imperative to integrate all stock-level activities dynamics and consider the evolving nature of limit values influenced by the decarbonisation efforts in the energy and industry sectors.

This article introduces a methodological framework designed to explore the potential evolution of the dwelling stock GHGE, with the ultimate goal of assessing their alignment with climate objectives. By using a national building stock database, alongside drivers of stock-level activities and scenarios for the decarbonisation of upstream sectors, it facilitates the creation of multiple scenarios and the calculation of yearly and cumulative Whole-Life Carbon (WLC) emissions.

France is taken as a case study to investigate the compatibility of its recent implementation of climate and sectoral policies. The findings suggest that prioritising the elimination of fossil fuel usage emerges as an optimal strategy for decreasing operational GHGE. Regarding embodied GHGE, the more ambitious the scenario, the greater its relative contribution, potentially accounting for up to half of the WLC emissions by 2050. In addition to the ambitious transformation of energy-inefficient dwellings, the deep decarbonisation of energy carriers and construction materials plays a pivotal role in the overall decarbonisation of the dwelling stock, while sufficiency measures significantly impact embodied GHGE.

Keywords: *environmental benchmarks; stock dynamics; scenario analysis; whole-life carbon; life-cycle assessment; carbon budgets*

6.3 Introduction

Building activities are significant contributors to climate change, responsible for 21% of global greenhouse gases emissions (GHGE), emitting 12 Gt CO_2eq annually (Cabeza et al., 2022). With an expected 75% increase in the floor area in the Global South and while a large part of the existing building stock is energy inefficiency in the Global North (IEA, 2021), the projected trajectories are alarming in the context of a shrinking remaining carbon budget to keep on the commitments of the Paris Agreement (United Nations, 2015). The development of scalable carbon budgets, from construction products to cities and national building stocks and its implementation into mandatory targets is then a prerequisite for achieving sound climate objectives (Habert et al., 2020b).

For many years, the spotlight in research and policy discussions had primarily been on operational GHGE. They have rightly received significant attention as buildings are long-term assets, and their energy use contribute substantially to climate change over their lifespan. However, there has been a notable shift in focus towards embodied GHGE which has been rising in relative and absolute terms, especially for new buildings (Röck et al., 2020). While they represent 25% of Whole-Life Carbon (WLC) emissions today, their share is expected to reach 49% by 2050 (UNEP, 2023). Between 1995 and 2015, emissions from material production increase by 120% between 1995 and 2015, with two-fifths of the footprint caused by construction (Hertwich, 2021). Thus, understanding the prospective dynamics of the stock in use is vital for effective environmental policy-making (Haberl et al., 2017).

6.3.1 Benchmark systems and studies

To address the urgent need for GHGE reduction, the development of robust WLC benchmarks in the building sector is essential. They should serve as crucial tools for assessing buildings environmental performance and help policymakers establish mandatory limit values. Beyond assessing the starting point, they should also help to specify future targets and reduction pathways that need to be dynamically updated to take into account new insights (e.g. planetary boundaries and technological advancements for example) (Lützkendorf et al., 2023). The International Standard on sustainability in buildings and civil engineering works (ISO 21678:2020) defines a framework for establishing benchmarks on sustainability in buildings. Three types are proposed : limit values ('upper or lower acceptable performance level'), reference values (best practice) and target values. The latter derives from top-down (TD) benchmark, while the first two types derive from bottom-up (BU) benchmark.

On one hand, bottom-up (BU) benchmarks relate to the values of the existing level of GHGE based on an empirical dataset. They are developed at a granular level, considering specific characteristics of buildings, and delve into factors like building size, age, materials and energy consumption patterns. When considering the building level, multiple studies have contributed to the field (Birgisdottir et al., 2023). Their strength lies in their ability to offer practical and tailored decarbonisation strategies. Nevertheless, BU benchmarks demand considerable time and resources for data collection and assessment, and there might be a lack of standardised comparison mechanisms across diverse contexts (e.g. geographic regions and building types). Data completeness and availability are also key challenges (Röck et al., 2022b). Another limitation is that they often rely on a limited set of case studies or archetypes buildings, focusing mainly on new construction, although recent trends indicate a shift towards data-driven approaches (Mouton et al., 2023). What's more, BU benchmarks only enable to compare metrics between different elements (e.g. components, buildings) but are not enough to ensure their alignment with planetary boundaries. There is indeed a gap in translating the stock-level activities (e.g. construction, deconstruction and renovation flows) from the individual building scale to the entire building stock.

On the other hand, top-down (TD) benchmarks encompass carbon reduction targets across various geographical regions and economic sectors. With the rising concerns related to planetary boundaries trespassing (Richardson et al., 2023), they draw inspiration from international climate agreements, such as the Paris Agreement (United Nations, 2015), and considerations related to the remaining carbon budget, which quantifies the total amount of carbon dioxide emissions that can be released into the atmosphere while still keeping global warming below a specific temperature target (Matthews et al., 2020), as well as national climate action plans. Several studies have proposed to downscale the remaining carbon budget down to national buildings activities, building stocks, individual buildings, life-cycle stages and components, for example in Switzerland (Priore et al., 2023) and Denmark (Horup et al., 2023). They generally aim to set scalable science-based target values (for instance per building floor area, e.g. $kgCO_2eq/m^2$), taking into account the dynamic evolution of the building stock which are scenario-dependant. Given the growing urgency of GHGE reductions, an approach based on top-down target values serves to underscore the magnitude of the transition required. However, challenges arise in the context of the ongoing debates concerning the fair allocation of budgets at both national and sectoral levels, which gives rise to ethical questions that are largely debated in the literature (Höhne et al., 2014) (Robiou Du Pont et al., 2016) (Steininger et al., 2021) (Hjalsted et al., 2021). Additionally, the translation of these targets into actionable measures at the building level presents inherent complexities.

The integration of TD and BU approaches emerges as a powerful strategy for comprehensive building stock decarbonisation. While TD benchmarks provide the overarching vision and motivation for action, BU benchmarks help to define ambitious limit values and supply tailored insights and solutions aligned with the characteristics of individual buildings or components. However, examples of such coupling are still scarce in the literature and rarely encompass all stock-level activities. In Switzerland, Hollberg et al. (2019) compare derived TD targets with BU benchmarks at component level in order to identify potential for environmental optimisation in the design process. In the UK, Li et al. (2022) the focus is on assessing different renovation strategies with national carbon budgets. In New Zealand (Chandrakumar et al., 2020b) and Denmark (Andersen et al., 2020), the emphasis is on comparing current performance at the building level with future target values, aiming to quantify the existing environmental performance gap.

6.3.2 Scenario analysis and framing of decarbonisation levers

BU benchmarks need to be coupled with stock-level activities dynamics at the building stock level in order to assess their compatibility with TD benchmarks. In that matter, scenario analysis offer a valuable tool into potential future developments of parameters shaping the trajectory of the building activities towards a low-carbon future. By combining the use of narratives, like the Shared Socioeconomic Pathways (SSP) scenario family (O'Neill et al., 2014) (Riahi et al., 2017), with industrial ecology techniques such as Material Flow Analysis (MFA) and Life-Cycle Assessment (LCA), one can explore a range of possibilities and devise targeted strategies to reduce WLC emissions. Alas, if numerous scenarios recognise and integrate buildings GHGE, they often focus mainly operational GHGE. As a result, building activities are not precisely integrated in decarbonisation pathways. This poor representation and lack of explicit holistic pathways prevent to have clear pathways for WLC emissions (Giesekam et al., 2018b).

In terms of levers, scenario and decarbonisation roadmaps tend to focus on efficiency and technological solutions in the use phase. It traduces the three pillars of decarbonisation usually represented in Integrated Assessment Models (IAMs), e.g. energy efficiency, decarbonisation of energy carriers and end-use switch (Waisman et al., 2019). Studies that take a more holistic approaches tend to add material efficiency to these strategies (Pauliuk et al., 2021). Sufficiency, behavioural measures and life-cycle perspectives solutions have been largely overlooked, despite their advantages in terms of economic, social and environmental benefits (Mata et al., 2020) (Cabeza et al., 2022). Several frameworks provide a structured way to address different aspects of GHGE reduction, underscoring the necessity of considering a range of strategies across multiple levels. Among them the Demand-side/Supply-side (Creutzig et al., 2018) (Creutzig et al., 2021), Sufficiency/Efficiency/Renewable (Saheb, 2021), and Avoid/Improve/Shift (Creutzig et al., 2022) frameworks have been previously used. The latter endorsed by the IPCC (Cabeza et al., 2022), the UNEP (UNEP, 2023) and EU studies (Ramboll et al., 2023), emphasises three key strategies when applied to the building activities. *Avoid* involves make the best-use of the existing stock in order to avoid production of materials and design buildings with low-energy demand. *Shift* entails transitioning to low-carbon energy sources and materials, reducing both operational and embodied emissions. *Improve* centers on enhancing the energy efficiency of existing buildings through upgrades and retrofits, and improving conventional materials and use them only when necessary. *Avoid* solutions can be limited by social factors, *Shift* solutions are often limited by resource availability and *Improve* solutions are limited by innovation and access to market.

6.3.3 Climate and sectoral policies

Several European Union (EU) countries, such as the Netherlands, Denmark, Finland, Sweden, and France, have recently implemented comprehensive GHGE requirements for new buildings in national standards (Buildings Performance Institute Europe, 2021). For example, in France, the new Environmental Regulation (RE2020) have established GHGE limit values for new construction (CEREMA, 2024) with decreasing targets by 2031 for both operational and embodied GHGE. In order to effectively advance the decarbonisation of the building activities, it is imperative to closely monitor the evolution of these standards in relation to science-based targets and to identify the key factors contributing to their achievement (Mata et al., 2020).

France's recent climate policy implementations present a notable case for study. These policies include the National Low-Carbon Strategy (SNBC) (Ministère de la Transition Écologique et Solidaire, 2020a) and the development of sectoral decarbonisation roadmaps (officiel de la République française, 2021), Building-focused policies also play a significant role, such as the new energy performance certificate (EPC) labelling method and the gradual ban on renting out energy-inefficient housing (MTES, 2021). First, the SNBC is the decarbonisation compass to achieve a state of net-zero emissions by 2050 (Ministère de la Transition Écologique et Solidaire, 2020a). It distributes sectoral-carbon budgets based on the SECTEN national GHGE inventory format (CITEPA, 2023). However, it falls short in providing comprehensive pathways for building activities, particularly due to its limited guidance on embodied GHGE (Pellan et al., 2023b). Additionally, the building sectoral decarbonisation roadmap (CSTB, Plan Bâtiment Durable, 2023) have underlined the need to use different levers, among which the renovation lever (Pellan et al., 2023a), without proposing clear pathways for their implementation. Furthermore, there is a diversity of scenarios concerning the dynamics of the building stock and the decarbonisation of many economic sectors (ADEME, 2021a) (RTE, 2022b) (négaWatt, 2022) (The Shift Project, 2021). Lastly, the Climate & Resilience Law (Journal officiel de la République Française, 2021) introduces a phased rental ban on energy-inefficient housing, with staggered deadlines (2025 for G, 2028 for F and 2034 for E). While this strategy undeniably brings energy and social benefits, the approach of renovating or demolishing buildings based on their EPC label has not been thoroughly examined in terms of WLC emissions. Moreover, it has not been compared with other strategies, such as those targeting the installation of fossil fuels. Notably, since 2022, the installation of new oil boilers for heating and hot water has been prohibited, aligning with the SNBC's objective to eliminate heating systems using coal and oil products by 2028. At the same time, the RE2020 imposes limits on operational GHGE, thereby constraining the use of natural gas primarily in new constructions. This presents a challenge, as a significant portion of the existing building stock continues to depend heavily on natural gas.

Thus, there remains a significant gap in integrating these elements into a comprehensive framework, hindering the ability to explore WLC emissions for multiple future projections. Furthermore, comparing these scenarios to life-cycle top-down budgets remains methodologically challenging. Indeed, they do not have the same granularity and do not always integrate the same scope of emissions. Additionally, these methodologies may not consistently align in terms of their temporal accounting systems.

6.3.4 Contribution of the paper

The socio-economic drivers influencing residential buildings differ significantly from those affecting non-residential buildings. Indeed, based on the concept of service provision, population and lifestyles (in particular floor area *per capita*), are often used to characterise prospective environmental impacts from dwellings (Müller, 2005). Our understanding of building stocks reveals a greater emphasis on residential buildings: building stock models and studies tend to focus on residential buildings (Röck et al., 2021), which can be attributed to the availability of more comprehensive databases related to the dwelling stock. What's more, residential buildings contribute the most to operational GHGE with 19% of global energy and process emissions, while non-residential buildings contribute 11% (UNEP, 2022).

Given these considerations, the study focuses on residential buildings and sets out to explore the complex interplay among diverse stock-level activities dynamics (including their socio-economic and policy determinants) and the decarbonisation of supply sectors that influence the future WLC limit values. This exploration is crucial for understanding how these factors collectively shape future WLC emissions, and how they compare with top-down budget constraints. This investigation gives rise to three central questions:

- What are the annual and cumulative WLC emissions of the dwelling stock when considering different combinations of prospective parameters for stock dynamics and upstream sectors transformation?
- Which targeted policies, in particular for renovation operations, should be preferred to maximise the decarbonisation of the dwelling stock?
- Which scenarios demonstrate compatibility with top-down budget constraints, and what are the key variables that have the most influence on the WLC emissions in the next decades?

6.4 Literature review

6.4.1 A lack of benchmark values for renovation operations

The necessity of establishing BU benchmark values for their association with stock-level activities dynamics motivates the evaluation and comparison of values for the different activities (e.g. new construction, renovation and demolition). As outlined in the introduction, several studies have proposed BU benchmarks, ranging from the component level to the assessment of hundreds of buildings. As an example, a recent analysis in five European countries have shown average values and data variability around different building use and building structures for different life-cycle stages. For residential buildings, embodied GHGE show a median value of 600 $kgCO_2eq/m^2$, ranging from 400 to 800 $kgCO_2eq/m^2$. For non-residential buildings, they show a median values of 600 $kgCO_2eq/m^2$, but with higher variability between 100 to 1200 $kgCO_2eq/m^2$ (Röck et al., 2022a).

Yet, often BU values are limited to new construction. For renovation, the scarcity of the data can be attributed to the lack of mandatory requirements. Additionally, there exists a diversity of classification for renovation operations (e.g. light or shallow renovation, deep renovation, energy renovation, etc) which often depends on the extent and parts of the building being renovated. As a result, it is difficult to have benchmarks values for different types of renovation works and their associated energy savings. Generally, higher embodied per m^2 are observed for individual dwelling than collective dwelling or office buildings. Technical and electrical systems usually accounts for more than half of the impact (Ramboll et al., 2023). Yet, various studies have underscored that the transition from fossil-fuel-based heating systems exerts the most substantial impact on GHGE and should be prioritised in renovation efforts (Galimshina et al., 2021). In practice, the concept of payback times, indicating the number of years required to offset the embodied GHGE investment through associated operational GHGE savings, is often used in studies. However, estimates for payback times vary widely, ranging from 6 to 70 years (HQE, 2022). Some studies calculate payback times based on the amount of embodied GHGE investment per jump in energy performance certificate (EPC) labels. For instance, they use values like 60$kgCO_2eq/m^2$ for a single EPC label jump and 150 $kgCO_2eq/m^2$ for two to three EPC label jump (RTE and ADEME, 2020).

6.4.2 Existing scenario analysis and roadmaps

At global and EU level

Numerous studies investigate the potential development of the building activities in the next decades. The scale of the studies often differ from geographical scales (e.g. continents, countries, cities, portfolio), as well as stock-level activities (e.g. renovation, new construction, demolition) and scopes of GHGE (operational, embodied or whole-life) or other environmental impacts considered (Röck et al., 2021). Global scenarios exist for residential buildings that focus on GHGE from space heating and cooling (Mastrucci et al., 2021) or material efficiency strategies (Pauliuk et al., 2021) (Fishman et al., 2021) , while multiple national scenarios are available for example in the USA (Berrill et al., 2022) (Arehart et al., 2022), Switzerland (Heeren and Hellweg, 2019), Sweden (Österbring et al., 2019) (Peñaloza et al., 2018), Australia (Stephan and Athanassiadis, 2017), Luxembourg (Mastrucci et al., 2020a) and Norway (Pauliuk et al., 2013b). At EU level, (Ramboll et al., 2023) use building archetypes and stock-level activities to scale up the emission for the entire European building stock. They design three scenarios (BAU, 'Tech' and 'Life') with the help of the EU Calc tool [1] which provides prospective carbon intensity factors for space heating as well as decarbonisation scenarios for construction materials. With a baseline of 1360 MtCO_2eq, among which 79% are operational GHGE and 21% embodied GHGE, the BAU scenario reaches 920 MtCO_2eq while the Tech scenarios reaches 438 MtCO_2eq and the Life scenario reaches 344MtCO_2eq in 2050.

Focus on existing French scenarios

In France, various organisations have proposed decarbonisation across all sectors, among which the French Agency for Ecological Transition (ADEME) (ADEME, 2021a), Negawatt (négaWatt, 2022) and The Shift Project (The Shift Project, 2021). In particular, ADEME in its 'Transition(s) 2050' propose a set of four scenarios, e.g. *Frugal generation (S1)*, *Regional cooperation (S2)*, *Green technologies (S3)*, *Restoration gamble (S4)* (Gaspard et al., 2023). When moving to the energy sectors, the French Transmission System Operator (RTE) provides in depth scenarios for the transformation of electricity grid in order to be aligned with ambitious climate goals (RTE, 2022b).

In the context of the building sector, there is unanimous agreement on the necessity of extensively renovating existing buildings to achieve carbon neutrality in France by 2050 (ADEME et al., 2022). Nonetheless, because of their reliance on the national GHGE inventory format, scenarios do not represent building activities in a holistic way and mostly focus on direct operational GHGE. Scenarios that aim to fulfill the SNBC's goals envision that buildings exclusively use low-carbon energy carriers by 2050. For individual buildings, the primary focus is on heat pumps, with limited use of biomass due to resource constraints. Collective dwellings are expected to connect to renewable energy-powered district heating systems where feasible, or use heat pumps otherwise. In the SNBC scenario, it is anticipated that 85% of new dwellings will switch to electricity, with the remaining 15% adopting biomass or district heating. For existing dwellings, the projected shift is 80% towards electricity and 20% towards a combination of biomass, district heating, and biogas (DGEC, 2021).

[1] Available at http://tool.european-calculator.eu/intro

6.5 Method

As discussed in Section 6.3.1, the integration of TD and BU approaches in the context of stock-level activities, their drivers, and the decarbonisation of upstream sectors is relatively unexplored. Moreover, national level scenarios often fail to connect with building stock and building LCA databases, missing an opportunity to leverage bottom-up information for a comprehensive assessment and tracking of the dwellings GHGE from a well-founded baseline.

To address this gap, the proposed methodology introduces a modular framework designed to investigate the potential drivers behind the evolution of the WLC emissions in residential dwelling stock, with the ultimate goal of dynamically assess their alignment with top-down carbon budgets. The versatility of the approach allows to create multiple scenarios and to highlight the key parameters which have the most substantial impact on WLC emissions. Its novelty lies in harnessing both advanced bottom-up stock and flow data alongside indicators from national scenarios, effectively bridging the gap between bottom-up and top-down methodologies. While specifically tailored to the French context, the versatility and applicability of this method to other nations with similar datasets underscore its value and potential contribution to the scientific community engaged in evaluating WLC emissions reduction strategies.

Figure 6.1 displays the different elements of the modeling framework. Initially, it presents the dwelling stock database along with the dynamics associated with different stock-level activities. Following this, the calculation of operational and embodied GHGE, and the respective prospective pathways for supply activities are introduced. The model parameters are then classified using the 'Avoid-Improve-Shift' framework. Subsequently, a selected set of family scenarios is presented to illustrate the possible combination of parameters, and their alignment with top-down carbon budgets.

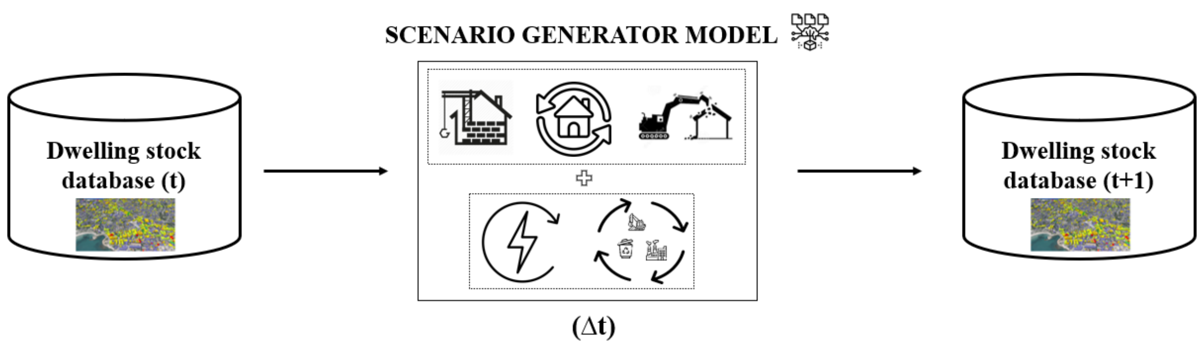


Figure 6.1: Methodology for stock dynamics and integration of energy carriers and construction materials

6.5.1 Dwelling stock database

Presentation of the BDNB and its indicators

The *Base de Données Nationale des Bâtiments* (BDNB) [2] is the French national building stock database. It is the result of geospatial merging of more than twenty databases from public organisations. The core of the BDNB is based on the matching of land taxes files ("Fichiers Fonciers" from the Centre for Studies on Risks, the Environment, Mobility and Urban Planning (CEREMA)), a 3D vectorial description of the buildings with a metric precision (BD TOPO from the National Institute of Geographic and Forest Information (IGN)), and a cadastral database (from Etalab, a department of the Inter-ministerial Directorate for Digital Affairs). It contains information such as the morphology of the buildings (surfaces, heights, number of floors), its materiality, the usage (e.g. individual or collective housing, office buildings, schools, etc). This information is meticulously compiled for each building, providing extensive detail crucial for accurate modeling. Moreover, the BDNB includes data on energy consumption and carbon performance in use. These data originates from the Energy Performance Certificate (EPC) label database managed by ADEME, which encompasses over seven million residential buildings, accounting for approximately 20% of the housing stock. For buildings lacking energy data, the BDNB employs probabilistic predictions using statistical and physical models. These innovative predictions focus on generating input data (such as thermal performance of walls) for subsequent simulations in physical models (Schetelat et al., 2020) (Schetelat, 2023).

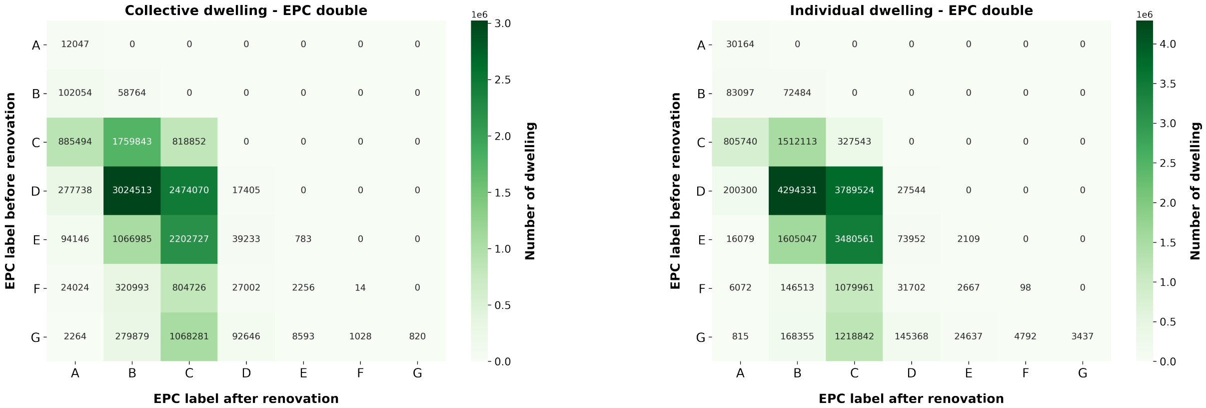
This study primarily concentrates on the energy and carbon information from the database, for which detailed graphs for the year 2020 are presented in Annex 9.5. However, the BDNB not only provides information on the current state of the dwelling stock but also facilitates predictions of future potential energy performance following renovations on millions of dwellings. These predictions are based on potential changes in heating and hot water systems, as well as improvements in the performance of walls, roofs, floors, and windows (detailed in SI 9.5.6). Figure 6.2 provides the number of dwellings passing from a EPC[3] label i to j for collective 6.2a and individual dwelling 6.2b respectively. For both types, the majority of dwellings are projected to achieve at least a C label post-renovation. The greatest shift is anticipated from D to B labels, largely due to the substantial number of dwellings currently at D. Such insights are valuable for assessing the potential future distribution of EPC labels on a national scale.

Calibration of energy values

At national level, the energy balance specifies energy flows for different sectors, including the *residential* sector. In France, it is given by the Statistical Data and Studies Department (SDES) (SDES, 2023). It aggregates energy data for all residential dwellings without differentiating by dwelling type or EPC label. The BDNB complements this dataset by providing these specific distinctions. In this study, these two data sources are integrated with the ultimate aim of determining the final energy consumption by energy carrier for each combination of dwelling type and EPC label. This calibration

[2] Available at https://gitlab.com/BDNB/base_nationale_batiment

[3] the EPC labels are taking into account both energy and carbon performance according to the new legislation (MTES, 2021)



(a) Collective dwelling **(b)** Individual dwelling

Figure 6.2: Change of EPC label per dwelling type according to the BDNB

process is pivotal for enabling comparisons between results obtained from the BDNB and those from national studies, which often rely on the energy balance. Specifically, it has been used for calculating the operational GHGE of the French building stock (Pellan et al., 2023b). Accordingly, the calibration ensures a consistent baseline, essential for monitoring emission trends over the coming decades. The following equation is employed to get the calibrated results:

$$E_{f,dwt,epc,n,calibrated} = E_{f,dwt,epc,n,bdnb} * \frac{E_{f,n,sdes}}{E_{f,n,bdnb}} \tag{6.1}$$

Where $E_{f,n,sdes}$ and $E_{f,n,bdnb}$ are respectively the final energy consumption of energy carrier n given by the SDES and the BDNB, $E_{f,dwt,epc,n,bdnb}$ is the final energy consumption by energy carrier n for each combination of dwelling type *dwt* and EPC label *epc* given by the BDNB, and $E_{f,dwt,epc,n,calibrated}$ is the calibrated final energy consumption by energy carrier n for each combination of dwelling type *dwt* and EPC label *epc*. There are two *dwt* (individual and collective), seven *epc* (from A to G) and seven n (electricity, natural gas, biomass, oil products, district heating, LPG and coal).

Finally, to get the primary energy consumption, the final energy consumption is multiplied by the primary energy factor :

$$E_{p,dwt,epc,n,calibrated} = E_{f,dwt,epc,n,calibrated} * PEF \tag{6.2}$$

Where PEF is the is the primary energy factor of energy carrier n, $E_{f,dwt,epc,n,calibrated}$ is the final energy consumption of dwelling type *dwt*, label *epc* and energy carrier n and $E_{p,dwt,epc,n,calibrated}$ is the primary energy consumption of dwelling type *dwt*, label *epc* and energy carrier n, which is the calibrated value considered in the further calculations to obtain the results.

At the end, it is possible to obtain the ratio of primary energy by m^2 for all combination of dwelling type and EPC label:

$$e_{p,dwt,epc} = \frac{\sum_n E_{p,dwt,epc,n}}{S_{dwt,epc}} \tag{6.3}$$

Where $\sum E_{p,dwt,epc}$ is the sum of primary energy consumption of all energy carriers in dwelling type *dwt* and label *epc*, $S_{dwt,epc}$ is the sum of surface in m^2 for dwelling type *dwt* and label *epc* and $e_{p,dwt,epc}$ is the ratio of primary energy by m^2 for all combination of dwelling type *dwt* and label *epc*.

6.5.2 Dynamics of the dwelling stock

In the study, yearly stock dynamics result from a combination of renovation and demolition potentials obtained from the BDNB. It is paired with a demand-driven approach for new construction.

Renovation and demolition potential

From the BDNB, a transition matrix (TM) that represents a numerical representation of Fig. 6.2 is created to represent the potential number of dwellings (and associated surface) transitioning from one specific EPC label before renovation to another EPC label after undergoing renovation:

$$TM = \begin{bmatrix} Dw_{A,A} & Dw_{A,B} & \cdots & Dw_{A,G} \\ Dw_{B,A} & Dw_{B,B} & \cdots & Dw_{B,G} \\ \vdots & \vdots & \ddots & \vdots \\ Dw_{G,A} & Dw_{G,B} & \cdots & Dw_{G,G} \end{bmatrix} \tag{6.4}$$

Where rows represent the EPC label before renovation and columns represent the EPC label after renovation. Each $Dw_{i,j}$ represents the number of dwellings (or surface) passing from a EPC label i to j. As it is assumed that dwellings cannot experience a degradation in their EPC label over the time period, all $Dw_{i,j}$ where i ≤ j are empty.

The scenario rationales are then constructed from reaching certain yearly level or targeting certain segments $Dw_{i,j}$. Two main scenarios are defined for renovation and demolition:

- **High Renovation Scenario (HRS)**: an equivalent of 750,000 dwellings is renovated per year. It results in more than 23 million dwellings renovated by 2050, representing two-third of the actual dwelling stock.
- **Medium Renovation Scenario (MRS)**: an equivalent of 250,000 dwellings is renovated per year. It results in less than 8 million dwellings renovated by 2050, representing 22% of the actual dwelling stock.
- **High Demolition Scenario (HDS)**: all dwellings $Dw_{i,j}$ where $G \leq i \leq D$ and $G \leq j \leq D$, plus $Dw_{G,C}$ and $Dw_{F,C}$ are demolished. It results in around 150,000 dwellings or 10,059,233 m^2 demolished per year, focused on dwellings which have poor performance and relatively low surface area (see SI 9.5.2).
- **Medium Demolition Scenario (MDS)**: all dwellings $Dw_{i,j}$ where $G \leq i \leq D$ and $G \leq j \leq D$, plus $Dw_{G,C}$ are demolished. It results in around 90,000 dwellings or 5,776,370 m^2 demolished per year.

Renovation and demolition dynamics

After determining the renovation potential and demolition potential over the specified time frame, these potentials are then combined with distribution functions. These functions are designed to allocate the potentials across the time period (e.g. 2020 to 2050) to create renovation and demolition paces. This allocation may follow different dynamics, such as a constant number of annual operations, a linear increase of operations fostered by renovation policies or a linear increase followed by a plateau signaling a potential technical or socio-economic limitation on further annual renovations. In order to calibrate the renovation data from 2020 to 2022, this study relies on the number of renovations accounted in the Effinergie+ database (Effinergie, 2023). It only accounts for deep and efficient renovation ('*BBC renovation*'), which is consistent with the logic of starting with the biggest renovation in the modelling order. The repartition of renovation operations between the different dwelling type (e.g. collective and individual dwellings) is based on the current repartition in number of dwelling of the stock (e.g. 55% individual dwellings and 45% collective dwellings).

Targeting renovation strategies

Subsequently, to distribute these annual rates to specific dwellings, two distinct targeting strategies are examined. The first strategy aligns with the phased rental ban on energy-inefficient housing (MTES, 2021). It initially focuses on the lowest EPC labels (e.g. with the worst performance), progressively moving towards the higher ones. In terms of renovation, the approach begins with segments that offer the highest potential for energy savings (e.g., $Dw_{G,A}$). Conversely, for demolition, the focus is first on segments with the lowest ratings and no prospects of energy performance improvement (e.g., $Dw_{G,G}$). The second strategy is designed to evaluate alternative policies aimed at phasing out fossil fuel utilisation. Following the elimination of F and G labels, which are to happen in the next decade, the focus shifts to eradicating fossil fuel dependence in dwellings rated E to C. After this phase, the targeting strategy reverts to the standard order.

Energy carriers changes in renovation operations

To reduce operational GHGE due to buildings operation and diminish reliance on fossil fuels, scenarios and policies frequently focus on three primary of low-carbon energy carriers: biomass, district heating, and electricity. Electricity, often used in conjunction with heat pumps, is by far the most prevalent of these. This study takes advantage of the French scenarios presented in 6.4.2 to apply percentage changes in energy sources depending on the dwelling type. For collective dwellings, it is assumed that 80% will transition to electricity and 20% to district heating. For individual dwellings, the expected shift is 80% to electricity and 20% to biomass.

Construction dynamics

For new construction, the method follows a demand-driven approach that require several steps. First, the surface area required to meet population needs on an annual basis is calculated each year until 2050. Subsequently, the projected potential growth in demand during two years (e.g. between t

and *t+1*) is summed with the surface area demolished during year t to determine the construction surface during year t. The following equations are employed:

$$S_{needs}(t) = K(t) * P(t) \tag{6.5}$$

$$S_{new}(t) = S_{needs}(t+1) - S_{needs}(t) + S_{dem}(t) \tag{6.6}$$

Where $S_{needs}(t)$ is the surface needs in year t, $K(t)$ is the number of m^2 *per capita* in year t, $P(t)$ is the national population in year t, $S_{new}(t)$ is the constructed surface in year t and $S_{dem}(t)$ is the demolished surface in year t from the transition matrix.

Later, the construction needs in surface are split between dwelling type, (e.g. individual housing and collective housing):

$$S_{new,dwt}(t) = S_{new}(t) * p_{dwt}(t) \tag{6.7}$$

Where $p_{dwt}(t)$ is the share of dwelling type *dwt* in year t from the total new constructed surface $S_{new}(t)$ in year t, and $S_{new,dwt}(t)$ is the new constructed surface of dwelling type dwt in year t.

Finally, the newly constructed surfaces are translated into constructed dwellings:

$$Dw_{dwt}(t) = \frac{S_{new,dwt}(t)}{S_{average,dwt}(t)} \tag{6.8}$$

Where $S_{average,dwt}(t)$ is the average surface of dwelling type *dwt* in year t and $Dw_{dwt}(t)$ is the number of construction dwellings *dwt* in year t.

6.5.3 Energy and operational GHGE calculations and energy carriers decarbonisation

Energy and operational GHGE calculation

To calculate operational GHGE of the stock, final energy consumption per energy carriers (expressed in kWh) needs to be coupled with emission factors (in kgCO_2eq/kWh) for each dwelling type and EPC label. First, the primary energy consumption for each energy carrier n resulting from renovation and demolition activities is given yearly by:

$$\begin{aligned} E_{p,dwt,epc,n}(t+1) = E_{p,dwt,epc,n}(t) \\ - (S_{ren,dwt,epc}(t) \cdot e_{p,epc,bren})(t) \\ + (S_{ren,dwt,epc}(t) \cdot e_{p,epc,aren})(t) \\ - (S_{dem,dwt,epc}(t) \cdot e_{p,epc})(t) \end{aligned} \tag{6.9}$$

Where $E_{p,dwt,epc,n}(t)$ and $E_{p,dwt,epc,n}(t+1)$ represent the primary energy consumption of dwelling type *dwt* with label *epc* and energy carrier n respectively in year t and $t+1$, $S_{ren,dwt,epc}(t)$ is the renovated surface of dwelling type *dwt* with label *epc* in year t, $S_{dem,dwt,epc}(t)$ is the demolished surface of dwelling type *dwt* with label *epc* in year t. $e_{p,epc,bren}(t)$ and $e_{p,epc,aren}(t)$ are respectively the primary energy consumption per m^2 for label *epc* before and after renovation.

For new construction, the surface per dwelling type is multiplied by the primary energy consumption per m^2 per dwelling type given by the RE2020:

$$E_{p,dwt,new,n}(t) = S_{new,dwt,n}(t) * e_{p,dwt,new} \tag{6.10}$$

Where $e_{p,dwt,new}$ is the primary energy consumption per m^2 for new constructed dwelling type *dwt*, $S_{new,dwt,n}(t)$ is the new constructed surface in m^2 of dwelling type *dwt* with energy carrier n in year t and $E_{p,dwt,new,n}(t)$ is the primary energy consumption of dwelling type *dwt* with energy carrier n in year t. $e_{p,dwt,new}$ is equal to 70kWh/m^2/year for collective dwelling and 55kWh/m^2/year. It is assumed that 90% of new collective dwelling are using electricity, and 10% are connected to district heating, while for new individual dwelling it is assumed that 80% are using electricity and 20% are using biomass.

At last, it is possible to calculate the operational GHGE of the entire stock at time t, by summing the final energy consumption of the remaining stock and the new constructed surface for each energy carrier n:

$$\theta(t) = \sum_{dwt,epc,n} (E_{f,dwt,epc,n}(t) + E_{f,dwt,new,n}(t)) * f_{\theta,dwt,n}(t) \tag{6.11}$$

Where $f_{\theta,n}(t)$ is the operational emission factor of energy carrier n, $E_{f,dwt,new,n}(t)$ is the final energy consumption of new constructed dwelling type *dwt* with energy carrier *n* in year *t* and $E_{f,dwt,epc,n}(t)$ is the final energy consumption of dwelling type *dwt* with label *epc* and energy carrier n in year t. $\theta(t)$ is the operational GHGE of the entire stock at time t, expressed in MtCO$_2$eq in the results.

Energy carriers decarbonisation

This study introduces three scenarios to investigate the evolving emission factors of critical energy carriers over time. The analysis specifically concentrates on electricity, district heating, and gas (through the integration of biogas in the gas network). These energy carriers are emphasised due to their projected dominance in future energy mixes, with electricity expected to play a particularly central role. Additionally, they represent significant decarbonisation opportunities in the coming years, making them pivotal in the context of reducing greenhouse gas emissions. However, it is still important to note that the emission factor for electricity in France is already low, primarily due to its production from low-carbon sources such as nuclear and hydropower. Despite this, the generation of electricity from gas power plants, a significant contributor to GHGE today, offers considerable opportunities for further decarbonisation.

In this study, three scenarios are employed for exploratory purposes. The 'Constant' scenario serves as a conservative baseline, assuming that emission factors remain unchanged from their 2022 levels. In contrast, the 'SNBC' scenario envisions highly ambitious pathways for electricity, natural gas, and district heating, aligned with the objectives of the SNBC. Additionally, a 'Half' scenario is introduced as a moderate option, representing a middle ground between the two extremes.

6.5.4 Embodied GHGE calculation and scenarios for future limit values

Statistical analysis of the RE2020 building LCA database

To calculate embodied GHGE at time *t*, new constructed, renovated and demolished surfaces are coupled with GHGE values per m^2. These values are derived from a statistical analysis of the RE2020 building LCA database (more information is provided in Annex 9.5). The database aggregates building LCA data compiled in accordance with the EN15978 Standard. This process-based approach often underestimates environmental impacts due to truncation issues (Crawford et al., 2018). Specifically, in the building context, employing various methods for the compilation of Life Cycle Inventory (LCI) data has demonstrated considerable variability in outcomes (Venkatraj and Dixit, 2021). However, the availability of building LCA using hybrid coefficients is limited, posing a challenge to the adoption of such comprehensive methods.

Figure 6.3 presents the GHGE values per square meter for individual and collective dwellings, broken down by life-cycle stages according to the EN-15978 standard.

The A1-A3 life-cycle stage is identified as the most impactful, whereas the C stage has the lowest impact. On average, collective dwellings exhibit a higher environmental impact per square meter compared to individual dwellings, although the difference is relatively modest.

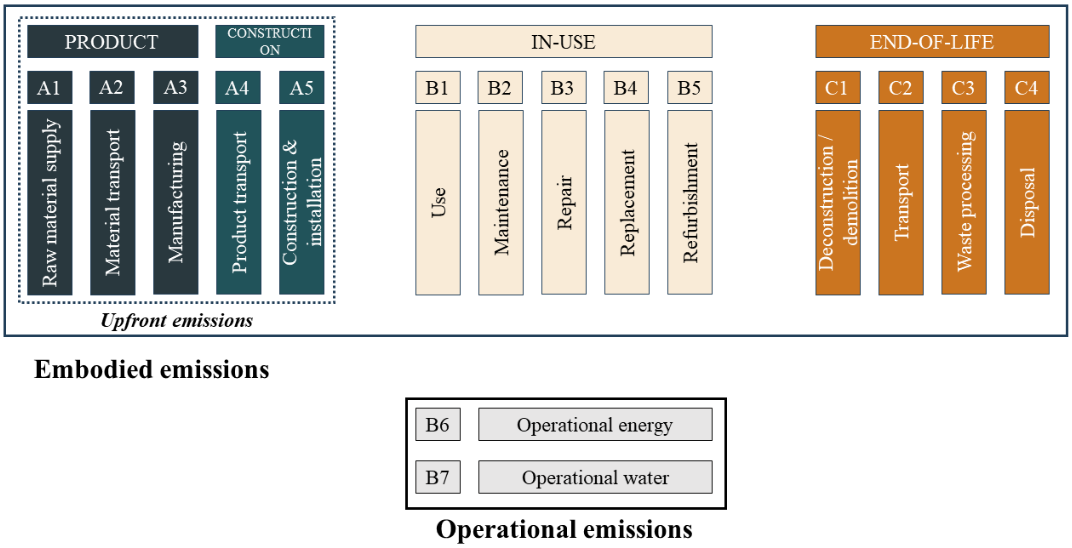
In this study, median values from life-cycle stages A and B are aggregated to determine the embodied emissions for new constructions. For demolitions, the median value from life-cycle stage C is used. For renovations, all life-cycle stages are accounted. This approach assumes that they encompass the end-of-life considerations for existing components within the building and any additional components introduced during renovation. A more detailed analysis is employed to have the values broken down by building component groups as outlined in the RE2020 (more information is given in SI 9.6). The performance level of the renovation, assessed based on the number of jumps in EPC label jumps, dictates which specific building component groups are affected. This methodology closely aligns with the approach used in the French *Quartier Energie Carbone* study (CSTB et al., 2022).

Calculation of embodied GHGE

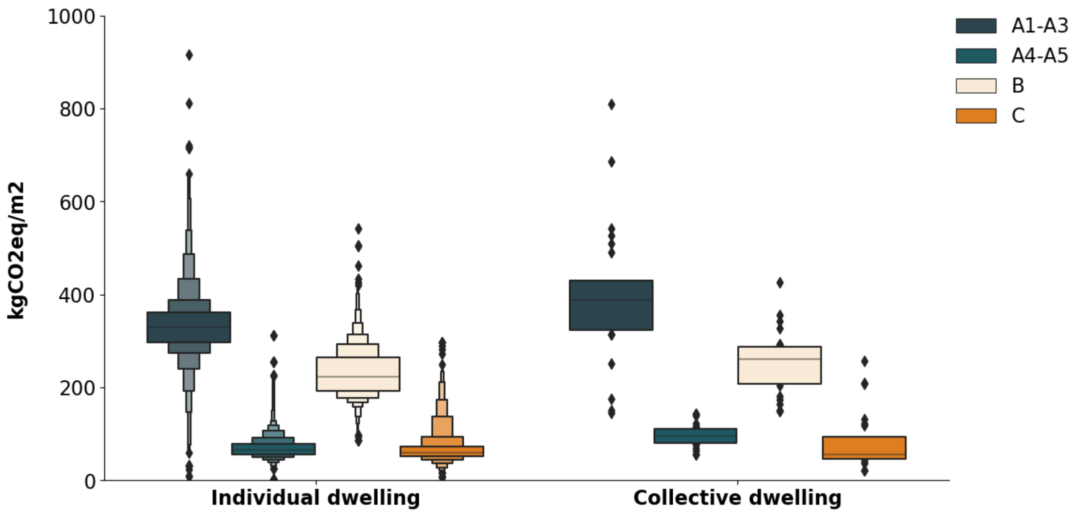
The calculation of embodied GHGE then follows the following logic:

$$\begin{aligned} e(t) = \sum_{dwt} \Big(& S_{new,dwt}(t) \cdot f_{\varepsilon,new,dwt} \\ & + S_{dem,dwt}(t) \cdot f_{\varepsilon,dem,dwt} \Big) \\ + \sum_{dwt,epc\,jump} & S_{ren,dwt,epc\,jump}(t) \cdot f_{\varepsilon,ren,dwt,epc\,jump} \end{aligned} \tag{6.12}$$

Where $S_{new,dwt}(t)$ is the new constructed surface of dwelling type *dwt* in year *t*, $S_{dem,dwt}(t)$ is the demolished surface of dwelling type *dwt* in year *t*, $S_{ren,dwt,epcjump}(t)$ is the renovated surface of dwelling type *dwt* for EPC label jump *epc jump* in year *t*, while $f_{\varepsilon,new,dwt}$, $f_{\varepsilon,dem,dwt}$ and $f_{\varepsilon,ren,epcjump}$ are respectively the values of embodied emissions (in $kgCO_2eq/m^2$) for new construction, demolition



(a) Life-cycle stages in the EN15978



(b) Building components embodied values per dwelling type and life-cycle stages per m^2 of living area

Figure 6.3: Embodied values per life-cycle stages

and renovation per dwelling type *dwt* and per EPC label jump for $f_{\varepsilon,ren,epcjump}$. Finally, $e(t)$ is the embodied GHGE of the entire stock at time t, expressed in $MtCO_2eq$ in the results.

Evolution of limit values

To model different trajectories of embodied GHGE limits in stock-level activities (e.g. $f_{\varepsilon,new}, f_{\varepsilon,dem}, f_{\varepsilon,ren}$), two scenarios are constructed. The first scenario, 'RE2020', is based on the currently planned declining GHGE limit values by 2031 of the RE2020. After this date, it assumes these values will plateau, indicating a technological stagnation where further reductions in GHGE are not feasible. The second scenario, 'RE2020+', is more ambitious as it extrapolates the decline in GHGE limits observed from 2022 to 2031 up to 2050. This scenario envisions the advent of breakthrough technologies or the widespread adoption of low-carbon materials, like bio-based materials or circular solutions. These scenarios are applied to $f_{\varepsilon,new}$ and $f_{\varepsilon,ren}$ while $f_{\epsilon,dem}$ is assumed constant over the period.

6.5.5 Framing of solutions for each parameters

The parameters used in the modelling process are classified in Table 6.1 using the Avoid/Shift/Improve framework presented in section 6.3.2 accompanied by examples of solutions for each category.

Table 6.1: Framing of model parameters in the 'Avoid-Improve-Shift' framework and examples of solutions

	Avoid	**Improve**	**Shift**
Parameters in the modelling framework	P, K, S_{dem}	S_{ren}	f_{θ}, f_{ε}, p_{dwt}, $S_{average,dwt}$
Example of solutions	Optimising the use of existing space	Extending building and components lifespan	Using bio-based materials and renewable energy

For 'Avoid' solutions, population (P), floor area *per capita* (K) and demolition potential (S_{dem}) are three variables that enable to modify the new construction surface. Thus, by applying low values to these parameters, it is possible to avoid new constructed surface and their associated GHGE, in particular the embodied GHGE which are preponderant in new construction (Röck et al., 2020). Solutions encompass optimising the use of existing stock , for instance, through the promotion of co-living arrangements or re-purposing unoccupied offices into residential spaces (Gaspard et al., 2023). For 'Improve' solutions, renovation potential plays a crucial role in enhancing the energy efficiency of dwellings. A higher renovation rate aligns with 'Improve' strategies aimed at improving the performance of existing structures. Examples of solutions include extending the lifespan of buildings and their components to spread their environmental impacts over a longer duration or adopting light construction techniques that adhere to material efficiency principles.

For 'Shift' solutions, operational (θ) and embodied (ε) limit values represent 'Shift' strategies, indicating a transition toward lower-carbon energy sources and materials. These transformation implies deep decarbonisation in the energy and industry sectors respectively. This shift also entails a change in current practices to increase the market share of low-carbon or carbon-negative options (Carcassi et al., 2022). Lastly, variables like the proportion of dwelling types (p_{dwt}) and the average size of dwellings ($S_{average,dwt}$) can also be viewed as 'Shift' strategies, though they closely align with 'Avoid' solutions. Indeed, prioritising collective dwellings and opting for smaller dwelling sizes can embody sufficiency strategies, fulfilling population needs while minimising environmental footprints. Collective dwellings typically depict smaller impact per *capita* when compared to individual dwellings. Encouraging smaller size dwellings also aligns with the core needs, preventing excessive energy and material consumption.

6.5.6 Selected scenarios

To manage the complexity arising from the numerous possible scenarios generated by various combinations of parameters in WLC emissions calculations, two primary sets of scenarios are studied: 'BAU' (Business As Usual) and 'AMB' (Ambitious). In the context of the study, 'BAU' represents outcomes based on existing policies, while 'AMB' models more ambitious outcomes aligned with the pledges announced by the SNBC. In both scenarios presented in this study, the 'Central' scenario for population growth projection provided by INSEE (INSEE, 2021) is used. This choice is motivated by the fact that population growth is exogenous from building activities, and therefore should not serve as an underlying lever for achieving ambitious decarbonisation targets. Beyond this commonality, the scenarios diverge in terms of square meters per *capita* (K), the proportion of dwelling types (p_{dwt}), and the average size of dwellings $(S_{average,dwt})$. Two assumptions are made regarding $K(t)$: either maintaining a constant number of m^2 *per capita* at the current level or enacting a linear decrease to reach 42 m^2 *per capita* inspired by values suggested by Negawatt and the IPCC (négaWatt, 2022) (Cabeza et al., 2022). The BAU scenario maintains the existing distribution of new construction between collective and individual dwellings and preserves the current average dwelling size. In contrast, the AMB scenario favors collective dwellings and gradually reduces the average dwelling size, reflecting an implementation of sufficiency measures. The BAU scenario not only demonstrates a higher construction and demolition rate but also exhibits fewer renovation activities that linearly grows by 2050. It also adopts more conservative pathways for energy carriers and construction materials decarbonisation. Conversely, the AMB scenario feature higher rates of renovation which plateau by 2040, and more ambitious trajectories for energy carriers and construction materials decarbonisation.

Table 6.2 provides a comprehensive list of the parameters that differ between these scenarios. Additionally the plotted stock-dynamics is available in Annex 9.5.

While displaying contrasting scenarios provides valuable insights, it is equally important to assess the parameters which have the most significant impact on WLC emission. To address this, the study introduces a sensitivity analysis in a second step to delve deeper into the impact of specific variables. To this end, this analysis integrates the dynamics of stock-level activities from both scenario sets and examines various decarbonisation pathways for energy carriers ('Constant', 'Half' and 'SNBC') and construction materials ('RE2020' and 'RE2020+'). The ultimate aim of the sensibility analysis is to determine whether the degree of supply-side decarbonisation significantly influences the outcomes across diverse scenarios for stock-level dynamics.

6.5.7 Comparing bottom-up pathways with top-down targets

To assess whether the dynamics of the dwelling stock align with climate objectives, this study proposes to combine the results of the described approach with previous work that focuses on defining scenario-based top-down budgets (Pellan et al., 2023b). The comparison helps to quantify performance gaps and illustrates in which top-down scenarios the dwelling stock scenarios may fit into. In Pellan et al. (2023b), budgets are allocated for all building activities, without specific differentiation by building type. Consequently, when comparing the outcome of the dwelling stock scenarios with

Table 6.2: Description of parameters used in 'BAU' and 'AMB' scenarios

	BAU	AMB
Renovation potential	250,000 dwellings/yr	750,000 dwellings/yr
Renovation pace	Linear rising until 2050	Plateau in 2040
Demolition	150,000 dwellings/yr	90,000 dwellings/yr
Population	Central (INSEE)	Central (INSEE)
m^2	43 (constant)	42 by 2050 (linear decrease)
p_{dwt}	41% individual 59% collective (constant)	25% individual 75% collective (linear decrease by 2050)
$S_{average,dwt}$	107 individual 57 collective (constant)	100 individual 57 collective (linear decrease by 2050)
Construction materials scenario	RE2020	RE2020+
Energy carriers scenario	Constant	SNBC

the allocation budgets, it is important to remember that a portion of these budgets is also designed for non-residential buildings. Table 6.3 provides values for the different scenarios and scopes of GHGE.

Table 6.3: Top-down annual budgets values in $MtCO_2eq$ derived from Pellan et al. (2023b)

	Operational GHGE (MtCO2eq)	Embodied GHGE (MtCO2eq)
SNBC scenario	63.7 in 2030 34.9 in 2040 6 in 2050	x
Announced Pledges Scenario	x	52.4 in 2030 34.4 in 2040 21.7 in 2050
Net Zero Scenario	x	44.2 in 2030 17.8 in 2040 2.2 in 2050

The budgets are based on the SNBC pathways for operational GHGE while embodied GHGE pathways are based on scenarios designed by the International Energy Agency (IEA). In particular, the original study focuses on three IEA scenarios: the Stated-Policies Scenario (STEPS), the Announced Pledges Scenario (APS), which is a predictive what-if scenario, and the Net-Zero Scenario (NZS), a normative transformative scenarios. The latter two are of particular interest in the present study, given their ambitious nature and close alignment with the climate objectives established in the Paris

Agreement. The APS assumes that climate targets made by countries are implemented fully and on time and is associated with a 1.7°C temperature rise in 2100, while the NZS is compatible with a 1.5°C temperature rise in 2100 with limited overshoot.

6.6 Results

Based on the description provided in 6.5.6, the first results highlight contrasted scenarios for the two proposed targeting strategies presented in Section 6.5.2. They are displayed on an annual basis to track their evolution over time, and cumulatively to align with the concept of the remaining carbon budget. Operational GHGE are delineated by EPC labels and energy carriers, while embodied GHGE are differentiated between the different stock-level activities (e.g. construction, renovation and demolition). In a second step, the result of the sensitivity analysis is shown to assess the evolution of the different stock-dynamics to different decarbonisation scenarios of supply sectors. Lastly, the results are compared to top-down annual carbon budgets to assess their compatibility with overall climate goals.

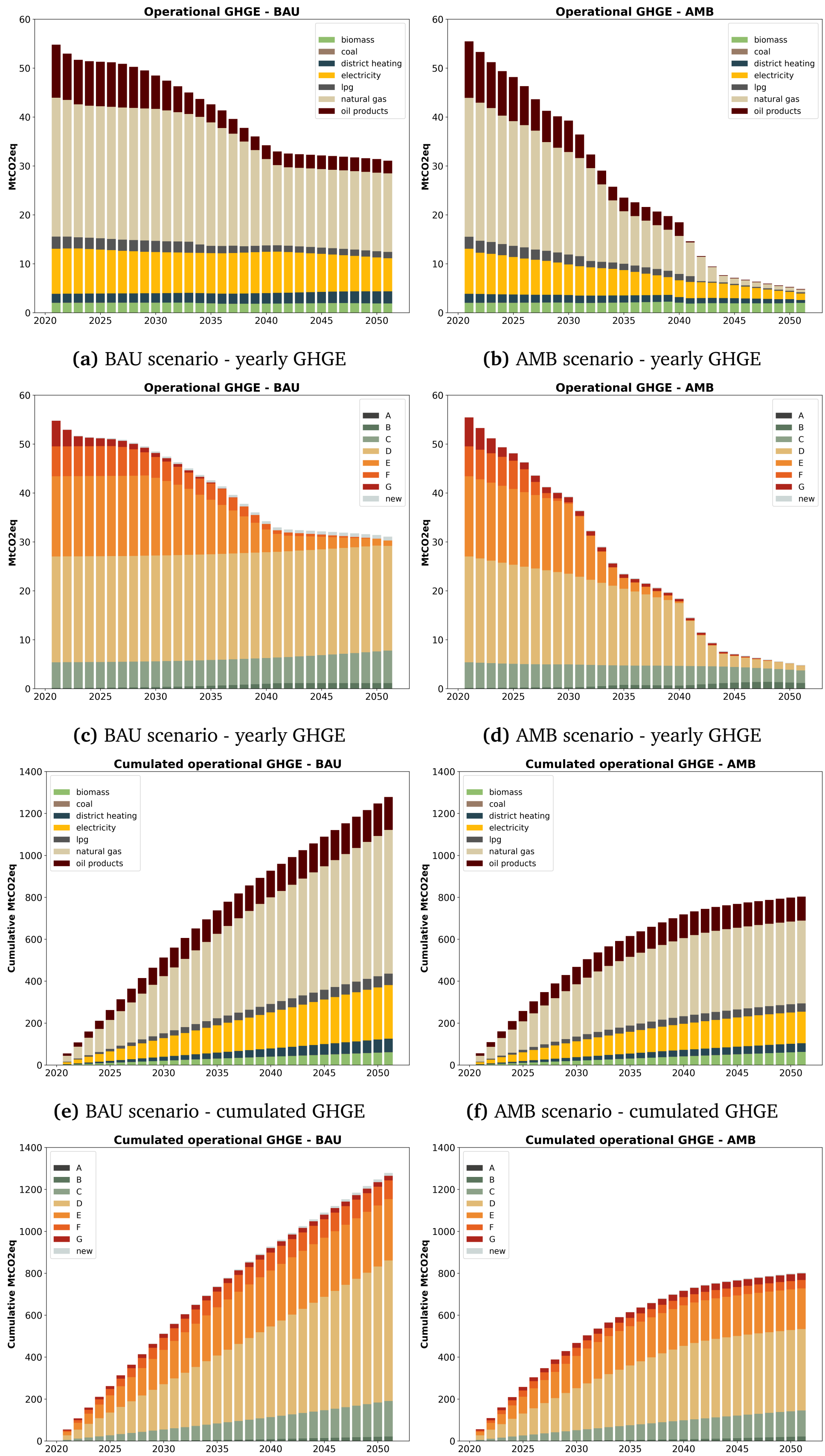
6.6.1 Results for selected scenarios

Operational GHGE results for the EPC targeting variant

In Figure 6.4, the BAU and AMB scenarios operational GHGE results by energy carriers and EPC labels are provided both for yearly results from 2020 to 2050 (top four graphs) and cumulatively (bottom four graphs).

The two scenarios show similar results with respect to three observations. Firstly, the share of the worst EPC labels and highest-emitting energy carriers decrease over the next decades as their renovation or demolition is addressed first. Secondly, there is a significant impact on cumulative operational GHGE from buildings with 'C' and 'D' labels and those relying on fossil fuels, especially natural gas. Thirdly, the contribution of newly constructed dwellings to both annual and cumulative GHGE is minimal in both scenarios.

Despite these similarities, the scenarios exhibit notable differences in GHGE trends. In the BAU scenario, starting from a baseline of 58 $MtCO_2eq$, there is a gradual decrease in annual GHGE, reaching 34 $MtCO_2eq$ after 30 years, equating to a 41% reduction. This decrease in GHGE, however, begins to plateau by 2040. The plateau is attributed to many dwellings undergoing renovation with relatively poor energy performance to better performance (e.g., $Dw_{E,B}$ and $Dw_{E,C}$) while already relying low-carbon energy sources, thereby limiting further reductions in GHGE momentarily. In contrast, the AMB scenario displays a steep decrease in annual GHGE to reach 8 $MtCO_2eq$ (e.g. a 86% decrease in 30 years). This scenario experiences two plateau phases, one between 2035 and 2040, and another between 2045 and 2050, for similar reasons as in the BAU scenario. However, due to a higher number of annual renovations targeting different dwelling segments, the overall GHGE reduction is more substantial. As a result, in the BAU scenario, cumulative operational GHGE continue to rise quite linearly, whereas in the AMB scenario, there is a slower increase starting from 2035, almost reaching a plateau by 2045. By 2050, the cumulative operational GHGE reaches 1334 $MtCO_2eq$ in



(a) BAU scenario - yearly GHGE

(b) AMB scenario - yearly GHGE

(c) BAU scenario - yearly GHGE

(d) AMB scenario - yearly GHGE

(e) BAU scenario - cumulated GHGE

(f) AMB scenario - cumulated GHGE

(g) BAU scenario - cumulated GHGE

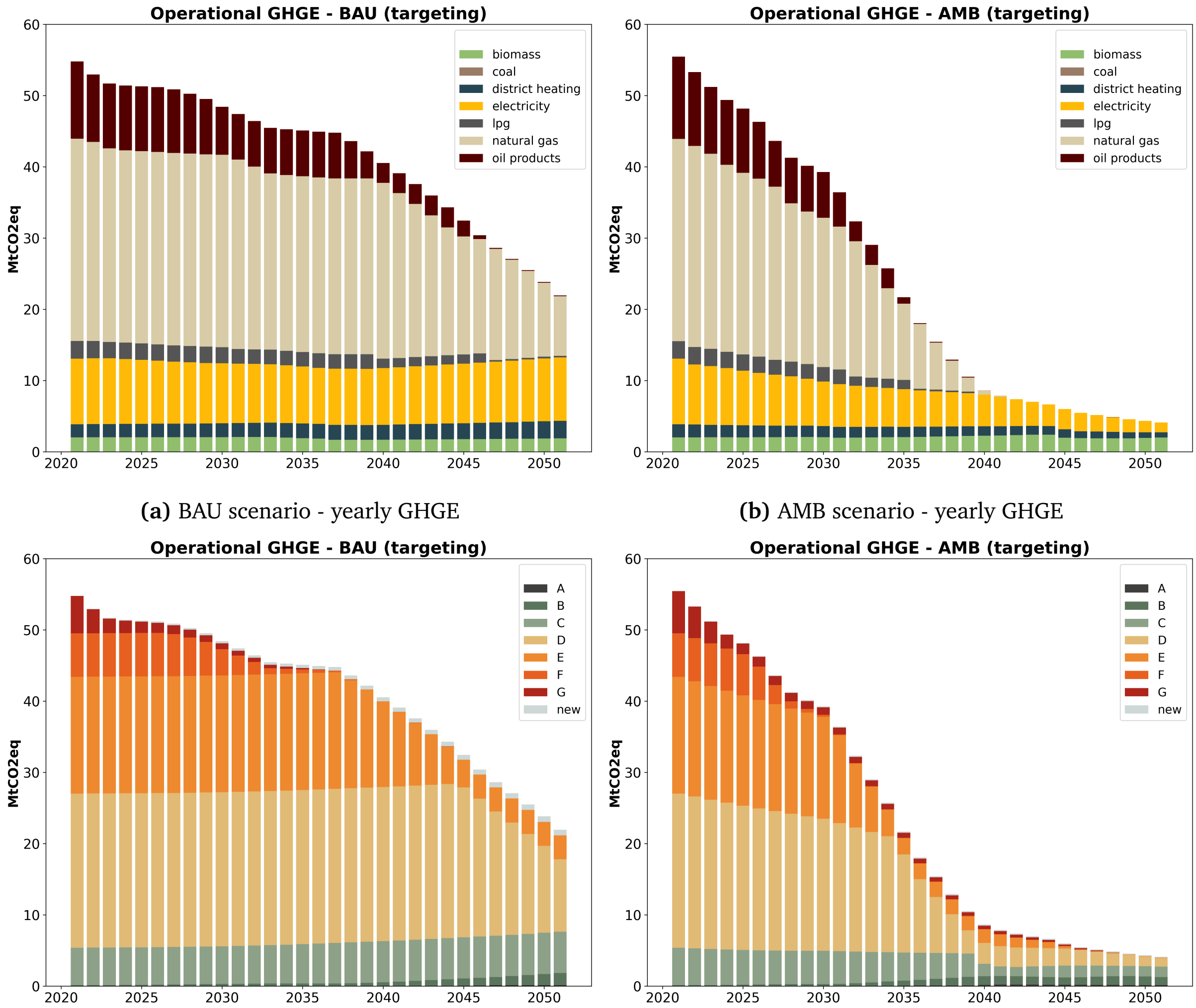
(h) AMB scenario - cumulated GHGE

Figure 6.4: Evolution of yearly and cumulated operational GHGE by energy carriers and EPC labels for BAU and AMB scenarios

the BAU scenario compared to 924 $MtCO_2$eq in the AMB scenario. This difference of 410 $MtCO_2$eq is roughly equivalent to France's territorial GHGE in 2020.

Operational GHGE results for the fossil fuel targeting variant

When looking at Figure 6.4, both scenarios experience plateaus that are attributable to the renovation of dwellings that, despite their relatively poor energy performance, already rely on low-carbon energy carriers. This observation suggests that a renovation strategy focused solely on targeting dwellings based on their EPC labels may be suboptimal for reducing operational GHGE. Figure 6.5 presents yearly operational GHGE for the alternative strategy of phasing out fossil fuels for E-D-C labels after addressing the most inefficient ones (e.g. F-G), as described in Section 6.5.2. These results should be analysed in conjunction with those from Figure 6.4 to discern the comparative effectiveness of these strategies.



(a) BAU scenario - yearly GHGE

(b) AMB scenario - yearly GHGE

(c) BAU scenario - yearly GHGE

(d) AMB scenario - yearly GHGE

Figure 6.5: Evolution of yealy GHGE by energy carriers and EPC in the fossil fuel targeting alternative scenario

In the BAU scenario, unlike the anticipated plateau, a more pronounced decrease is observed after 2035. This reduction is largely attributed to the diminishing use of natural gas and oil products, the latter being phased out by 2047. In 2050, the annual operational GHGE reach 22 $MtCO_2eq$, e.g. a 35% decrease compared to Figure 6.4 for the same year. On the other hand, there is a higher share of 'E' labels, reflecting a less intensive effort towards their removal. The results show a similar pattern for the AMB scenario. The expected plateau in 2035 does not materialize, and instead, there is a sharp decline until 2041, coinciding with the complete phase-out of all fossil fuels. In the final decade, the residual operational GHGE predominantly arise from low-carbon energy carriers, such as electricity, district heating, and biomass.

Embodied GHGE results for selected scenarios

Turning to embodied GHGE, the disparities between the different targeting variants are relatively minor. Consequently, only the results for the second variant are discussed, since it demonstrates superior performance.

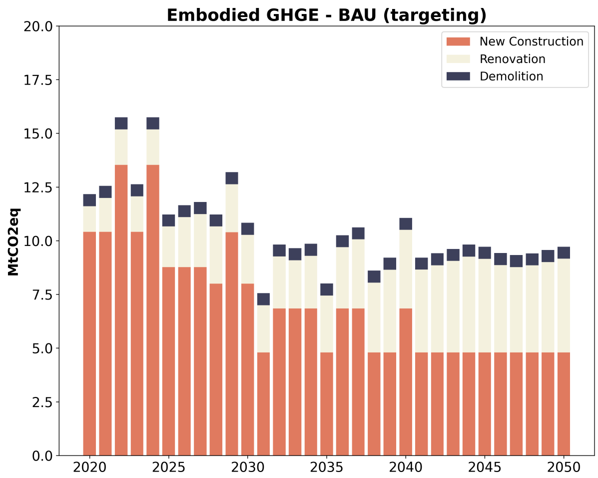
Compared to operational GHGE results, the difference between the BAU and AMB scenarios is less pronounced in absolute terms. Yet the repartition of GHGE between the different stock-level activities is very different between the two scenarios. Figure 6.6 presents both the annual (top) and cumulative (bottom) results for the two scenarios.

In the BAU scenario, the higher rate of construction significantly influences embodied GHGE. Here, new construction accounts for 67% of the cumulative embodied GHGE, with annual contributions never falling below 40%. Conversely, in the AMB scenario, new construction makes up only 40% of the cumulative GHGE, and its yearly contribution decreases over time. In this scenario, renovation activities begin to dominate by 2030, eventually stabilizing at around 70%. In both scenarios, the impact of demolition remains consistent due to a fixed demolition rate, contributing relatively minor amounts to the total embodied GHGE.

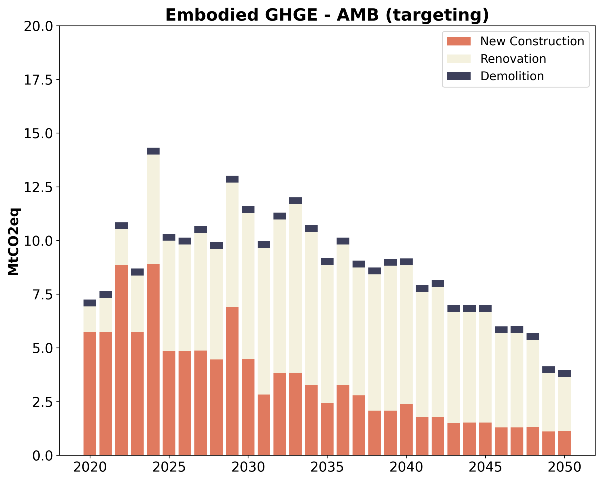
6.6.2 Sensitivity analysis on upstream sectors decarbonisation pathways

By combining the two set of family scenarios for stock-dynamics with different energy carriers and construction materials decarbonisation scenarios described in Section 6.5.3, the sensitivity analysis displays distinct outcomes. They are presented for the fossil fuel targeting variant and are designed to illustrate the influence of the supply-side parameters on the yearly operational and embodied GHGE for a same stock-dynamics scenario. The sensitivity analysis also incorporates the two variants of renovation paces described in Section 6.5.2.

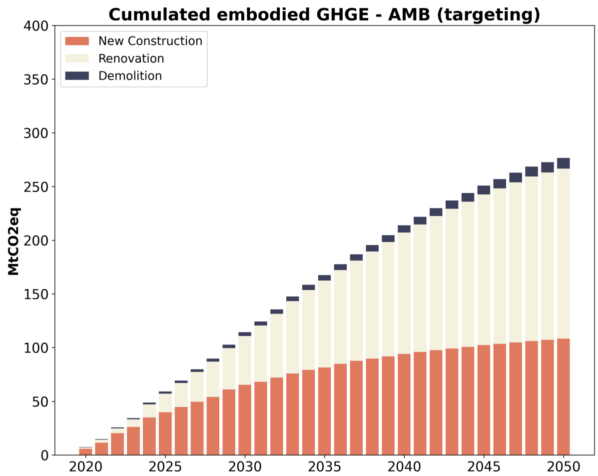
The analysis results in six variants for operational results (e.g. 'Constant', 'Half' or 'SNBC' pathways combined with 'Linear' or 'Plateau' renovation paces), and four variants for embodied results (e.g. 'RE2020' and 'RE2020+' combined with 'Linear' or 'Plateau' renovation paces). Figure 6.7 provides the yearly operational GHGE (top) and embodied GHGE (bottom) sensitivity results. In examining operational GHGE, significant variations are observed across both BAU and AMB scenarios compared to previous results, where the BAU scenario aligned with less ambitious targets and the AMB scenario corresponded to more ambitious ones, as detailed in Table 6.2. Here, the sensitivity results differ for a same stock-dynamics scenario. For instance in 2050, the BAU scenarios project operational GHGE



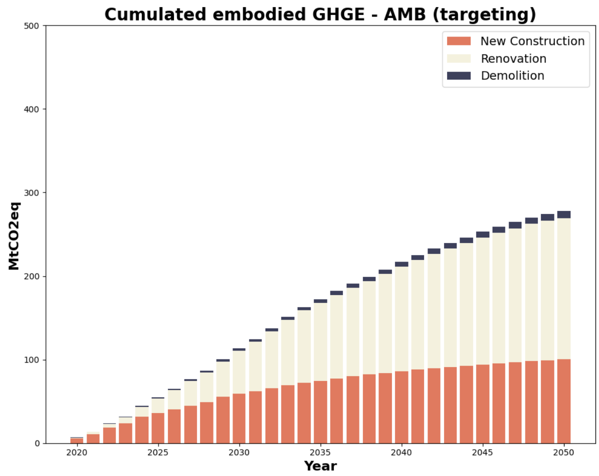
(a) BAU scenario - yearly GHGE



(b) AMB scenario - yearly GHGE



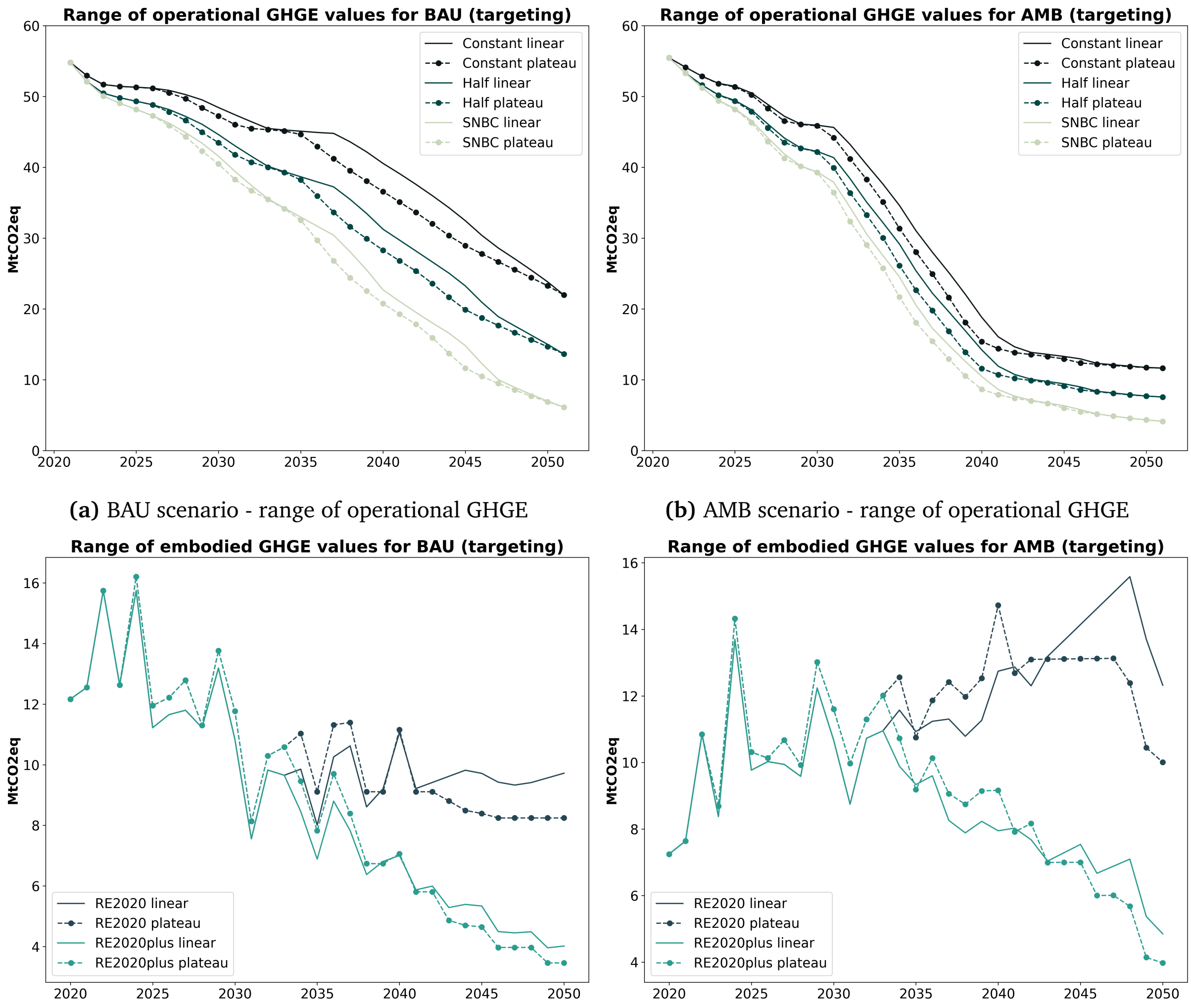
(c) BAU scenario - cumulated GHGE



(d) AMB scenario - cumulated GHGE

Figure 6.6: Evolution of yearly and cumulated embodied GHGE by stock-level activities for BAU and AMB scenarios

at 22, 14, or 6 $MtCO_2eq$ under the 'Constant', 'Half', and 'Quarter' energy carriers scenarios respectively. In contrast, the AMB scenarios anticipates 12, 8, or 4 $MtCO_2eq$. This disparity highlights the pivotal role of energy carriers in the decarbonisation process and their potential impact on reducing operational GHGE. Nevertheless, only the most ambitious scenario (e.g. 'SNBC') paired with the BAU attain similar GHGE levels as the AMB scenarios. This coupling might however be considered very unlikely, as a more energy-efficient stock is also a prerequisite for the successful decarbonisation of the energy sectors. This outcome highlights the significance of stock-dynamics, particularly the impact of extensive renovation activities, exemplified by an annual difference of 500,000 dwellings between the BAU and AMB scenarios. Regarding the pace of renovation, the distribution model that reaches a plateau by 2040 unsurprisingly exhibits superior overall performance. This finding supports the notion that initiating ambitious renovations policies as early as possible yields beneficial outcomes in terms of operational GHGE reduction. Turning to embodied GHGE, a notable difference starts from 2031 between the 'RE2020' and 'RE2020+' pathways. When examining the pace of renovations, the linear increase trend GHGE surpasses the plateau trend GHGE between 2035 and



(a) BAU scenario - range of operational GHGE

(b) AMB scenario - range of operational GHGE

(c) BAU scenario - range of embodied GHGE

(d) AMB scenario - range of embodied GHGE

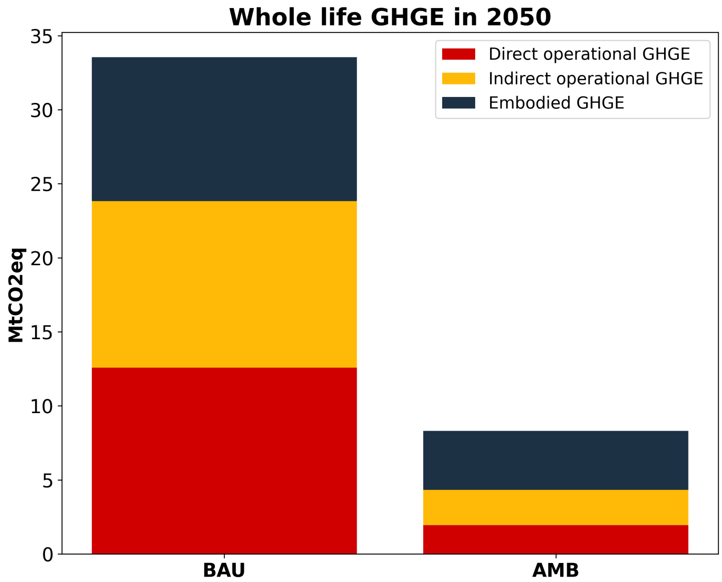
Figure 6.7: Sensibility analysis for BAU and AMB scenarios with different energy carriers and construction materials decarbonisation scenarios

2040. By this date, the number of renovation operations is higher but the construction materials have already begun their decarbonisation process, showing already lower impact. Also, the deeper renovations (in terms of EPC label jump) have already happened.

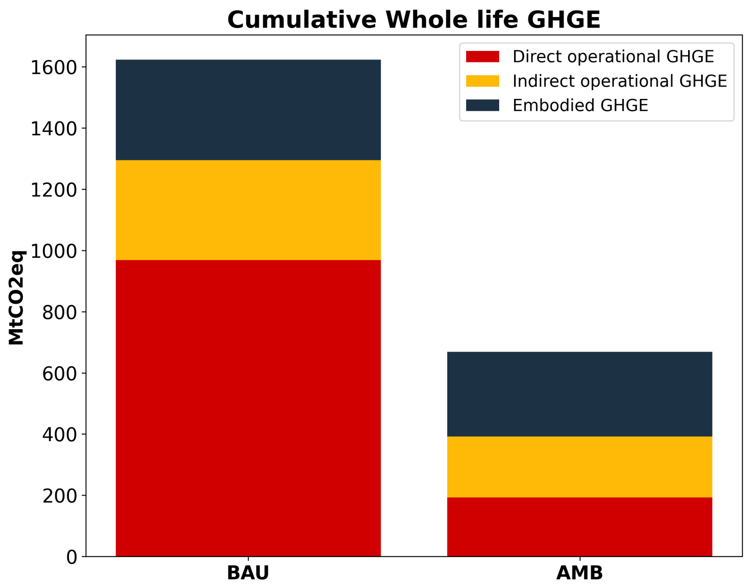
6.6.3 WLC emissions and comparison with top-down budgets

Ultimately, by integrating operational and embodied results, it is possible to represent WLC emissions of the residential dwelling stock. Figure 6.8 illustrates WLC emissions results for the two scenarios in the year 2050 and on the cumulative 2020-2050 period. The GHGE are categorised into direct operational GHGE, indirect operational GHGE, and embodied GHGE, corresponding to Scope 1-2-3 respectively in the GHG Protocol (GHG Protocol, 2011).

When examining operational GHGE in 2050, both scenarios reveal a growing proportion of indirect operational GHGE. Compared to the initial situation in 2020, where direct operational GHGE represent 80% of operational GHGE (Pellan et al., 2023b), they represent only half of the total in both



(a) WLC emissions in 2050



(b) Cumulative WLC emissions

Figure 6.8: 2050 and cumulative WLC emissions for BAU and AMB scenarios

scenarios in 2050. The growing importance of indirect operational GHGE is due to the replacement of fossil fuel to electricity and district heating.

Another observation is the importance of embodied GHGE, which are heavily influenced by renovation rates and construction activities. The more ambitious the scenario, the largest the share of embodied GHGE in the WLC emissions. Indeed, the drastic reduction of operational GHGE enabled by the renovation activities and demolition-reconstruction activities have backlashes in terms of the materials needed especially for renovation. In the AMB scenario, embodied surpasses 50% of WLC emissions in 2050. These trends align closely with EU studies and TECH/LIFE scenarios in EU studies, where embodied GHGE surpasses operational GHGE between 2040 and 2045 (Ramboll et al., 2023).

When compared to the top-down budgets, the AMB scenario presents values that are well lower the combined SNBC-APS values and that align with the SNBC-NZS values. In contrast, the BAU scenario outpaces the combined SNBC-APS values. As the budgets encompass all building activities, that would mean that residential activities are consuming all or more than the entire budgets. Thus, the SNBC-APS budget appear reachable but would necessarily require an ambitious policies for stock-dynamics, notably a reduction of construction activities and an increase of renovation activities targeting the right dwellings and using low-carbon materials. To reach the more ambitious goal defined by the SNBC-NZS combined pathways, a more profound decarbonisation of supply sectors might be necessary, as well as a deeper decrease of new construction in order to decrease the embodied GHGE. As for the operational GHGE, it seems unrealistic to reach renovation paces higher than those from the AMB scenario, which already reach 750,000 dwellings per year.

6.7 Discussions

A primary advantage of the method is its ability to present results on a large scale (e.g. national level), while simultaneously providing a detailed representation of the dwelling stock. This capability is facilitated by using the BDNB, an open-source national building database. It offers a comprehensive picture of actual buildings energy performance, encompassing details like EPC labels and the distribution of energy carriers by dwelling type. Moreover, the method's capacity to model targeted policies over time is of substantial policy relevance, as it assists in guiding the direction of future policy-making efforts towards optimal decarbonisation. For example, the study uncovers that policies targeting fossil fuel yield considerably greater emission reductions compared to strategies solely focusing on renovations based on EPC labels. This finding underscores the importance of prioritising fossil fuel reduction in residential buildings as a more effective approach for decarbonisation. Yet, relying on the BDNB for its renovation scenarios remains a limit of the study. Indeed, the choice of renovations in this analysis reflects an energy-focused perspective rather than a more holistic WLC emissions view, where the sequencing of renovations would be guided by factors such as the carbon payback time.

Advancements in building stock modeling techniques could provide a more thorough analysis of dwellings' materiality which can be greatly beneficial for assessing the embodied GHGE of the different stock-level activities. In particular, it would be valuable for renovations, where different operations can potentially yield similar operational energy savings while having very different embodied GHGE depending on the materials used. Emerging modeling techniques that use bill of quantities or macro components (such as detailed material descriptions, construction assemblies, and building systems) are gaining attention (Tirado et al., 2021) (Stephan et al., 2022). However, applying these methods on a national scale presents significant challenges. Indeed, the complexity of creating detailed archetypes at such a scale and the extensive data required for an in-depth bottom-up analysis are notable obstacles. To extend building stock analyses into the future, a comprehensive approach would also involve assessing the decarbonisation potential of upstream sectors and how this could influence the future environmental performance of energy sources and construction materials in buildings. In this context, prospective LCA holds promise for integrating both foreground and background modifications (Mendoza Beltran et al., 2018) (Sacchi et al., 2022). Yet, it requires detailed information, including life-cycle inventory (LCI) data that are needed to describe the bill of quantities in different building types.

In the method, relying on the statistical analysis of the RE2020 LCA database allows for the derivation of realistic GHGE values per square meters that are applicable on a large scale. This approach not only streamlines the evaluation of the relative impact of different stock-level activities on embodied GHGE but also facilitates the assessment of various emission scopes in relation to WLC emissions framework. Additionally, the adaptability of employing the same LCA database for both new constructions and renovations aligns well with modern construction practices, enhancing the practicality and relevance of the methodology. As for the prospective pathways, the ability to rely on existing national scenarios and expected legislation facilitates the assessment of future values.

The simplified treatment of embodied GHGE timing is also a limitation of the study. In a more detailed analysis, the GHGE from module 'B' in construction and renovation activities should be distributed over time to accurately reflect the replacements of the various components at the end of their lifetime. While such a detailed approach might alter the profile of annual GHGE, suggesting a potential shift of emissions to later years, it is important to note that this would not significantly affect the total cumulative emissions over time. Yet, it is important to note that maintenance-related renovations, such as the replacement of heating systems at the end of their lifetime, are not included in the study for dwellings that are not impacted by renovation operations in the transition matrix. For instance, the maintenance of 'A', 'B' and 'C' dwellings initially is not considered in this analysis. Consequently, the actual share of embodied GHGE in WLC emissions might be underestimated in this study, suggesting that embodied GHGE could constitute a larger portion of the WLC emissions.

While decarbonisation levers are classified in the 'Avoid-Improve-Shift' framework, there are still limited modelling parameters for sufficiency measures, and they only have an influence on embodied GHGE. It's worth noting that this limitation is not unique to the current study, as research on lifestyle changes and sufficiency policies is comparatively underrepresented in modelling when compared to techno-economic aspects (Saujot et al., 2021) (Saheb, 2021) (Ellsworth-Krebs, 2020). Future investigations focused on new construction could prioritise the modelling of additional 'Avoid' solutions, such as optimising vacant spaces and exploring changes in building usage. Additionally, the energy modelling of 'Avoid' solutions in relation to operational GHGE should be expanded to encompass low energy consumption behaviors. An alternative approach to assessing GHGE could also prioritise metrics based on per *capita* or per dwelling rather than the conventional per square meter metrics. For instance, while collective dwellings typically show higher CO_2eq/m^2 values, their average size per dwelling is significantly smaller compared to individual dwellings. Adopting these alternative metrics could encourage a reduction in dwelling sizes, which aligns with the principles of sufficiency policies.

Finally, another area for future research lies in examining the interplay among the three mitigation levers—'Avoid,' 'Improve,' and 'Shift'—especially how 'Avoid' and 'Improve' strategies impact 'Shift' measures. Within the context of building activities, these dynamics could be explored in relation to stock-dynamics. Specifically, the research could focus on determining the optimal extent of new construction avoidance and the level of ambition required in renovations to ensure the availability of low-carbon energy carriers and construction materials. This approach would be particularly relevant to operational GHGE considerations in electricity, biomass, and biogas, as well as to embodied GHGE in the context of biomass.

6.8 Conclusion

The imperative connection between sectoral and climate policies becomes evident in ensuring alignment with climate objectives such as carbon budgets. Alas, they are still today often designed in isolation from one another. Additionally, sectoral policies often overlook the life-cycle impacts of their activities, concentrating primarily on specific life-cycle stages or stock-level activities, rather than adopting a more holistic approach.

This article aims to address this gap by introducing a modular framework designed to explore the potential evolution of the dwelling stock GHGE and assess its alignment with top-down carbon budgets in the French context. Taking advantage of a national building stock database alongside prospective drivers of stock-level activities, the framework enables the creation of multiple stock-dynamics scenarios. These scenarios encompass varying levels of new construction, renovation, and demolition activities. Additionally, they include targeted approaches for existing stock, focusing on their energy performance or their main energy carriers. The framework also incorporates scenarios for the decarbonisation of energy carriers used in dwellings, as well as for the limit values designed for construction, renovation, and demolition activities. This approach facilitates the generation of multiple scenarios thereby enabling the identification of ranges in WLC emissions and discerning the key factors driving it.

The results indicate that the most ambitious scenario showcased in this study demonstrates significant progress in decarbonisation, offering a potential pathway in line with ambitious carbon budgets. In terms of levers, a substantial transformation of the existing stock is essential for the successful decarbonisation of the dwelling stock. The deep decarbonisation of energy carriers and construction materials play a pivotal role to achieve ambitious targets for operational and embodied GHGE respectively. Additionally, the implementation of sufficiency measures is critical in minimising the environmental impact associated with new constructions.

This research highlights the necessity of a comprehensive approach in addressing future GHGE in the building activities. It emphasises the importance of integrating both operational and embodied, yearly and cumulative GHGE to ensure sectoral policies are aligned with climate policies.

7

Assessing current and future embodied emissions of new buildings: a prospective analysis through a building LCA database

Contents

This chapter introduces the third journal article of the PhD thesis which has been submitted in the 'Journal of Cleaner Production'. It might be subject to modifications in the coming months as part of the peer-review process. Please refer to Appendix 9.6 for the Supporting Information accompanying this publication.

CONTRIBUTIONS

- **Marin Pellan** - Conceptualisation, Data analysis, Formal analysis, Investigation, Methodology, Writing - original draft
- **Félix Dubois** - Software (database)
- **Denise Almeida** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Mathilde Louërat** - Conceptualisation, Supervision, Validation, Writing - review & editing
- **Guillaume Habert** - Conceptualisation, Supervision, Validation, Writing - review & editing

7.1 Highlights

- Prospective LCA from national building LCA database.
- Building typologies identification through association rule mining and clustering.
- Integration of IAMs scenarios for construction materials production phase.
- Results highlight substantial decarbonisation potential of upstream sectors.
- Current construction practices will not enable with stringent carbon budgets.

7.2 Abstract

In the building sector, evolving legislation increasingly mandates the implementation of Life-Cycle Assessment (LCA) during the construction phase. This includes setting evolving limit values for greenhouse gas emissions (GHGE), encompassing both operational and often-overlooked embodied emissions. The advent of mandatory LCA completion has fostered the growth of building LCA databases, enhancing analyses of energy consumption, materiality and geometry for new constructions. However, traditional static LCA approaches do not account for the timing of emissions nor the dynamic changes in upstream sectors like energy and industry, crucial for assessing building typologies against future performance benchmarks.

This paper presents a methodology that combines a data-driven analysis of a building LCA database with a prospective LCA framework. Leveraging the French RE2020 building LCA database, this approach evaluates the embodied GHGE of various building typologies against both current and anticipated future benchmark values. Initially, the method integrates advanced building stock aggregation techniques, such as association rule mining and clustering, to identify representative buildings based on their material and geometric characteristics. Subsequently, it models the impact of decarbonising upstream sectors on the embodied performance of these typologies.

The research offers insights into how different building typologies align with evolving environmental performance standards. It highlights the current gap in embodied GHGE between building typologies, notably those using bio-based materials. The prospective findings underscore the significant decarbonisation potential within industrial sectors. Yet, meeting ambitious environmental targets necessitates a paradigm shift in construction practices, highlighting the imperative to refine modelling approaches to include material efficiency strategies and prioritising the use of low-carbon materials.

Keywords: *new construction, building archetypes, bottom-up modelling, life-cycle assessment, prospective studies, clustering*

7.3 Introduction

7.3.1 Context

Building activities are significant contributors to climate change, responsible for 21% of global greenhouse gases emissions (GHGE), emitting 12 Gt CO_2eq annually (Cabeza et al., 2022). Buildings generate two types of emissions. On the one hand, operational GHGE result from energy consumption within buildings and are further classified as *direct* operational GHGE, which originate from onsite combustion and the release of fluorinated gases, and *indirect* operational GHGE, stemming from the offsite generation of electricity and heat. On the other hand, embodied GHGE are associated with the entire life-cycle of buildings, encompassing stages from resource extraction to end-of-life (Cabeza et al., 2022).

Traditionally, attention has predominantly centered on the operational GHGE of buildings. This focus is attributable to their generally poor energy performance and the extensive use of fossil fuels, factors that contribute to substantial emissions throughout their extended lifespans. Yet, recent shifts in research and policy have spotlighted the critical issue of embodied GHGE which has been rising in relative and absolute terms. This is particularly evident in new buildings, where embodied GHGE can constitute up to 90% of Whole-Life Carbon (WLC) emissions (Röck et al., 2020). At the building stock level, embodied GHGE currently account for 25% of WLC, but predictions suggest this could double by 2050 under a BAU scenario (UNEP, 2023). Strategies for reducing building GHGE are often categorised within the Avoid-Improve-Shift framework (Creutzig et al., 2022). *'Avoid'* encompasses efforts aimed at reducing the overall demand for building space, *'Improve'* focuses on enhancing material efficiency, building design, and energy performance, and *'Shift'* involves adopting low-carbon materials and energy carriers (UNEP, 2023). Operational GHGE have been considered more straightforward to address through measures like energy-efficient systems and low-carbon energy sources, enabling the achievement of net-zero operational carbon buildings (WBCSD and Arup, 2021). In contrast, embodied GHGE linked with hard-to-abate sectors (Davis et al., 2018) such as cement and steel production, present more significant decarbonisation challenges and costs. While the adoption of low-carbon materials, such as bio-based or earth-based materials, along with circular economy strategies can help reduce embodied GHGE, conventional materials remain necessary in certain building parts, such as building structure.

7.3.2 Life-cycle assessment of new construction

Today, new construction represents 70% of building stock embodied GHGE in the EU context, largely due to low renovation rate. Of these emissions, 70% are emitted upfront at the time of construction (Röck et al., 2022c). In response, several countries such as the Netherlands, Denmark, Finland, Sweden, and France have taken pioneering steps by incorporating GHGE standards for new buildings into national regulations (Buildings Performance Institute Europe, 2021). France's Environmental Regulation (RE2020) (CEREMA, 2024), for example, sets declining mandatory limit values for reducing both operational and embodied GHGE by 2031. Two years after its implementation, the

RE2020 observatory [1] provides a platform for sharing analyses on new construction, notable for the extensive number of data available.

Life-cycle assessment (LCA) has rapidly emerged as the preferred approach for evaluating the WLC emissions and other environmental impacts of buildings. Standardised by ISO 14040-14044, LCA provides a comprehensive framework for assessing the environmental impacts across all stages of a system's life cycle (Hellweg and Milà i Canals, 2014). This comprehensive approach aims to support informed and comparative decisions, and helps to identify environmental impacts hotspots for further improvements. Within the European Union, the standard EN15978 serves as the primary guideline for assessing building impacts, while the standard EN15804 guides the creation of the environmental product declarations (EPDs) for construction products. While LCAs have traditionally focused on the scale of individual buildings, there is a growing trend towards applying these studies at larger scales, from urban districts to cross-national regions (Mastrucci et al., 2017). This shift towards macro-level LCA studies is crucial for evaluating the aggregate environmental impacts and guiding national policies on energy efficiency and sustainable building practices.

Recent research has evolved from establishing benchmarks through a limited set of case studies, often characterised by diverse methodologies and data sources (Birgisdottir et al., 2023), to using expansive databases like energy performance certificates (EPC) and building LCA databases that offer a broader view. A notable example includes the aggregation of hundreds of building LCAs from five European countries, revealing average values and ranges of variability for embodied GHGE (Röck et al., 2022c). This research found that residential buildings typically exhibit an average embodied GHGE of 600 $kgCO_2eq/m^2$, with a variability ranging from 400 to 800 $kgCO_2eq/m^2$. Non-residential buildings, while also averaging 600 $kgCO_2eq/m^2$, display a much wider variability, from 100 to 1200 $kgCO_2eq/m^2$. The challenges related to data availability, completeness, cleaning and harmonisation are essential for enhancing the accuracy and reliability of LCA studies, thereby facilitating more effective environmental assessments and influence on policy-making (Röck et al., 2022d). Indeed, due to different system boundaries and lack of documentation, it is often difficult to compare LCA results (Resch and Andresen, 2018).

Methodologically, ISO 21678:2020 (ISO, 2020) provides a comprehensive framework to guide the creation of sustainability frameworks, adaptable through either a top-down or a bottom-up approach. Top-down benchmarks are informed by absolute targets such as the remaining carbon budgets (IPCC, 2022), while bottom-up benchmarks derive from a statistical analysis of an empirical dataset. It is critical to understand that benchmarks focus on performance without favoring specific products or technologies, maintaining neutrality towards the types of buildings or materials required to achieve certain performance levels (Lützkendorf et al., 2023). They distinguish three types of values namely *limit values* ('upper or lower acceptable performance level'), *reference values* (best practice) and *target values* (often determined through top-down approaches).

[1] https://re-batiment2020.cstb.fr/opee/

7.3.3 Prospective LCA for buildings

The static approach of LCA has faced criticism, particularly when applied to buildings, which are assets with long lifespans (Fnais et al., 2022). Notably, the critique centers on the fact that emissions occur at various stages over time, with embodied GHGE presenting in spikes, and operational GHGE recurring over the operational life of the building. Recognising the temporal dynamics of emissions is crucial (Lueddeckens et al., 2020), necessitating the consideration of different projection years for construction, operation, renovation, and demolition phases, as these activities extend across several decades. In addition, it is essential to align the timing of emissions accurately with the corresponding socio-economic and technical systems, reflecting the broader temporal context in which construction, operation, and demolition unfold over an extended period (Mendoza Beltran et al., 2018).

Traditionally, assessments of the production and end-of-life stages for buildings have depended on static databases, capturing the current state of GHG emissions embodied in construction materials. However, the production and processing of these materials, especially energy-intensive ones like cement and steel, are closely linked to the energy used in manufacturing and are subject to continuous changes and expected future transformations. Despite this, the dynamic nature of these factors is often overlooked in evaluating embodied GHG emissions at the building stock level over a multi-decade horizon. Prospective LCA, defined as a *'LCA that models the product system at a future point in time relative to the time at which the study is conducted'* (Arvidsson et al., 2023) introduces a methodology for assessing environmental impacts at a future point, incorporating technological and socio-economic forecasts. By evaluating product systems into scenarios that account for future technological and socio-economic contexts, prospective LCA aims to understand the uncertainty inherent in forecasting the future. Methodologically, incorporating scenarios in prospective LCA necessitates modelers to consult additional, exogenous databases beyond traditional LCA resources. The integration of scenarios narratives and metrics from Integrated Assessment Models (IAMs), which offers global coverage, enable the representation of potential futures in a systemic manner. Recently, the premise Python package (Sacchi et al., 2022) built on the Brightway2 suite (Mutel, 2017a) enables to automatically modify the ecoinvent life-cycle inventory (LCI) database (Wernet et al., 2016) with information from two IAMs, namely IMAGE and REMIND.

Although buildings have not been the primary focus in prospective LCA studies, which have predominantly concentrated on energy and mobility sectors (Bisinella et al., 2021), recent research has started to bridge this gap. For example, (Bruhn et al., 2023) has compiled a comprehensive literature review and provided guidelines for applying prospective LCA specifically to the building sector. (Alaux et al., 2023) investigated mitigation strategies for production materials and its influence in new building construction, but do not integrate IAMs scenarios systematically to change the background. In a detailed study, (Zhang et al., 2024) consider background changes for electricity, steel and cement. They couple national LCI databases (e.g. UVEK and KBOB) with ecoinvent (Wernet et al., 2016). They further enriched their analysis with material flows for Switzerland from (Heeren and Fishman, 2019) to display future impacts of different building types at national level.

7.3.4 Contribution of the study

Recent studies have attempted to bridge the gap between top-down carbon budgets and bottom-up approaches that integrate stock dynamics, as seen in the UK (Li et al., 2022), New Zealand (Chandrakumar et al., 2020a) or France (Pellan et al., 2024). However, a comprehensive analysis leveraging a full-scale building LCA database to explore how various building typologies align with both top-down and bottom-up environmental benchmarks remains to be conducted. Additionally, the application of prospective LCA in new construction is still nascent, despite its emerging recognition as a leading methodology capable of accurately forecasting future building emissions. This approach could crucially enable the evaluation of building carbon performance relative to future benchmarks (Lützkendorf et al., 2023).

For this purpose, this study seeks to harness the RE2020 database to evaluate the current and future embodied GHGE of new buildings in France. It specifically focuses on modelling *'Improve'* strategies by analysing the effects of decarbonising the upstream sectors involved in buildings construction on the GHGE performance across different building typologies. This research aims to answer three pivotal questions:

- How can the identification of building typologies through a building LCA database be streamlined using data-driven techniques?
- How can these identified building typologies compare to current benchmarks?
- Considering the anticipating changes derived from IAMs, how might these building typologies perform against future benchmarks?

7.4 Method

The methodological framework of this study leverages a building LCA database to examine the performance of distinct building typologies, defined by their construction assemblies and geometries. First, a statistical analysis of their current embodied GHGE is conducted. Then, their future embodied GHGE is modelled under prospective scenarios that impact the production phase of construction materials and equipments over time. The overarching goal is to evaluate how the future performance of these typologies stands in relation to predetermined target values derived from (Pellan et al., 2024), offering insights into potential areas for improvement and alignment with climate goals.

Figure 7.1 provides a visual summary of the methodological steps proposed. The process begins with an overview of the building LCA database, detailing the selection criteria for the study's sample. It then progresses to the identification of building typologies through the analysis of construction assemblies combined with geometric characteristics, through a combination of statistical and machine learning techniques. Subsequent stages focus on selecting decarbonisation pathways for construction materials and integrating these pathways into the LCA calculation of buildings. This integration is critical for assessing the anticipated performance of each building typology under future scenarios, facilitating their comparison with target values.

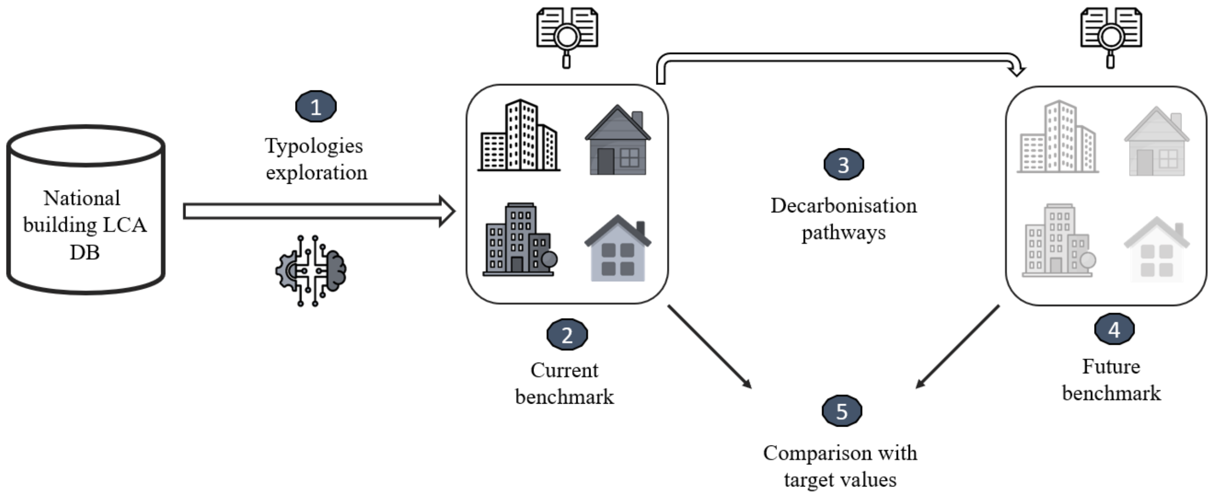


Figure 7.1: Overview of the proposed method

7.4.1 RE2020 building LCA database

Presentation of the RE2020 database

The RE2020 mandates the completion of a building LCA for new construction of residential, office and education buildings in accordance with the EN15978 standard, with minor national adaptations (additional information on the RE2020 is provided in the Supplementary Information). They should encompass the production stage (A1-A3), construction stage (A4-A5), in-use stage (B1-B7), end-of-life stage (C1-C4) and the beyond building life cycle stage (D). Carbon calculations are conducted across four areas: building components and equipment and construction site activities, which are the focus of this study, as well as energy consumption and water usage. The regulation details 13 categories of building components and equipment outlined in Table 7.1.

For each category, Environmental Product Declarations (EPDs) from the INIES database [2] are employed to model the life-cycle impacts of products, including their lifespan. The INIES database serves as the primary source of EPD data for construction materials in France, featuring both collective EPDs (representing multiple manufacturers) and individual EPDs (specific to a single manufacturer). In instances where an EPD is not available, modelers may resort to 'default data' which incurs a 30% penalty that serves as a security coefficient.

In this study, all building LCAs submitted as of September 2023 were extracted from the database, amounting to 13,477 entries. To enable the identification of building archetypes, a filtering process was applied to retain only those buildings with complete information on materiality, such as structural, roof, and wall types. After applying these criteria, the dataset was refined to 6,007 building LCAs, corresponding to 10,739 dwellings. Notably, the distribution between housing types is uneven, with a significant majority of 5,858 cases (accounting for 6,169 dwellings) being individual housing, in stark contrast to the 149 entries for collective housing (encompassing 4,570 dwellings),

[2] https://www.inies.fr/

Table 7.1: RE2020's groups and macro groups

Groups	Name	Macro groups
1	Roadwork and diverse	-
2	Foundations and infrastructure	Structural work
3	Structure and masonry	Structural work
4	Roof and cover	Second work
5	Interior partitions, suspended ceilings, components and joineries	Second work
6	Exterior surfaces (facades), components (doors and windows) and joineries	Second work
7	Interior coatings (floors, walls, and ceilings)	Second work
8	HVAC equipment	
9	Sanitary installations	Technical groups
10	Electrical equipment	Technical groups
11	Special electrical equipment (systems, controls, and communication)	Technical groups
12	Interior transport equipment (elevators, etc.)	Technical groups
13	Local electricity production equipment	Technical groups

highlighting a disparity in the focus of current LCA submissions. For this reason, this study focuses primarily on individual housing.

7.4.2 Method for building typologies identification

Characterisation and aggregation of building stock are fundamental processes in building stock modelling (Mastrucci et al., 2017) (Röck et al., 2021). As this study uses a building LCA database, the material and energy modelling phases are consequently streamlined thanks to the presence of EPDs. They offer data that helps in the detailed characterisation of building materials along with their impacts, as well as final energy consumption calculated for each energy carrier (e.g. electricity, natural gas, biomass, oil products and heat from district heating). Yet, the important number of buildings still requires a sound method for characterisation.

A prevalent method for stratifying building stocks into uniform subgroups involves segmentation based on categorical variables. Construction year and building type are frequently used variables for segmentation, with building size, climate zone, and renovation needs also being common criteria (Röck et al., 2021). While this deterministic approach yields valuable insights into building characteristics and performance, it has faced criticism for its potential to miss the diversity present within a building stock. The subjective nature of such classifications can also introduce bias (Borges et al., 2022), suggesting that while useful for overarching studies, it may not be as effective for in-depth analysis. Additionally, such deterministic methods might not detect less obvious patterns or correlations not directly defined by the chosen variables. In contrast, clustering is a machine learning technique that provides a more nuanced capture of buildings diversity, especially when managing multiple variables (Gomes et al., 2022). Clustering algorithms, which partition a dataset into groups or clusters without prior knowledge of group membership, are designed to uncover hidden structures and recognise similarities among data points. In the context of building stock modelling, clustering has been largely employed in Urban Building Energy Modelling (UBEM) (Johari et al., 2020) and in studies that aim to identify buildings with high renovation potential (Verellen and Allacker, 2020). However, its application in building LCA studies remains limited, primarily due to the lack of comprehensive databases that can support such detailed analysis. This gap indicates a significant opportunity for advancing building LCA methodologies through the adoption of clustering or hybrid approaches that can more accurately reflect the complexities and diversities of building stocks (Gomes et al., 2022). Combined with identified building typologies defined by material passports (Lanau et al., 2019), it could facilitate the creation of building archetypes that combines materiality, geometry and energy metrics.

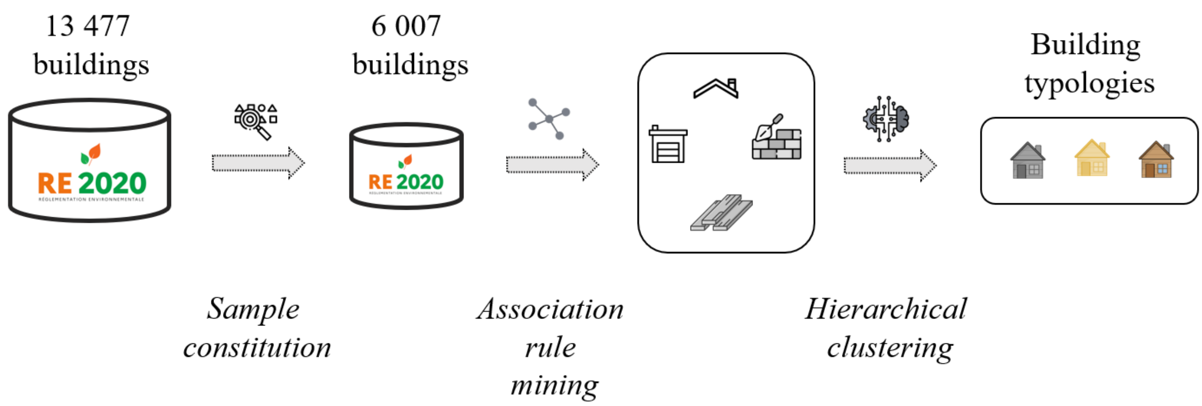


Figure 7.2: Method for finding building typologies

Figure 7.2 illustrates the chosen method to determine building typologies and choose representative buildings for latter LCA application. The sample formation marks the initial step in the method, which then employs statistical techniques to analyse the material composition of buildings and seeks correlations among five key structural elements. Using association rule mining, the method identifies significant associations among these elements, effectively pinpointing combinations that frequently occur together. This process facilitates the identification of building typologies based on common construction features. Subsequent to identifying these key associations, the method applies hierarchical clustering within each identified group to categorise buildings further based on their geometric attributes. This step ensures buildings with similar structural and geometric characteristics are grouped together, enhancing the specificity of the typologies. Finally, within each group, the method selects the medoid (e.g. the building whose sum of dissimilarities to all the buildings in the cluster is minimal) of the largest cluster as the representative for that typology for subsequent LCA calculations. This approach aims to ensures that the chosen representative building closely mirrors the common characteristics of the group, providing a solid basis for accurate LCA analysis.

Unveiling material associations in building typologies

In this study, the classification of buildings as either individual or collective forms the initial step, using a deterministic process for preliminary segmentation. For each building type, the study focuses on the material characteristics of buildings by examining five key variables: the main structure, the structural material as well as the roof, floor, and foundation types. To uncover relationships between these variables within the dataset, the study employs association rules mining. This technique generates rules that depict the likelihood of associations between variables, facilitating the identification of recurring construction archetype patterns within the database. Key metrics in association rule mining include support, confidence, and lift. The support of an itemset X measures the frequency of variable association within the dataset and is given by:

$$\text{Support}(X) = \frac{\text{Number of transactions containing } X}{\text{Total number of transactions}} \tag{7.1}$$

Later, the confidence measures the probability of seeing the consequent given the antecedent and is calculated as follow:

$$\text{Confidence}(X \Rightarrow Y) = \frac{\text{Support}(X \cup Y)}{\text{Support}(X)} \tag{7.2}$$

Finally, the lift evaluates how much more frequently the antecedent and consequent co-occur than would be expected under statistical independence :

$$\text{Lift}(X \Rightarrow Y) = \frac{\text{Confidence}(X \Rightarrow Y)}{\text{Support}(Y)} \tag{7.3}$$

These metrics enable a comprehensive examination of material combinations and associations, significantly enhancing the study's contributions to construction assembly archetype development. In the study, the *apriori* algorithm implemented through the *mlextend* library (Raschka, 2018) facilitates this analysis by first identifying individual items that meet a minimum support threshold, then combining them into larger sets that maintain the required support level. It helps to indicate combinations of building characteristics that commonly coexist beyond the minimum support threshold.

Clustering analysis for geometrical representation

Upon the identification of building archetypes through association rule mining, the next step involves pinpointing representative geometries. Indeed, the database offers rich geometric variables for buildings, such as surface area, height, and specific areas for the building's bay, wall and floor. The objective is to select geometries that, when combined with building archetypes, produce representative models for further analysis. To identify representative geometries within the building LCA database, hierarchical clustering is employed. The Euclidean distance, which measures the spatial distance between two points in multidimensional space as the square root of the sum of squared differences between corresponding elements, is used to quantify the similarity between buildings. This metric is chosen for its precision in reflecting the physical differences among various building geometries. Following this, an agglomerative approach is adopted, where the Ward linkage method is applied to iteratively merge clusters. This method is particularly effective in minimizing variance within clusters, thereby ensuring their homogeneity. Its selection is due to its capability to generate compact and distinct clusters, which are crucial for the meaningfulness of this study. To ascertain the optimal number of clusters, the Elbow method is applied. This involves analyzing the within-cluster sum of squares to identify the ’elbow point’, e.g. the stage at which the addition of more clusters ceases to significantly enhance within-cluster homogeneity. These calculations are facilitated by the *scipy* library (Virtanen et al., 2020).

7.4.3 Prospective pathways for upstream sectors

Prospective trajectories with premise

The derivation of decarbonisation pathways in this research is facilitated by the use of the *premise* package (Sacchi et al., 2022), which transforms the ecoinvent database (Wernet et al., 2016) using data from IAM scenarios. Modifications made to the database typically address three key areas: the introduction of novel technologies, the regionalisation of new or existing technologies, and alterations in the market composition and system efficiency of current technologies. For instance, in transforming the cement sector, premise adjusts both the energy-related GHGE and the calcination GHGE. The adjustment in energy-related GHGE is achieved by altering the distribution of kiln technology across regions and their energy consumption, which is then adjusted by a scaling factor to mirror improvements in energy efficiency. For the calcination GHGE, the changes involve incorporating a Carbon Capture and Storage (CCS) LCI dataset into the clinker production activities within ecoinvent, accounting for its energy demand. More information on the transformation of the different sectors is available from the *premise* documentation[3].

Relying on *premise* enables the generation of prospective data for all activities and products within the ecoinvent database, tailored to specific IAM scenarios. In this study, two well-established IAMs are employed namely, IMAGE (van Vuuren et al., 2021) and REMIND (Baumstark et al., 2021). Table 7.2 summarises the scenarios associated with each model, and their global mean surface temperature (GMST) increase by 2100.

Table 7.2: IAM scenarios used in the study

SSP-RCP scenarios	Model	GMST increase by 2100
SSP2-RCP19	IMAGE	1.2-1.4 °C
SSP2-RCP26	IMAGE	1.6-1.8 °C
SSP2-x (NDC)	REMIND	2.5 °C
SSP2-RCP19 (PkBudg500)	REMIND	1.2-1.4 °C
SSP2-RCP26 (PkBudg1150)	REMIND	1.6-1.8 °C

In a visual representation shown in Figure 7.3, cement and reinforcing steel, as key activities related to construction, are depicted to highlight the potential discrepancies that can arise across different

[3] https://premise.readthedocs.io/en/latest/transform.html

models and scenarios. The values per functional unit are standardised to a baseline index of 100 for the year 2020, with linear interpolation applied between decades.

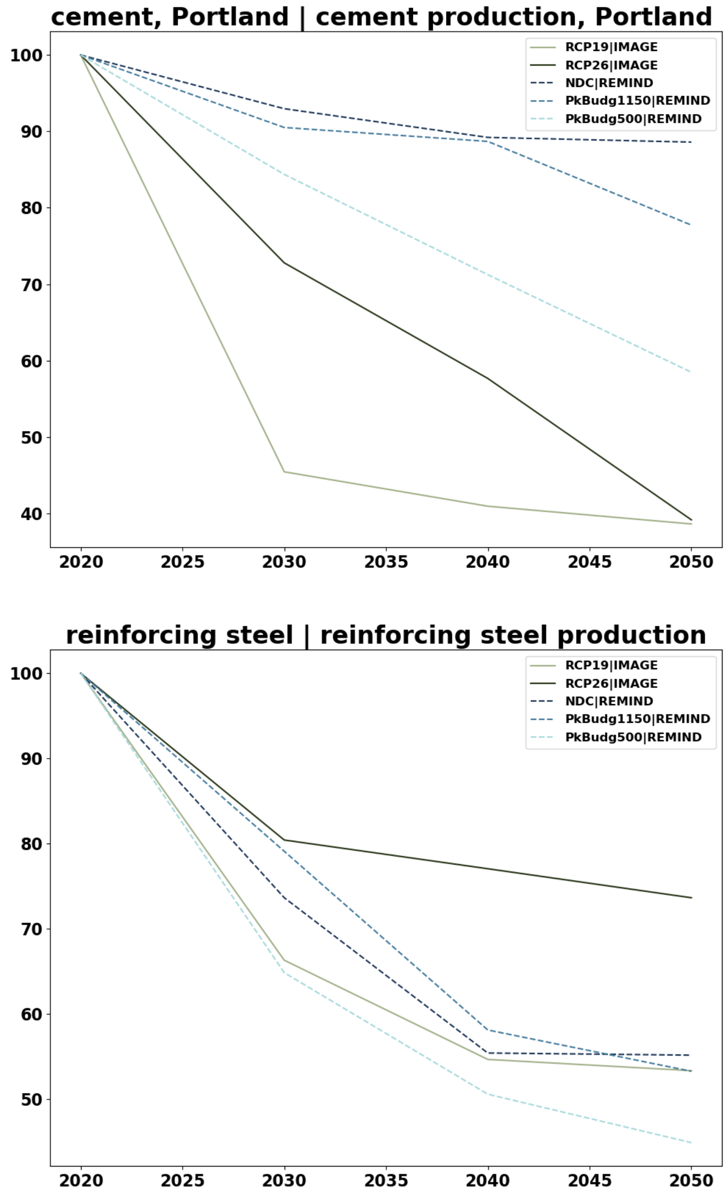


Figure 7.3: Illustrative examples of decarbonisation pathways for cement and reinforcing steel production using IAM scenarios described in Table 7.2.

A notable observation is that the decarbonisation pathways may significantly diverge between models, even among scenarios that project a similar GMST increase by 2100, such as IMAGE RCP2.6 and REMIND PkBudg1150. For instance, the IMAGE model predicts an early and substantial decarbonisation of the cement sector, attributed to the widespread adoption of CCS technology. Consequently, incorporating a variety of scenarios from different IAMs is beneficial for sensitivity analysis. An interactive dashboard[4] developed by the *premise* developers facilitates the exploration of different variables for each IAM, which can help explain the variation between them.

[4] https://premisedash-6f5a0259c487.herokuapp.com/

Association of ecoinvent activities and EPDs

Building LCAs within the RE2020 database are composed of EPDs. However, EPDs typically do not disclose their detailed LCI data for direct use and transformation by practitioners. This lack of transparency can stem from proprietary concerns, as manufacturers may consider detailed LCI data to be sensitive or competitive information. Reconstructing LCI data from EPDs presents significant challenges due to the aggregated nature of the information they provide. Indeed, EPDs summarise the environmental footprint of a product across various impact categories, without offering the granular data on material compositions, energy consumption, or specific process emissions that would be necessary for a detailed life-cycle analysis. Therefore, attempting to reverse-engineer LCI data from the summary information in an EPD presents significant challenge and is prone to inaccuracies. Given the expansive number of buildings catalogued in databases like RE2020, which aggregate countless EPDs for different materials, the task of individually reconstructing LCI data for each EPD becomes unfeasible.

To navigate the complexities of correlating the decarbonisation pathways of construction materials with their EPDs, a streamlined approach has been developed in this study. This approach assigns each EPD to the predominant material type found within the EPD, subsequently linking it to a corresponding ecoinvent activity. Such a connection facilitates the association of EPDs with the modified ecoinvent activities conducted by the *premise* package, effectively mapping them onto appropriate decarbonisation pathways. In this study, the material classification system within the INIES database is used. This strategy mirrors the concept of employing 'surrogate data' found in simplified LCA methodologies (Gradin and Björklund, 2021). However, in this context, it specifically involves assigning 'proxy' decarbonisation pathways to various EPDs, based on their INIES nomenclature and corresponding activities in ecoinvent. Given that EPDs provide a comprehensive view of a product's life cycle, finding a single ecoinvent activity that captures this holistic perspective would generally be overly simplistic and potentially compromise the robustness of the analysis. In this method, a focus is placed on aligning the production phase of the EPDs (e.g., phases A1-A3) with similar production activities in ecoinvent. This matching process is relatively straightforward and significantly encompasses a substantial share of life-cycle impacts, since the production phase typically accounts for a considerable proportion of the overall environmental footprint of construction materials. Consequently, the method adjusts the production phase emissions of each EPD according to the decarbonisation factors associated with the relevant ecoinvent activities, as defined by the most recent INIES product classification. In instances where direct mapping is not feasible, an average decarbonisation factor derived from all other activities within the specific model-scenario coupling is used. For EPDs that report negative values due to carbon sequestration, a conservative approach is adopted by not applying any decarbonisation factor, considering that the EPDs do not differentiate between emissions and sequestration within the A1-A3 phase. Details on the mapping between ecoinvent activities and INIES product categories are provided in the SI in the *pyam* format (Huppmann, Daniel et al., 2021).

7.4.4 Timing of embodied GHGE calculation

The computation of embodied GHGE for buildings adheres to the EN15978 standard, yet the emissions are annualised to reflect their occurrence over time. This includes emissions from the year of construction, emissions associated with the replacement and maintenance of various products in accordance with their lifespan, as well as emissions from the end-of-life phase. Table 7.3 outlines the timing of these emissions, aligned with the modules specified in the EN15978. In the RE2020, the reference period is set to 50 years. Notably, it is hypothesised that the GHGE from module A are assumed to occur in year 0.

Table 7.3: Timing of emissions in WLC emissions calculation

EN-15978 Module	Time	Description
A1-A3	$t=0$	Raw material extraction, transport & manufacturing
A4-A5	$t=0$	Transport & Construction
B1-B5	$t\in[1,50]$	Maintenance and repair, depending on the components lifetime
B6-B7	$t\in[1,50]$	Energy & water use
C1-C4	$t=50$	End-of-life treatment

The calculation of embodied is decomposed in four main phases, e.g. (1) the emissions that occur before and at building construction, represented in module A, (2) the emissions that occur during building construction lifetime due to use, maintenance or repair, represented in module B (3) the emissions due to the replacement of construction materials and equipment, represented in module B and (4) end-of-life emissions, represented in module C.

For the A phase, the embodied emissions ε^A of any building at time t is calculated as follow:

$$\varepsilon^{A}_{building}(t)=\sum_{p}Q_p*((f^{A1-A3}_{\varepsilon,p}*\Delta(t))+f^{A4-A5}_{\varepsilon,p}) \tag{7.4}$$

Where Q_p is the quantity of product p in the relevant unit defined by the EPD, $f^{n}_{\varepsilon,p}$ is the emission factor of product p for the relevant n phase and $\Delta(t)$ is the decarbonisation factor impacting only the A1-A3 phases in this study.

For the B1-B5 phases, the embodied emissions ε^{B1-B5} of any building at time t should take into account the lifetime, maintenance and replacement of the different products and equipments. The number of replacements during the 50 year lifetime of the building is given by:

$$R_p=Max(1,\frac{Lt_{building}}{Lt_p}) \tag{7.5}$$

Where R_p is the number of replacement of product p occurring during the building lifespan $Lt_{building}$ (fixed at 50 years), and Lt_p represents the lifetime of product p.

As a result, the embodied emissions ε^{B1-B5} of any building at time t is calculated as follow:

$$\varepsilon_{building}^{B1-B5}(t) = \sum_{p}\left(Q_p \cdot f_{\varepsilon,p}^{B1-B5} \cdot \frac{Lt_{building}}{Lt_p^2}\right) + \sum_{p}\left((R_p - 1) \cdot \left((f_{\varepsilon,p}^{A1-A3} \cdot \Delta(t)) + f_{\varepsilon,p}^{A4-A5} + f_{\varepsilon,p}^{C1-C4}\right) \cdot \Psi(t, Lt_p, R_p)\right) \tag{7.6}$$

Where $\Psi(t, Lt_p, R_p)$ is a conditional function indicating whether a replacement occurs at time t, based on the lifetime Lt_p of product p and the total number of replacements R_p over the building's lifespan. This function is applied to reflect the conditionality of replacements and their impact on the embodied emissions calculation at time t. When replacements do not occur at time t or when $R_p \leq 1$, only the emissions associated with maintenance, which are amortised over the lifetime of the products, are considered.

Finally, for the C phase the embodied emissions ε^C of any building at time t is calculated as follow:

$$\varepsilon_{building}^{C}(t) = \sum_{p} Q_p * f_{\varepsilon,p}^{C1-C4} \tag{7.7}$$

7.4.5 Comparison with target values

After determining the annual embodied GHGE for the various building typologies, the method's concluding step involves comparing these calculated emissions with the target values sourced from (Pellan et al., 2024). Table 9.5 presents these target values, categorised by dwelling type and life-cycle stage per decade, including specific figures for the year 2022.

Table 7.4: Target values per dwelling type and life-cycle stages in $kgCO_2eq/m^2$ derived from Pellan et al. (2024)

Dwelling type	LC-stage	2022	2030	2040	2050
Collective	A1-A3	413	324	198	103
Collective	A4-A5	97	76	46	24
Collective	B1-B5	260	204	124	65
Collective	C	49	38	23	12
Individual	A1-A3	330	245	155	81
Individual	A4-A5	67	50	31	16
Individual	B1-B5	223	166	104	55
Individual	C	60	45	28	15

Given that decarbonisation pathways predominantly influence the A1-A3 production phase, as detailed in the preceding section, prospective comparisons are logically limited to this phase. This phase encapsulates emissions occurring in the initial year of each construction project, aligning with the focus on upstream impacts.

7.5 Results

First, the results showcase current benchmarks derived from the curated database, highlighting embodied results categorised by RE2020 groups for both individual and collective buildings. Due to the uneven number of building types in the sample, subsequent results focus on individual buildings as they represent the major part of the sample. Results are structured in line with the established methodology, sequentially detailing the insights from association rule mining, hierarchical clustering, and prospective LCA calculations.

7.5.1 Current benchmarks

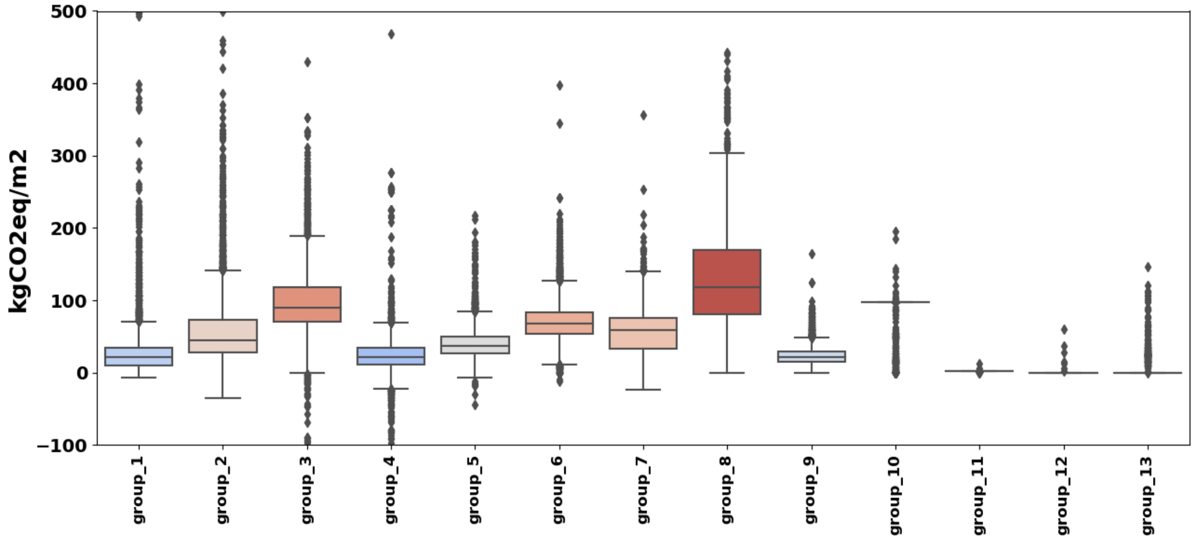
Figure 7.4 showcases the GHGE performance in $kgCO_2eq/m^2$ for both individual and collective housing types for the 13 groups specified in Table 7.1. Additionally, the median values for the 13 groups are given in Supplementary Information.

For individual buildings, 'Structure and masonry' and 'HVAC equipment' emerge as the most significant contributors to the embodied GHGE. This pattern holds true for collective housing as well, although with 'Foundations and infrastructure' and 'Exterior surfaces, components and joineries' also contributing substantially to the overall impact in this category. Further analysis on energy indicators reveals distinct preferences for energy carriers and systems between housing types (a Sankey diagram is provided in the Supplementary Information). This divergence can be attributed to the varying limit values established by the RE2020 regulation for different building types, with individual buildings subjected to more stringent requirements compared to collective buildings. In individual buildings, a clear preference for electricity as the primary energy carrier for both heating and hot water is evident, as it being present in approximately 95% of instances for both applications. Heat pumps are the overwhelmingly preferred heating solution, being used in 95% of cases. As for hot water systems, there is a nearly even split in preference, with storage tanks being used in 50% of cases, closely followed by heat pumps at 48%. Conversely, the energy landscape for collective buildings is more balanced. In terms of energy carriers, electricity accounts for 41% of heating solutions but is more closely followed by natural gas, renewable energy systems (including solar and biomass), and district heating networks accounting for 23%, 17%, and 19% of the heating solutions, respectively. When it comes to heating and hot water generation, heat pumps and boilers lead, constituting 41% and 34% of heating solutions, and 27% and 33% of hot water solutions, respectively. However, it is important to note that these findings for collective buildings may not fully mirror the actual situation due to the limited number of collective buildings in the sample.

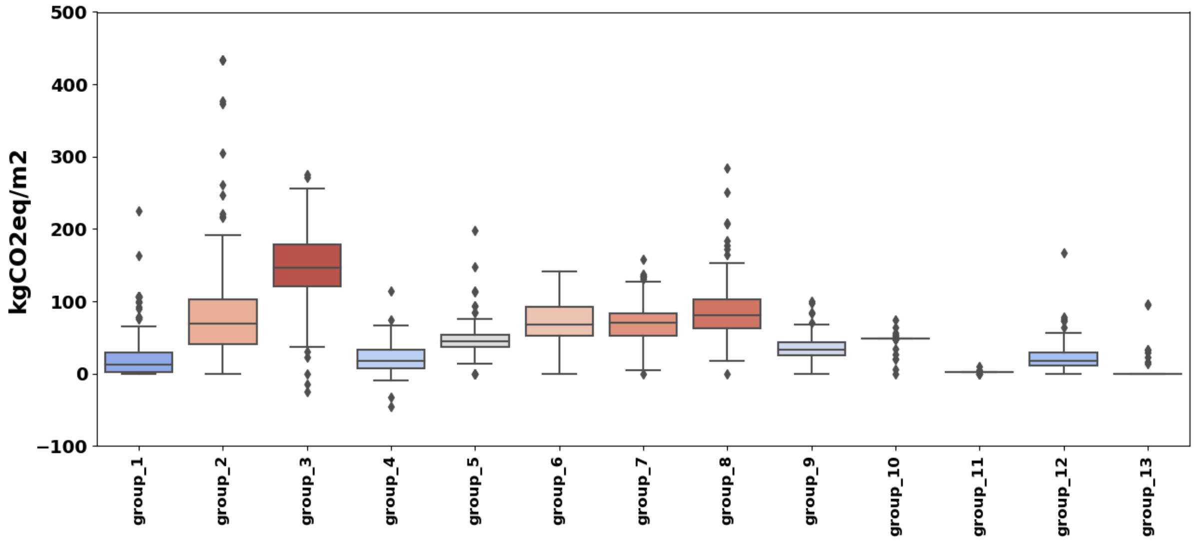
7.5.2 Identification of building typologies

Material associations and correlation analysis

In the sample, the distribution of choices within each variable is highly uneven. For instance, masonry constitutes nearly 90% of the main structural solutions, with concrete and clay brick make up 60% and 30% of structural material choices, respectively. Hollow beams and spinner soles dominate the floor and foundation categories, accounting for 80% and 70% of selections.



(a) Individual buildings



(b) Collective buildings

Figure 7.4: Median values per RE2020 groups outlined in Table 7.1 in kgCO_2eq per m^2 of living area for individual and collective buildings. Values are proposed using the semi-dynamic RE2020 LCA method (see Supplementary Information)

Given these distributions, the main structural element (e.g. concrete, clay brick or wood) is chosen in addition to the building type for further categorisation due to its influence on the 'Structure and masonry' emissions, which are one of the largest of the 13 groups. By applying the *apriori* algorithm (Raschka, 2018) across all individual buildings, and separately within the three primary categories of structural materials, the analysis enables the evaluation of support, confidence, and lift metrics for each category, as illustrated in Figure 7.5.

These metrics reveal distinct patterns among the structural material types, particularly in terms of support and lift. Concrete and clay brick structures, due to their prevalence in the sample, exhibit significantly higher support levels than wood structures. Conversely, wood structures demonstrate higher lift values, suggesting that while less common overall, wood is strongly associated with certain building characteristics or uses. Confidence levels for all three typologies range from 0.5 to nearly 1, underscoring the reliability of these associations. High confidence values imply that when a building is constructed with one of these materials, there is a strong likelihood that it will also exhibit the associated characteristics identified by the rules. For instance, a high confidence value in the context of wood structures could indicate a robust association with certain types of flooring or roofing, reinforcing the material's specific application or appeal within certain construction practices.

While support offers insight into current market shares, it is not the primary criterion for selecting typologies in this study. Instead, confidence and lift serve as more pertinent metrics for identifying associations among the five building elements due to their ability to highlight meaningful relationships. To select representative buildings based on these elements, rules with the highest number of elements, alongside superior lift and confidence scores, are selected. This process culminates in the identification of three distinct categories, detailed in Table 7.5.

Table 7.5: Association of the key elements for the three building types based on their main structural material

	Concrete buildings	**Clay brick buildings**	**Wood buildings**
Main structure	Masonry	Masonry	Frame
Roof	Monopent	3 panels	2 panels
Floors	Hollow beam	Solid slab	Hollow beam
Foundation	Spinner soles	Deep walls	Spinner soles

Hierarchical clustering of geometrical attributes

Figure 7.6 showcases dendrograms for the three distinct building typologies, illustrating the variance in cluster formation and distances among them. In hierarchical clustering, the dendrogram serves as a key visualisation tool, mapping the process of cluster formation in a tree-like diagram. It illustrates the sequence and distances of cluster mergers, with the merge height on the Y-axis indicating the distance or dissimilarity between two combined clusters. The dashed line across the Y-axis signifies the optimal cluster count as determined by the Elbow method, a point where adding more clusters leads to diminishing returns in terms of reducing within-cluster variance. At the dendrogram's base

(X-axis), each leaf signifies an individual data point (e.g. a building in the analysis). Notably, the dendrogram for clay brick buildings indicates a higher degree of dissimilarity among them, and thus a larger optimal number of clusters. This suggests a wider variation in the geometrical attributes within clay brick buildings compared to other types. On the contrary, wood buildings exhibit lower merge distances, implying a greater homogeneity in their geometrical attributes. This observed homogeneity could also partially stem from their fewer numbers in the dataset, which naturally results in fewer opportunities for variance.

7.5.3 LCA calculations

Timeline of embodied GHGE per building typologies

In Figure 7.7, the embodied GHGE are shown by RE2020 groups as they occur overtime, while the dashed line show the cumulative values. The first peak corresponds to upstream emissions, e.g. at the year of construction, the small peaks correspond to replacements of the different construction elements that reach their end of lifetime. The peak at the end corresponds to end-of-life emissions.

In terms of upstream GHGE, the concrete and clay brick buildings demonstrate exhibit similar embodied emissions levels, with approximately 500kgCO_2eq/m^2 emitted in the construction year. Conversely, the wooden building display lower embodied emissions with around 300kgCO_2eq/m^2. When considering the cumulated GHGE over the 50 year reference period, the concrete building report values close to 1000kgCO_2eq/m^2 while the clay brick and wood buildings report values close to 800kgCO_2eq/m^2, the latter demonstrating significant end-of-life emissions.

Prospective calculations and comparison with target values

Figure 7.8 displays upstream GHGE (e.g. corresponding to module A emissions in the EN15978) results under the RCP 1.9 scenario, as projected by the IMAGE model. This visualisation compares the construction of the same building in different years (2020, 2030, 2040, and 2050), assuming the quantity of construction materials remains unchanged. The aim is to explore the decarbonisation potential for each typologies through adjustments in upstream sectors as defined by the IAM scenario. The IMAGE RCP1.9 scenario predicts very aggressive decarbonisation pathways up to 2030, followed by a more moderate decline from 2030 to 2050. This transition explains the less pronounced emissions reduction observed post-2030. For example, concrete and steel, key materials in construction, exhibit significant decreases in emissions, with concrete showing a steep decline (e.g., 53% from 2020 to 2030 and 60% by 2050) and steel following a rapid reduction (e.g., 34% from 2020 to 2030 and 47% by 2050). This is due to the predominant role of CCS in the IMAGE model for these sectors. Overall, relative to the 2020 baseline values, the three building typologies demonstrate GHGE reductions of 34%, 39%, and 40% for the concrete building, 27%, 31%, and 32% for the clay brick building, and 35%, 43%, and 43% for the wooden building by 2030, 2040, and 2050, respectively. The smaller emissions reductions observed for clay brick buildings can be linked to the significant emissions contributions from aluminium and ceramic, materials which exhibit minimal emissions reduction according to the IAM scenario. Among the three distinct building typologies analysed, wooden buildings demonstrate a notable presence of negative values. This outcome is attributed to the carbon sequestration benefits associated with wood as a structural material in this typology.

These observations highlight the considerable influence of upstream decarbonisation on the embodied footprint of building constructions, underscoring the importance of material-specific pathways for comprehensively model the future environmental performance of new buildings. Nevertheless, when compared to the target values displayed in Table 9.5, only the wooden building demonstrate lower values, except for the year 2050. For concrete and clay brick buildings, a discrepancy from the target values is observed starting from 2020, which significantly increases over the years, except for 2030 where concrete buildings almost perfectly match the target values. These findings indicate that aligning with broader climate targets, such as carbon budgets established for the entirety of building activities (Pellan et al., 2023b), necessitates a shift in the market share distribution among different building typologies, favoring those with performance similar to wooden buildings or better.

Sensitivity analysis on IAMs scenarios

The different IAMs do not display identical decarbonisation pathways across different sectors to achieve the GMST targets set by RCP scenarios. In the Method section, Figure 7.3 illustrated how outcomes for various activities diverge significantly, depending on whether the IMAGE or REMIND model is employed, despite both scenarios aiming for the same GMST by the end of the century. Thus, investigating the implications of employing these distinct models and scenarios becomes crucial to assess the differences across the IAMs employed. To do that, Figure 7.9 offers a sensitivity analysis based on the models and scenarios outlined in Table 7.2, focusing on the net upstream emissions from all materials and equipment, specifically for 2030 and 2050.

Across all building typologies, the IMAGE RCP1.9 scenario demonstrates the lowest emissions for both 2030 and 2050. Additionally, a consistent order among scenarios is observed for both years across all typologies, with the exception of the concrete archetype. For this archetype, the alignment shifts from being closest to REMIND's NDC and PkBudg1150 scenarios in 2030, to mirroring the IMAGE RCP1.9 scenario by 2050. These findings underscore the importance of incorporating a range of IAM scenarios in prospective LCA analyses to capture a comprehensive view of potential future emissions.

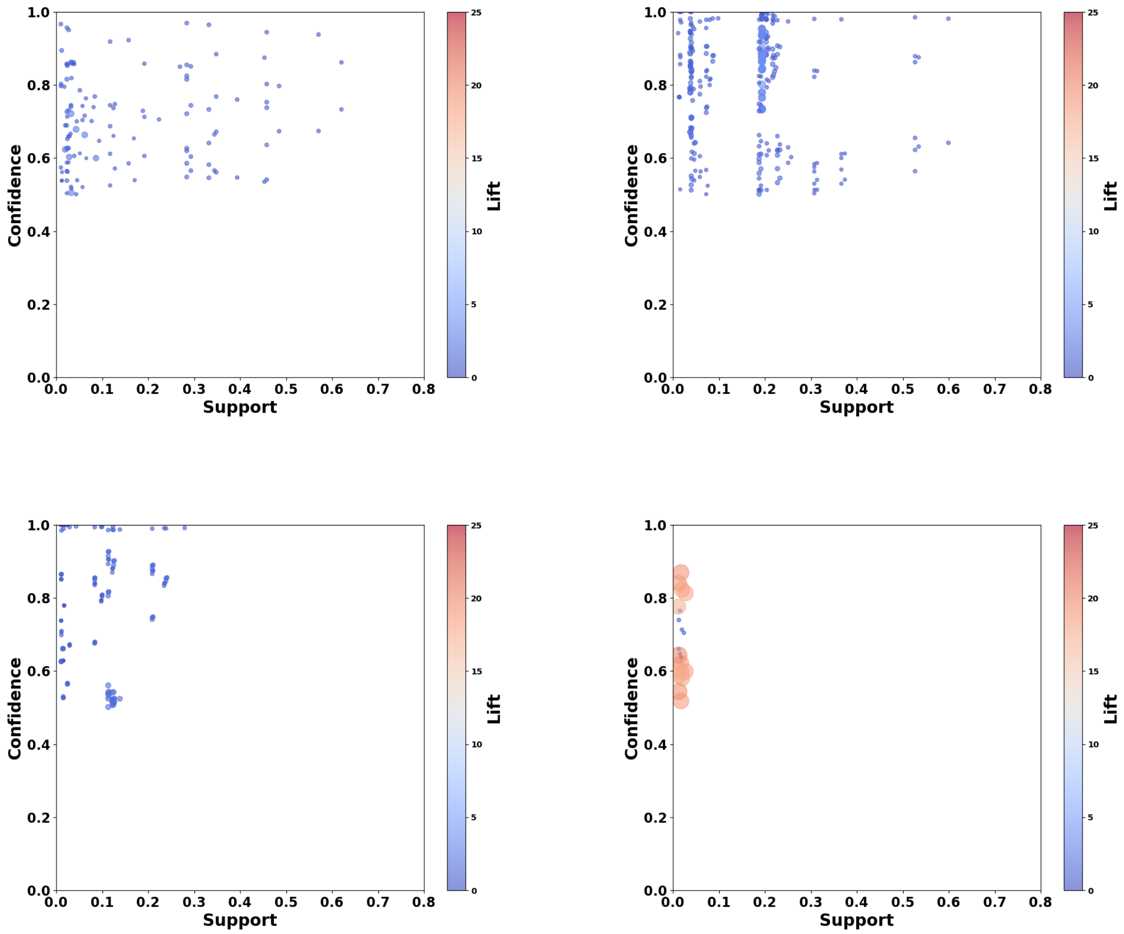


Figure 7.5: Association rules results for all individual housing and for three types of structural material

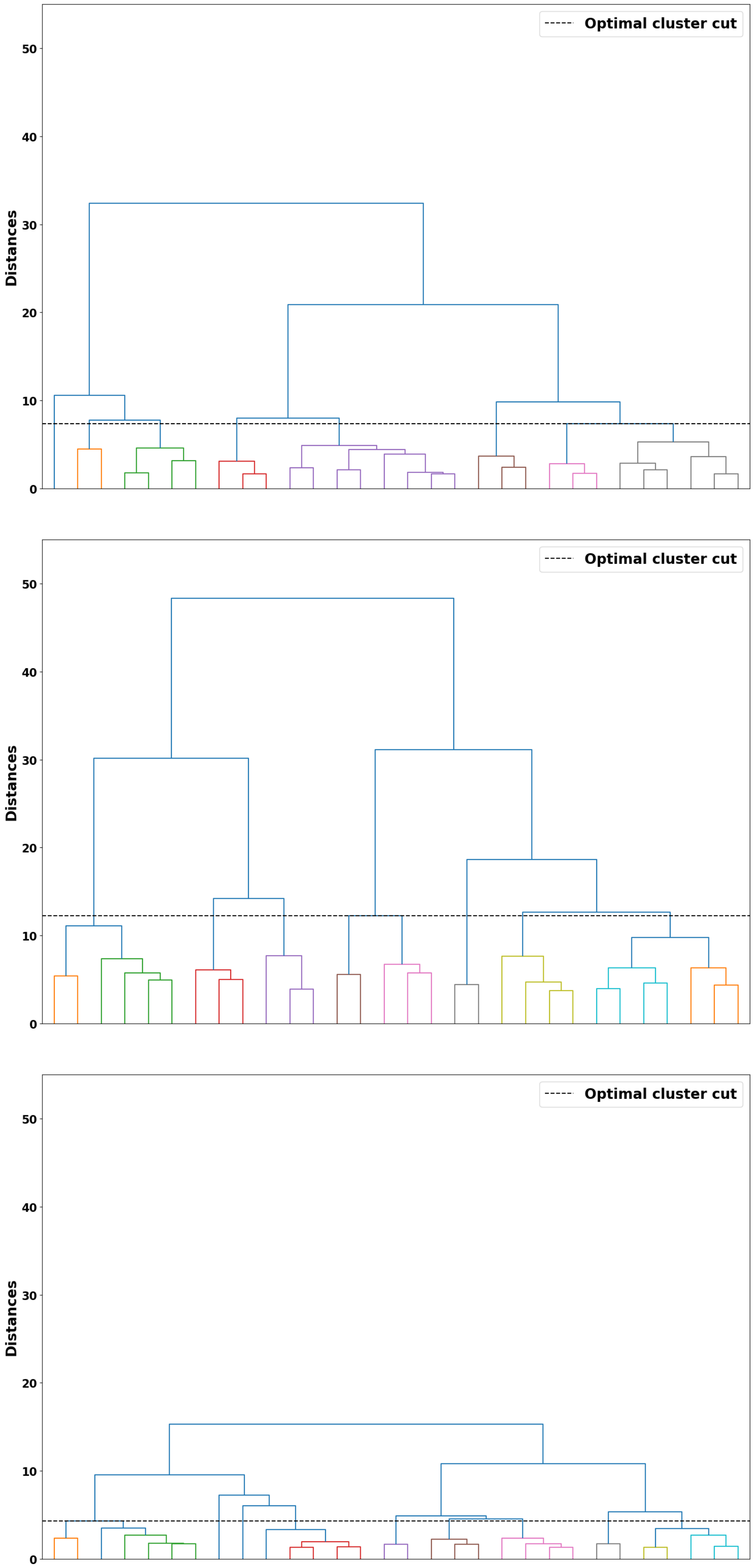


Figure 7.6: Dendrogram for the three building typologies

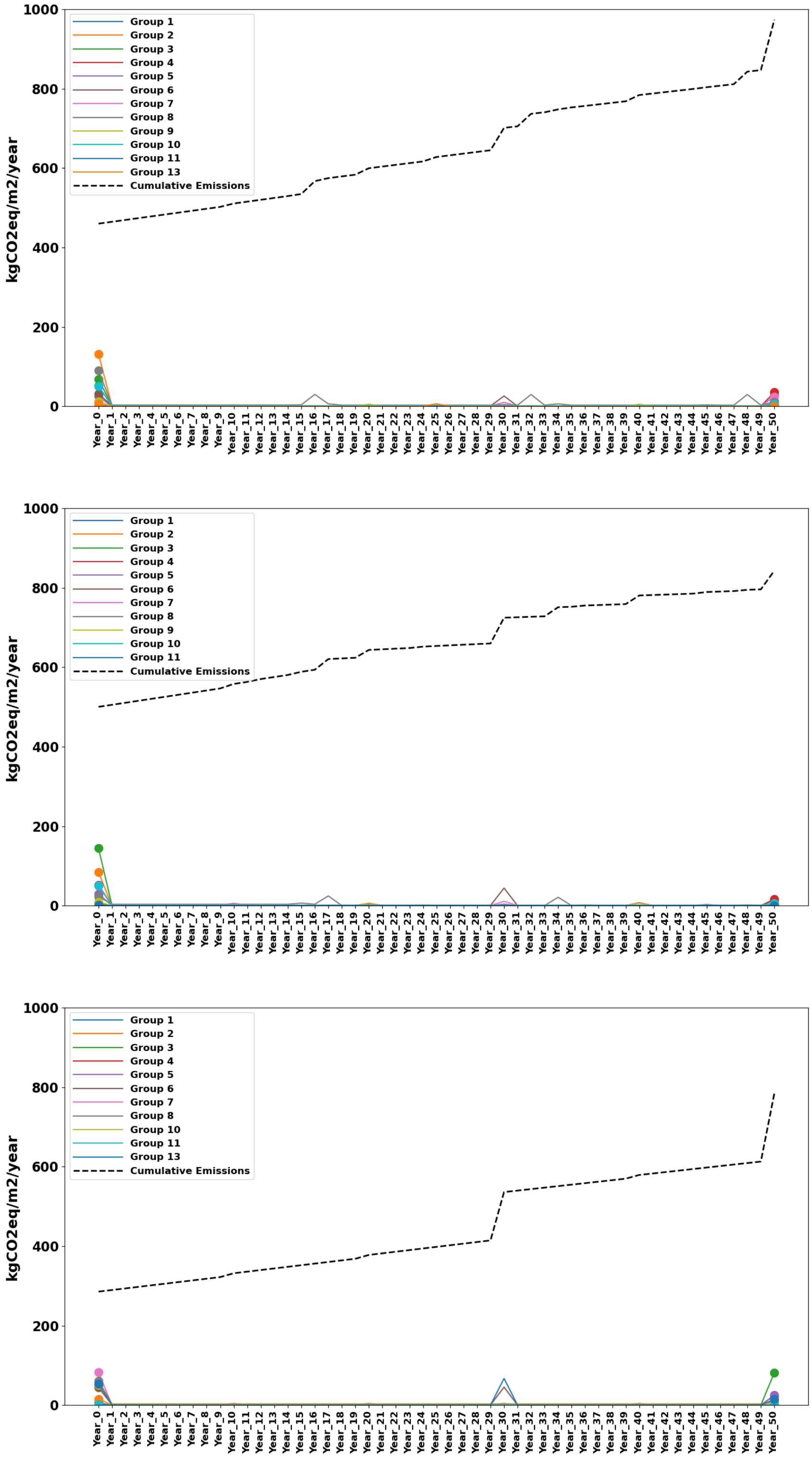
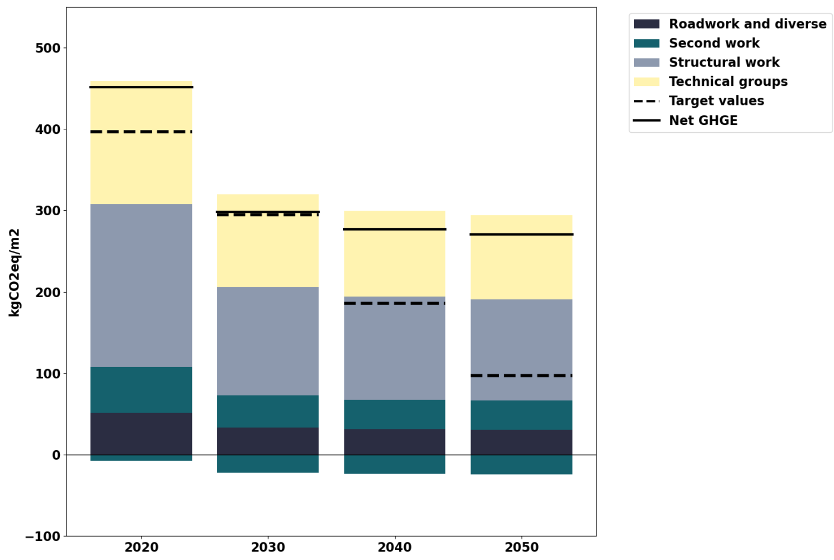
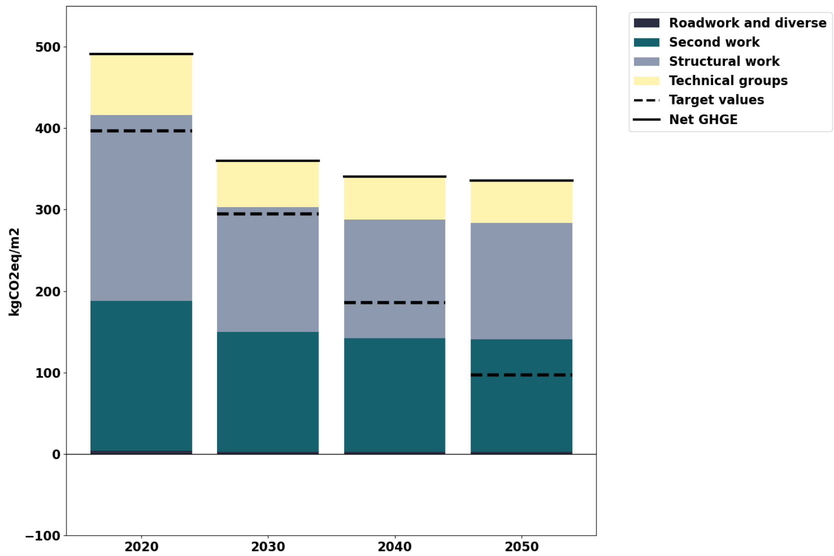


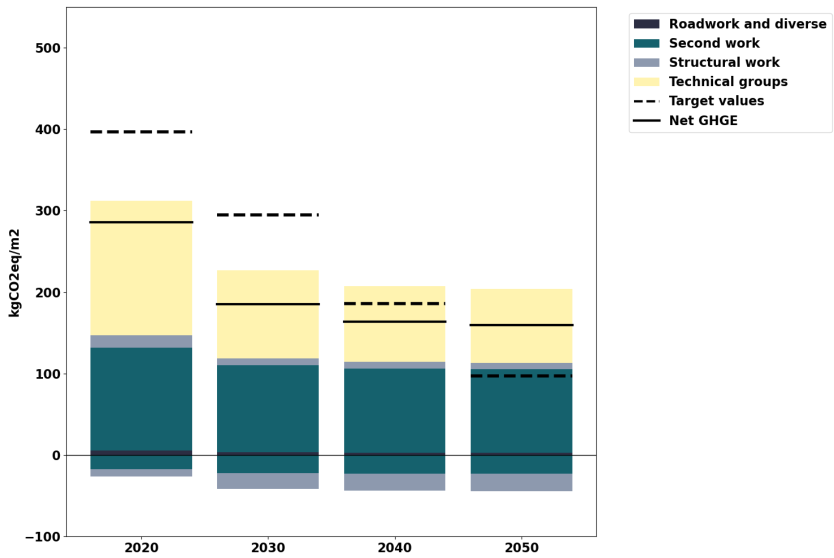
Figure 7.7: Temporal profile of embodied GHGE for the three



(a) Individual housing, concrete



(b) Individual housing, clay brick



(c) Individual housing, wood

Figure 7.8: Illustration of upstream embodied GHGE for the three individual building typologies under the IMAGE RCP1.9 scenario. Results are displayed by decades by 2050. The dashed lines per decades indicate the target values defined in Table 9.5

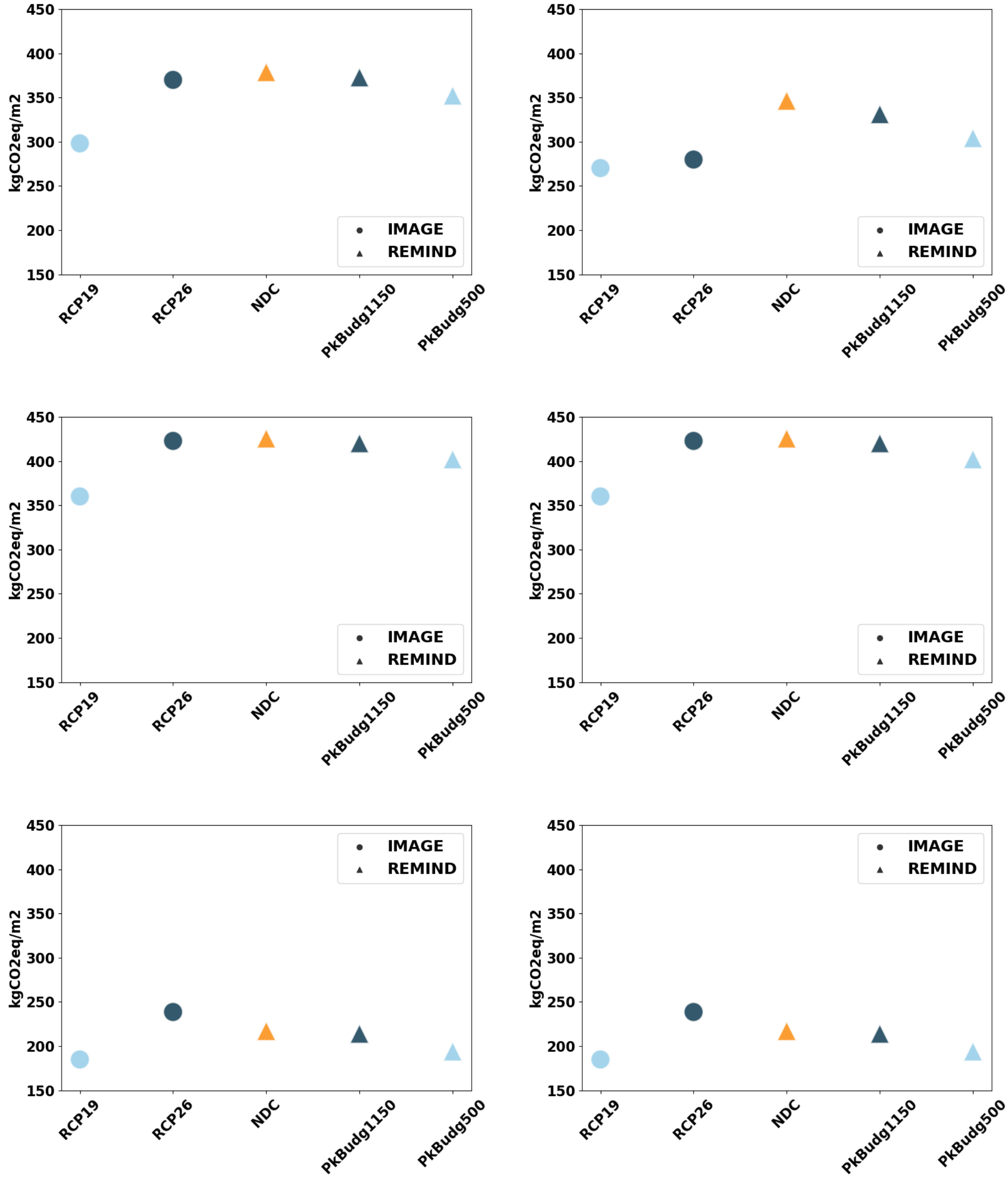


Figure 7.9: Sensitivity analysis on IAM models and scenarios for the three building typologies for 2030 and 2050

7.6 Discussions

7.6.1 Building stock characterisation

The method is one of the first step to apply detailed characterisation on a building LCA database. These types of data-driven and hybrid approaches have mainly focused on energy studies. By following these steps, it enables to take a more holistic approach, targeting embodied GHGE of buildings which have been largely overlooked. Nonetheless, future studies could use the same type of approaches to study other type of environmental impacts. The more buildings in the LCA database (e.g. the RE2020 database), the richer the analysis derived from the association and clustering would be, enabling to have more differentiation. In this study, a small set of variables have been put in both steps. Enlarging these to more variables would enable to take a broader perspective.

7.6.2 Environmental data

premise

In theory, a perfect alignment exists between IAM scenarios and prospective LCI databases when all variables and projections from the IAM are fully incorporated into the database. However, the current integration facilitated by the *premise* package falls short of this ideal, as it incorporates only a subset of IAM variables. Specifically, *premise* focuses on variables related to power, steel, cement, fuel production, and transport. Consequently, significant sectors which impact construction materials industry like heat production or chemicals remain unaddressed. Moreover, the integration of considered sectors into the *premise*-generated databases is not without its limitations. This is partly because certain IAM variables may not be readily available, such as specific efficiency metrics, or sometimes they are not included in the *premise* transformations, like the fuel mix used in cement production. As a result, databases produced through *premise* do not achieve full consistency with IAM scenarios, particularly regarding climate targets. Especially when ambitious climate targets are in place, relying on *premise*-generated databases could likely lead to an overestimation of GHGE, since sectors anticipated to undergo significant mitigation measures remain unchanged in the model (Sacchi, 2023a). Therefore, while *premise* offers valuable insights for integrating decarbonisation pathways into prospective LCA, it is essential to recognise its current limitations and the potential implications for accurately projecting GHG emissions in line with IAM scenarios.

EPD data

The use of EPD data presents a nuanced picture. On one hand, EPDs significantly streamline the completion and comparison of building LCAs against both regulatory limits and benchmarks derived from bottom-up and top-down methodologies. This advantage is particularly evident in this research, as it allows for reliance on the LCAs of a broad range of buildings. This approach circumvents the common challenge in many studies of justifying the representativeness of specific buildings due to limited LCA data availability. Furthermore, EPDs facilitate the calculation of WLC emissions and the establishment of current benchmarks, offering precise insights into the GHG impact at present time. On the other hand, the lack of access to underlying LCI data poses significant limitations, particularly for conducting detailed prospective and dynamic LCA studies. This barrier, along with the absence of uncertainty assessments, is well-established (Marsh et al., 2023) Moreover, the unavailability of such data impedes transparency and reproducibility, benefits typically afforded by studies with access to LCI data, as seen in Switzerland (Zhang et al., 2024). To address this gap, the current study attempts to align ecoinvent activities with EPD categories using the INIES nomenclature. While this method enables a rapid evaluation of the decarbonisation potential across different building typologies, thereby offering valuable insights for policymakers and stakeholders, it also complicates the direct application of the resulting LCI database. Direct access to an LCI database would further elucidate the impact of changes in background activities, such as electricity or transport, on various sectors. An additional challenge stems from the use of process-based LCI data, which tends to underestimate impacts due to truncation issues (Crawford et al., 2018). In response, hybrid LCI databases represent the state-of-the-art, as demonstrated in Australia with the EPIC database (Crawford et al., 2022). However, the lack of such databases in the French and EU contexts poses challenges to their adoption in research. Thus, securing access to LCI data or creating LCI archetypes emerges as a logical direction for future studies, although with its own set of hurdles.

7.6.3 Beyond's upstream sectors decarbonisation

This study centers on evaluating the decarbonisation potential resulting from changes in upstream sectors. However, it is important to note that various other decarbonisation strategies exist, such as material efficiency and sufficiency strategies, which are starting to be quantitatively assessed (Ipsen et al., 2024). Integrating these levers more accurately would provide a fuller understanding of the decarbonisation capabilities inherent within building activities.

Furthermore, to extrapolate these findings to a national scale, incorporating scenarios that reflect varying market shares of different building typologies could offer insights into the impacts of favoring certain types of construction. This approach would not only broaden the scope of analysis but also inform policy decisions by highlighting the environmental implications of promoting specific construction practices.

7.7 Conclusion

This paper introduces a methodology that combines a data-driven analysis of a building LCA database with prospective life-cycle assessment (LCA) techniques. Utilising the French RE2020 building LCA database alongside scenarios from Integrated Assessment Models (IAMs), this approach aims to provide a nuanced understanding of how different building typologies may align with evolving target values.

Significant emphasis is placed on employing advanced building stock aggregation methods such as association rule mining and clustering to identify buildings that exemplify specific material compositions and geometric characteristics. While such methods have been applied previously in building stock databases, transferring these approaches to a building LCA database represents a novel approach. As building LCA databases become more prevalent, this work represents an important step towards a data-driven approach to LCA analysis. To project future impacts, detailed modelling correlates material-specific decarbonisation pathways from IAMs with the material specifics listed in Environmental Product Declarations (EPDs).

This research not only reaffirms the well-documented variations in embodied performance across different building typologies but also underscores the significant influence that decarbonisation of upstream sectors has on the embodied footprint of building constructions. It highlights the critical need for material-specific pathways to accurately model the future embodied performance of new buildings. Results indicate substantial potential for decarbonisation from upstream sectors, with reductions reaching up to 60% in the most ambitious scenarios. Achieving more demanding targets will require finely tuned modelling of demand-side solutions, such as material efficiency strategies, which are not integrated in this work. Furthermore, at a national level, meeting ambitious carbon budgets would necessitate a shift in current construction practices, particularly in the market share of different building typologies, as the least environmentally performant ones currently dominate and will not meet future ambitious target values.

8
Discussions

Contents

This chapter critically evaluates the conducted research and its outcomes, aiming to present a thorough analysis of the main limitations encountered within the approaches detailed in previous chapters, while also delineating clear avenues for future research. Initially, the discussion focuses on extending the scope of emissions accounting and enhancing top-down carbon budget methods by incorporating a more detailed integration of scenario analysis within the input-output matrix. Additionally, the applicability of these methods to assess other environmental impacts is examined. Following this, the chapter highlights a range of possibilities for future development in bottom-up building stock modeling, emphasising the potential for more advanced refined modelling. Finally, the strengths and limitations of using a building LCA database along with prospective LCA methods is critically reviewed, with an eye towards understanding how these tools can be improved or expanded to better assess the environmental impacts of buildings.

8.1 Introduction

This chapter seeks to critically assess the methodologies used and the results disclosed in the preceding three chapters. It particularly highlights the shortcomings of the existing approaches, elucidates the underlying reasons for these limitations, and suggests directions for future research to enhance the robustness of the assessments.

Table 8.1 summarises the various issues discussed, alongside their corresponding chapters and the topics for future investigation. Each topic identified has a dedicated section in this chapter, ensuring a structured and comprehensive evaluation of the research conducted.

Table 8.1: Summary of identified limits in the thesis and avenues for future research in the different Chapters

Topics	**Related chapter(s)**	**Identified limits and avenues for future research**
Emissions accounting	Chapter 5	• Bottom-up accounting of land-use change emissions caused by buildings • Estimation of carbon storage and sequestration
Budget setting	Chapter 5	• Prospective modification of the IO structure • Regionalisation of IO table
Stock dynamics	Chapter 6 and 7	• Regionalisation • Additional sufficiency levers • Integrating qualitative scenarios
Building stock modelling	Chapter 6 and 7	• Coupling optimisation and exploration modelling • Hybrid methods for building stock characterisation, particularly for renovation and demolition targeting • Demand side solutions
Improvement of prospective LCA methods	Chapter 7	• Automation or creation of LCI archetypes • Use of hybrid coefficients • Lean towards consequential approaches
Improvement of benchmarks	Chapters 6 and 7	• Benchmarks for renovation • Benchmark for other environmental impacts
Decarbonisation levers inter-dependencies	Chapter 5, 6, and 7	• Levels of dependencies between Avoid-Improve-Shift levers, in particular with electricity and biomass resources • Potential competition between technologies

8.2 Extending the scope of emissions accounting

8.2.1 Integration of land-use change emissions associated with buildings

In Chapter 5, the developed accounting framework provides a comprehensive analysis of both operational and embodied greenhouse gas emissions (GHGE) arising from building activities. However, it does not address land-use emissions, which arise from changes such as the transformation of agricultural or forested areas into urban developments. This topic is also absent from the IPCC's Building chapter (Cabeza et al., 2022), which does not discuss emissions from land-use change, indicating a significant research gap.

Indeed, these changes can lead to significant emissions of CO_2, primarily from the alteration or destruction of biomass and soil carbon stocks. National emission inventories track these emissions using the IPCC's six land use categories (e.g. forest land, cropland, grassland, wetlands, settlements, and other lands) and a resulting matrix that tracks the 36 possible transitions (CITEPA, 2023). In France, land-use emissions have been quantified at approximately 4.8MtCO_2 (Haut Conseil pour le Climat, 2023) in 2022. However, this framework lacks the granularity to specifically identify emissions from building activities. At a time where policies like France's *Zéro Artificialisation Nette (ZAN)* aim to mitigate land transformation, future research can take advantage of emerging databases [1] to provide a bottom-up estimation of land-use emissions caused by buildings. These analysis can be further enriched with details by regions and building types. These potential results would be valuable to add in the accounting framework developed as part of Chapter 5, thus providing a complete picture of the emissions caused by buildings that include land-use change emissions.

8.2.2 Carbon storage and sequestration associated with the building activities

In Chapter 5, the carbon storage benefits associated with the use of bio-based materials (e.g. through photosynthesis) and the carbon sequestration associated with cementitious materials that occur along buildings lifetime (e.g. through carbonation) have not been quantified and integrated in the accounting framework. While carbon storage from bio-based materials is typically accounted for in national emission inventories under the land-use, land-use change, and forestry (LULUCF) sector, there are no specific details about the proportion attributable to buildings or their components. Conversely, carbon sequestration from cementitious materials during their life cycle is generally not included in national inventories (Xi et al., 2016). While some research suggest buildings could act as carbon sinks (Churkina et al., 2020), a more detailed characterisation of the global building stock's current and future potential as a carbon sink is needed (Arehart et al., 2021). Moreover, concerns about net losses in forest carbon due to poor forest management and deforestation underscore the complexity of this issue (Pomponi et al., 2020).

Enhancing the quantification and understanding of these mechanisms could enrich the emissions-focused accounting framework of this thesis. Through a prospective bottom-up life-cycle modelling of building stocks, it can become possible to capture when and where carbon storage and sequestration occur, possibly down to specific building components. This presents a promising research direction.

[1] See https://artificialisation.developpement-durable.gouv.fr/ in the French context

However, careful selection of LCA methodologies is crucial, especially in accounting for biogenic carbon, as methodological choices can significantly impact outcomes (Hoxha et al., 2020).

8.3 Budgets setting

Research opportunities and challenges in Input-Output models

In Chapter 4, the discussion centers on the challenges and opportunities of coupling inherently static Input-Output (IO) models with dynamic scenarios from Integrated Assessment Models (IAMs), notably using the comprehensive review proposed by Lefèvre (2023). The primary hurdle identified in this thesis is related to data availability rather than methodological issues. Chapter 5 introduces an approach for integrating contribution analysis results with decarbonisation pathway rates from various industries, according to the scenarios provided by the IEA. This approach may seem simplistic when compared to other studies mentioned in Chapter 5, which adapt the IO model's structure based on exogenous assumptions, often concentrating on the electricity sector. Such adjustments involve modifications to the inter-industry flow matrix (Z), the environmental matrix (B), or the final demand vector (y), as implemented by Wiebe et al. (2018) using IEA's detailed data from 2015, which is not open source. It is important to note that the 2023 IEA data set freely available [2], including scenarios like STEPS, APS, and NZS (which are documented in Chapter 3), does not freely provide this type of detailed information, which makes it difficult to implement on a large scale in a database such as Exiobase.

Another significant challenge is downscaling IO data to regional or city levels, which would significantly increase policy relevance by supporting sub-national actions. Despite the general scarcity of data at these more granular scales, instances exist, as evidenced by studies in Brussels (Athanassiadis et al., 2018) and method developed by Wiedmann et al. (2021) for several cities, indicating the potential and ongoing efforts to surmount these data constraints.

Beyond carbon budgets

As discussed in the Introduction, the Remaining Carbon Budget (RCB) emerges as one of the most studied Planetary Boundaries (PBs). While this thesis predominantly concentrates on refining the RCB through a downscaling process, it is pertinent to consider the extension of this approach to other identified PBs. However, unlike climate change or stratospheric ozone depletion, which are global issues, certain PBs manifest more prominently at regional or local scales (e.g. land system change or freshwater use). Consequently, the methodology for integrating these PBs may necessitate a shift from downscaling to potentially upscaling from bottom-up studies (Bai et al., 2024). Additionally, the national scale might appear less relevant for downscaling or upscaling for certain PBs, an example being the freshwater use where catchment areas provide a more meaningful scope of analysis. If refining the scope of downscaling or upscaling are scientific challenges, the issues of allocation remain again ethical and political questions.

[2] https://www.iea.org/data-and-statistics/data-product/world-energy-outlook-2023-free-dataset-2

If it remains a largely accepted framework, the PB framework has encountered criticism on several fronts: (a) from earth system scientists, concerning the determination of boundaries, the omission of critical boundaries, and the subjective nature of some established values; (b) regarding the framework's predominant Global North perspective, which overlooks issues of global equity; and (c) the critique concerning the democratic legitimacy of the PBs, which have largely been delineated by natural scientists without broad societal participation (Biermann and Kim, 2020).

8.4 Building stock dynamics

In Chapter 6, the dynamics of the building stock by 2050, including renovation, demolition, and new construction, are quantitatively assessed. The annual rates of renovation and demolition are determined by the number of dwellings or the surface area affected each year. Targeted buildings for these interventions are identified based on their placement within the transition matrix. This matrix maps out changes in Energy Performance Certificate (EPC) labels, specifically noting differences pre-renovation and post-renovation. New construction, on the other hand, adopts a demand-driven approach, predicated on three factors namely population growth, per *capita* square meter demand, and demolition rates, with projections extending to 2050.

This methodological framework, while functional, could be perceived as overly simplified. A more nuanced approach might incorporate additional variables suggested by the *'Imaginons les bâtiments de demain'* initiative (ADEME and CSTB, 2022) [3] , which outlines 22 factors within four categories: context, supply, demand, and policies. In particular for new construction, incorporating measures of sufficiency into the model represents another avenue for research. Existing scenarios incorporate a variety of sufficiency levers, as outlined by Gaspard et al. (2023). These measures could include, but are not limited to, changes in building usage (e.g., converting office spaces into residential units), segmentation of large buildings into smaller units, promotion of co-living arrangements across different generations, reduction in the number of secondary residences, and lowering vacancy rates.

Additionally, the analysis of new construction is currently conducted at a national scale within the thesis. A significant opportunity for enhancement lies in the regionalisation of stock dynamics, introducing data on a more granular level to reflect regional or city-specific trends. This would allow for the simulation of regional variations in development attractiveness based on factors such as employment opportunities or anticipated climatic conditions.

Lastly, integrating elements of social science and qualitative dimensions into quantitative models presents a challenge, yet it is a crucial endeavor. Such integration is often cited as a limitation in net-zero scenarios, highlighting the need for a more comprehensive approach that balances quantitative rigor with qualitative insights (Saujot et al., 2021). For instance, as explored in Chapters 2 and 3, Integrated Assessment Models (IAMs) exhibit limited capacity to represent societal transformations, such as behavioral dynamics, temporal transformation processes, and societal heterogeneity (Trutnevyte et al., 2019). Enhancing collaboration between modelers and social scientists could yield more realistic models, generate innovative solutions to climate mitigation, and improve the model-

[3] https://www.batimentdemain.fr/

ing of public acceptance (Trutnevyte et al., 2019). The development of the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017a), documented in Chapter 3, exemplifies efforts to integrate qualitative narratives into Integrated Assessment Models (IAMs). However, bridging the gap between disciplines such as economics and engineering, which lean towards positivist approaches, and social sciences, which often embrace constructivist methodologies, presents intrinsic challenges due to their differing epistemological foundations. Positivist models in economics and engineering focus on quantifiable data, rational choices, and deterministic laws, seeking to predict human behavior through mathematical formulations. These models value objective analysis but may oversimplify complex social interactions. In contrast, constructivist approaches in qualitative research prioritise understanding human experiences and behaviors within their specific contexts. These methods yield detailed, context-specific insights that highlight the subjective nature of reality but often resist broad generalisation that may be necessary for policy modeling (Elsawah et al., 2020).

8.5 Bottom-up building stock modelling

As highlighted in Chapter 2.2, data availability has significantly improved the capabilities for enhanced modelling of the building stock. However, existing models still struggle with the challenge of delivering reliable information on a macro scale (Stephan, 2022). Chapter 6 leverages data from the French National Building Stock Database (BDNB), which provides detailed insights into the renovation potential and characteristics of the building stock. A more sophisticated framework was introduced as a proof of concept in Pellan et al. (2023a). The subsequent subsections will detail the challenges identified by this thesis and that could be addressed by future bottom-up building stock models.

8.5.1 Building stock characterisation

In Chapter 2, both archetype and building-by-building modelling approaches are discussed. The extensive data available on millions of buildings enhances the potential to refine these methods for more precise characterisation of building stocks. Access to such detailed data supports the selection and modeling of archetypes and expands the scope of building-by-building analyses, assuming computational challenges are addressed.

In the thesis, buildings are characterised on a national scale in Chapter 6 by taking advantage of a building-by-building energy simulation conducted and stored within the French National Building LCA database (BDNB). Buildings are then aggregated according to their Energy Performance Certificate (EPC) label before and after renovation. This method differs from a strict building-by-building approach, which would involve tracking and monitoring the life-cycle performance of individual buildings over time. Chapter 7, further explores how archetypes for LCA modelling are selected using a data-driven approach from a building LCA database. This method diverges from traditional methods that often depend on building stock databases rather than building LCA database.

For future research, the primary challenge involves incorporating sufficient data to accurately reflect the stock and capture the heterogeneity among buildings, ideally introducing socio-economic data along traditional physical metrics. In this context, hybrid methods that blend deterministic classifications with clustering approaches could offer a robust solution by leveraging the strengths of both strategies (Borges et al., 2022). This approach has been implemented in Chapter 7 but could ideally be conducted in a more complete building stock database such as the BDNB. For example, modellers could initially categorise the building stock into known groups (e.g., by building types, climate zones) and then apply clustering algorithms within each category to account for the diversity in building attributes such as geometry, energy consumption, or wall insulation performance. Such hybrid techniques would allow for specific modelling of the varied combinations of categories and clusters. From a computational standpoint, they offer the benefit of applying resource-intensive methods, such as Hierarchical Clustering or K-Medoids, by segmenting the original datasets into distinct strata. The key challenge lies in selecting which parameters to incorporate, aligning with the objectives of the study while recognising variations without generating an overly large number of clusters. Furthermore, forthcoming research should undertake comparisons of the results yielded by various algorithms to evaluate their appropriateness.

8.5.2 Energy simulation

The analysis of building stock energy demand forms the cornerstone for calculating operational GHGE as argued in Chapter 2. In the thesis, Chapter 5 first adopts a top-down approach by relying on the national energy balance to calculate the baseline operational emissions and the underlying carbon budgets outlined by the SNBC. This approach provides a macro view of energy consumption across the building sector. Subsequently, Chapter 6, shifts the focus to a more granular analysis by examining the energy demand of individual buildings. This is achieved using data from previous simulations conducted under the BDNB, which applies a linear energy simulation model to each building. This method allows for detailed, building-specific insights into energy usage and efficiency improvements.

From the literature review done in Chapter 2, it is advisable to use engineering-based models that encompass all forms of energy demand, such as heating, domestic hot water, cooling, ventilation, lighting, and other appliances. These models are better suited for simulating various renovation types. They should be able to include operations that may incorporate novel construction materials and equipment with increased efficiency. Yet, a significant challenge exists in the aspect of time calculation. At the level of building stock, employing linear programming techniques has been proven to markedly enhance performance, as it enables the modelling of the entirety of French buildings within a reasonable time frame (Rit et al., 2023). Consequently, this approach opens up the possibility of modelling multiple stock dynamics scenarios, encompassing detailed renovations and demolition operations on a building-by-building basis. Such detailed information could then be integrated with a Life-Cycle Assessment (LCA), as it has been done in Chapter 6.

A critical direction for future research involves incorporating prospective weather conditions using weather forecast files in the modelling framework. This would allow for an in-depth analysis of the implications for heating and cooling demands, which are likely to undergo significant changes across different regions as a result of increasing temperatures due to climate change. Such an approach would enhance the accuracy and relevance of building performance simulations, reflecting the evolving climate realities more closely. Moreover, incorporating agent behaviour and socio-economic conditions into the model could significantly improve its accuracy by reflecting actual behaviours more closely. This adjustment could, for instance, improve the modelling of rebound effects. Currently, the reliance on EPC labels, while simplifying the analysis and providing an initial estimate, has been criticised for its lack of realism when compared to actual data on energy consumption (Conseil d'analyse économique, 2024). A vital direction for future research involves comparing model predictions with actual energy consumption, as verified through measurement campaigns. This comparative analysis should span across various building typologies and extend to different socio-economic contexts to ensure a comprehensive understanding of energy use patterns. Such studies would not only validate the accuracy of predictive models but also illuminate how diverse conditions influence building energy performance.

8.5.3 Material inventory modelling

Chapter 7 takes advantage of a building LCA database that offers comprehensive material inventory, although limited to new construction. At the building stock level, the majority of studies rely on Material Intensity Coefficient (MIC), as highlighted in Chapter 2.2, while detailed information at a more granular level, such as component and assembly levels, remains scarce. There is a pressing need for more comprehensive compilation of databases on construction assemblies. In line with efforts to create MIC databases (Heeren and Fishman, 2019), a similar approach should be applied to construction assemblies. Enhancing the accuracy of construction assembly data through improved building stock characterisation, by integrating not just building age and geometry but also energy performance metrics, could significantly contribute to the field. This approach is equally applicable to renovations, where detailed modelling could facilitate more nuanced analyses of the embodied impacts associated with various renovation strategies. Additionally, the application of expert rules is crucial for accurately reflecting the suitability of different renovation packages to diverse buildings. Such rules should take into account real-world factors like architectural heritage, heating, and ventilation systems, ensuring renovation approaches are both effectively possible and effective.

8.5.4 Coupling and comparing optimisation and explorative approaches

Modelling approaches are typically categorised into two main types: simulation (or exploration) and optimisation (Guivarch et al., 2022). The methodologies developed in Chapter 6 and 7 predominantly align with the first category. However, the strategy for sequencing renovations and demolitions in Chapter 6 incorporate elements of optimisation, as the approach prioritises the renovation or demolition of the most energy-consuming buildings first, although not through an optimisation model.

Integrating and contrasting both approaches can offer deeper insights. Within the context of building stocks, extensive research has demonstrated the advantages of prioritising renovation and demolition operations, a finding corroborated by the outcomes presented in Chapter 6. Therefore, a more sophisticated optimisation approach could be developed to specifically target certain dwellings. This method could either be integrated with or contrasted against exploratory scenarios to underline the differences in outcomes. Optimisation could focus on a single objective, such as cost, energy consumption, or GHGE, or it could encompass multiple objectives to create a Pareto front. The latter approach enhances decision-making by illustrating trade-offs between competing objectives but requires additional decision-support methodologies, like Multi-Criteria Decision Analysis (MCDA), to effectively parse and prioritise these objectives.

8.6 Improvement of prospective LCA methods for building stocks

8.6.1 Lack of LCI data

In Chapter 7, one of the principal limitations identified in integrating building stock assessments with product-level analyses is the availability of life-cycle inventory (LCI) data. This issue is particularly pronounced in this thesis, as the primary data source for building LCA are the Environmental Product Declarations (EPDs) available in the INIES database. Unlike comprehensive LCI data, EPDs typically do not disclose their underlying inventory details. This lack of transparency creates a substantial obstacle for applying detailed prospective LCA methodologies in the extensive array of building LCA data available in the RE2020 database. Indeed, transforming LCI data with inputs from IAMs is crucial for modeling the evolution of building activities and assessing the role of different sectors in the decarbonisation process. Furthermore, the absence of comprehensive LCI data hinders the application of advanced dynamic LCA frameworks, limiting the scope of sustainability assessments in the building sector.

A potential solution to this challenge is the manual creation of LCI databases for various categories of building materials and components. However, this approach is inherently labor-intensive and likely to be incomplete, potentially overlooking specific product differences crucial for accurate environmental assessments. The challenge is compounded by the complexity involved in capturing the nuanced environmental impacts of diverse building materials. Automation presents an alternative solution, often viewed as a means to manage the complexity encountered with numerous technology scenarios and a vast array of components, leading to a multitude of modeling choices (Steubing et al., 2016) (Haun et al., 2022). Zhang et al. (2024) demonstrated the use of a simple fuzzy lookup function to align the Swiss LCI database with Ecoinvent. However, applying similar automation techniques for matching products from the INIES database to ecoinvent is problematic due to significant differences in terminology.

Lastly, the example of Australia's EPiC database (Crawford et al., 2022) illustrates the potential benefits of using hybrid coefficients in the building context. Future research could explore how the application of hybrid LCI data influences the environmental impact assessments of different building typologies compared to traditional process-based methods. Such investigations are currently limited by the scarcity of hybrid LCI databases, underscoring the need for more comprehensive data resources in this area.

8.6.2 Towards consequential prospective approaches

The integration of Integrated Assessment Models (IAMs) with industrial ecology tools (e.g. LCA, IOA) have opened promising avenues for future research as extensively documented in Chapter 2. In the LCA landscapes, attributional approaches have traditionally dominated the field. Nonetheless, consequential approaches have been recognised for their aptitude in evaluating the broad adoption of public policies, including their indirect effects (Almeida, 2022). In the context of a net-zero economy, substantial efforts across all economic sectors are imperative, with expected significant impacts on both production and consumption landscapes. Therefore, it becomes crucial to adopt large-scale approaches capable of identifying marginal suppliers. Such approaches are essential for implementing a life-cycle sustainability assessment framework (Guinée et al., 2011). This framework should not only consider environmental aspects but also integrate economic and social evaluations to ensure a holistic assessment of sustainability

Although the integration of IAMs with attributional LCI databases was the initial focus, recent efforts have extended to encompass consequential LCI databases (Maes et al., 2023). Applying these advanced methodologies to building activities offers a promising path forward, particularly in light of the imperative Renovation Wave. This approach enables not only the examination of the direct environmental impacts associated with building activities but also the exploration of the broader, large-scale indirect effects that such policy initiatives could exert on the economy.

8.7 Improvement of bottom-up benchmarks

8.7.1 Bottom-up benchmarks for renovation

In Chapter 6, the use of the French building LCA database (RE2020 database) facilitates the creation of bottom-up benchmarks for new construction, with the analysis encompassing a significant number of buildings, although predominantly focused on individual housing. For renovation benchmarks, the hypothesis is that the extent of renovation, as indicated by the improvement in Energy Performance Certificate label, influences the building components (e.g. building groups as indicated by the RE2020) touched by renovation operations. Consequently, renovation benchmarks are extrapolated from new construction values.

This methodological simplification arises primarily from the data scarcity concerning renovation activities, which hampers the establishment of distinct benchmarks for renovation projects. The scarcity of the data can be attributed to the lack of mandatory requirements. Additionally, there exists a varied classification of renovation types (e.g. light or shallow renovation, deep renovation, energy renovation, etc) which often depends on the extent and parts of the building being renovated. As a result, it is difficult to have benchmark values for different types of renovation works and their associated energy savings. Access to a comprehensive dataset detailing various renovation operations across multiple building types could allow for the generation of statistical analyses, leading to the formulation of limit, reference, and target values for renovations tailored to specific building typologies. Such an approach would facilitate a deeper understanding of how renovations of a comparable nature in terms of operational GHGE savings can entail varied levels of embodied GHGE investments. In practice, the concept of payback times, indicating the number of years required to offset the embodied GHGE investment through associated operational GHGE savings, is often used in studies. However, estimates for payback times vary widely, ranging from 6 to 70 years (HQE, 2022). This variation underscores the need for a more refined approach to developing bottom-up benchmarks for renovations, which would allow for adjustments to be more accurately tailored to the unique characteristics of buildings. Employing a combination of hybrid techniques, including deterministic and clustering classification, could facilitate the revision of currently outdated and imprecise benchmarks. An example of such imprecision can be seen in the values cited by RTE and ADEME (2020) which suggests 60kgCO_2eq/m^2 for a single EPC label jump and 150 kgCO_2eq/m^2 for two to three EPC label jump.

Ideally, these improvements could culminate in the establishment of compulsory limit values for renovations, akin to those set for new constructions under France's RE2020 framework. However, a more concerted effort is required to monitor renovation activities and gather LCA data from these operations. Should these renovation benchmarks become available, a methodology similar to that detailed in Chapter 7 could be later employed for renovation analysis. This entails the use of prospective bottom-up stock modelling, incorporating both an energy simulation model and a component-based model, to evaluate how various renovation strategies align with the established limit, reference, and target values.

8.7.2 Beyond carbon benchmarks

In terms of benchmarks, an exclusive focus on carbon could inadvertently lead to a 'carbon tunnel vision,' overlooking other physical constraints that may interact with the goal of decarbonising building activities. For example, constraints related to metals, particularly relevant in the energy and transport sectors (de Koning et al., 2018), yet intrinsically linked to building activities decarbonisation, highlight the necessity of developing comprehensive benchmarks. These benchmarks should not only encompass carbon but also extend to various metals and mineral materials used within the building sector (Bendahmane, 2024). Such an approach could facilitate the establishment of mandatory limit values, similar to those developed for carbon in the RE2020 regulation. While the growing availability of data, for instance through building LCA databases, may simplify the creation of bottom-up benchmarks, devising top-down benchmarks presents more challenges, due to the difficulties of having absolute targets.

8.8 Decarbonisation levers inter-dependencies

Decarbonisation strategies are commonly conceptualised within the Avoid/Improve/Shift or Demand-side/Supply-side frameworks, as discussed in Chapter 3. While this conceptualisation aids in clarification, the inter-dependencies among these strategies are less frequently examined, yet they are critical. However, there is often an implicit relationship between decarbonisation levers, with the success of one being contingent upon the activation of another. In the realm of building activities, the decarbonisation of electricity and the supply of biomass, especially wood, serve as illustrative examples. The adoption of low-carbon electricity is fundamental in all decarbonisation scenarios, to decrease operational GHGE of buildings. However, the success of the decarbonisation of electricity significantly depends on the performance of the building stock, particularly the rate and effectiveness of renovations which are needed to reduce overall electricity demand. Some studies focused on the electricity sector have incorporated sensitivity analysis on the performance of the building stock to investigate its impact from a security, environmental and economic point of view (RTE and ADEME, 2020). In the thesis, Chapter 6 explores the impact of different decarbonisation pathways for electricity for a same stock scenario, assessing the potential consequences of failing to decarbonise the electricity grid on the operational GHGE of the building stock. Future research should delve deeper into these connections. Similarly, regarding biomass, the level of new construction that supports a sustainable timber supply, facilitating responsible forest management, warrants scrutiny. Various studies have indicated that the large adoption of timber construction is limited by the availability of sustainably managed forest products (Göswein et al., 2022). Further integrated analysis that combines forest management with sophisticated models for new construction could offer insights into the sustainable level of new construction that balances climate goals with other environmental pressures, such as biodiversity.

Analysing the decarbonisation strategies of various sectors in isolation, especially within activities that depend on multiple sectors, risks missing a holistic view. To address this, there's a need for a deeper analysis of the prerequisites for major decarbonisation levers, employing integrated models that consider the demand for key low-carbon solutions across all sectors to determine the feasibility of their supply. For instance, recent research has highlighted that decarbonisation strategies for steel and cement are significantly contingent on the availability of CO_2 transport and storage infrastructure, ample renewable electricity, and low-carbon hydrogen (Watari et al., 2023). Future studies should incorporate uncertainty analysis and scenarios that envisage failures in these strategies to evaluate their implications for building activities.

From an economic perspective, achieving deep decarbonisation, particularly in sectors that are challenging to decarbonise, becomes exponentially costly. This is especially true when the decarbonisation effort is focused on the production side and heavily relies on carbon capture and storage technologies (Favier et al., 2018). Exploring the willingness and capacity of companies to invest in the face of a significant demand reduction could provide valuable insights.

Furthermore, the competition and inter-dependencies between technologies for the same decarbonisation lever warrant examination. Under varying system-level conditions, identifying which technologies are crucial for achieving decarbonisation, whether they depend on other critical technologies, or if they compete with each other, is essential (Pye et al., 2019). Such analysis can offer guidance for the planning of public policies.

9

Conclusion

Contents

The conclusion chapter completes the thesis by summarising the insights offered in the different chapters. It then outlines the contributions and implications of the results for both the scientific community and policy makers. Finally, it summarises the perspectives and outlooks that future research could examine.

9.1 Summary

The primary objective of this doctoral dissertation was to develop life-cycle carbon budgets and to model explorative scenarios that enables the quantification of the French building activities life-cycle emissions. Guided by three pivotal research questions (e.g. 1, 2 and 3) introduced in Chapter 1, this research navigated through the complex landscape of emission accounting, scenario analysis, and the prospective Whole-Life Carbon (WLC) emissions calculation of the building activities through three main questions:

1. **Emission accounting and carbon budgets**: how to extend existing approaches to capture the entire scope related to building activities?
2. **Scenario analysis, stock-dynamics and benchmark values**: how to compare prospective bottom-up WLC emissions and top-down derived carbon budgets?
3. **New construction and prospective LCA**: how to consider and model the impact of the decarbonisation of upstream sectors for different building typologies?

An initial literature review presented in Chapter 2 delineated the current state-of-the-art, identifying both the strengths and gaps within environmental assessment methods, building stock modelling and their integration in Chapter 2. Furthermore, an examination of existing scenarios, both internationally and within the French context, was provided in Chapter 3, underscoring the wealth of literature and hypotheses from which this dissertation benefits. Both reviews highlighted several key insights:

- **Emission accounting**: established guidelines for emission accounting exist, yet they often do not adequately address cross-sectoral and cross-border impacts. Due to this gap, a more comprehensive approach had to be developed to address Research Question 1.
- **Prospective analysis**: this approach, characterised by its diversity and lesser degree of standardisation, offers critical guidance into future scenarios. However, its integration with industrial ecology needs strengthening. Scenario analysis, a critical component in addressing research questions 1, 2 and 3, has been extensively discussed in Chapter 3.
- **Input-Output Analysis (IOA)**: IOA provides significant insights for examining supply-chain impacts at a macro scale. However, to facilitate forward-looking studies, such as future carbon budget analyses pertaining to Research Question 1, it must be integrated with other tools and methods. This integration has been developed in Chapter 5.
- **Life Cycle Assessment (LCA)**: As a standardised method widely used in building environmental assessments, LCA enables the establishment of sound bottom-up benchmarks, relevant to Research Question 2. Despite its widespread use, limitations related to the temporal dimension persist. Nevertheless, recent advancements in linking LCA with prospective tools have broadened its applicability in forward-looking studies, especially relevant in the context of research question 3.

- **Hybrid-LCA**: Combining the strengths of IOA and LCA, hybrid-LCA remains a complex methodology, predominantly accessible to experts. Data availability, particularly in the French context, presents a significant challenge to its application within this thesis.
- **Building Stock Modelling (BSM)**: The efficacy of BSM techniques hinges on data accessibility, which is crucial for enhancing building stock representation through sophisticated material modelling. The integration of construction assemblies libraries further refines this modelling process. Importantly, coupling BSM with environmental assessment methods markedly improves the coherence and consistency of building environmental assessments.

Informed by these insights, the thesis systematically addressed the research questions through detailed analyses presented in three independent research papers encapsulated in Chapters 5, 6 and 7. The analysis progressively narrowed its focus, beginning with the entire spectrum of building activities and culminating in considerations applied in the specific context of new construction.

1. Initially, a detailed accounting methodology was outlined, facilitating the extension of sectoral carbon budgets, which are inherently limited in scope. This involved employing various life-cycle inventory methodologies to capture the WLC emissions of French buildings, including a detailed assessment of embodied GHGE, which are often overlooked in policy discussions and global scenarios. Subsequently, this accounting framework was integrated with both national and international scenarios to illustrate varying ambitions in carbon budgeting, implying different levels of decarbonisation across all economic sectors.
2. Adopting a top-down approach to carbon budgeting at the level of building activities, the exploration of scenarios was then conducted at the residential activities level. This focus was chosen due to the availability of detailed data for the residential building stock, e.g. the BDNB in the French context, which provides comprehensive information on buildings, including usage, living surface area, materiality, and energy consumption before or after potential renovations. With this detailed baseline, a modelling framework was introduced to project the evolution of the stock and its associated WLC emissions. Alongside a robust baseline, this framework incorporated multiple national scenarios concerning variables such as the emission factors of energy carriers, the number of square meter per *capita* or the possible evolution of embodied impacts per square meter in stock-level activities. Ultimately, this methodology enabled the visualisation of a scenarios aligning with ambitious carbon budgets, paving the way for more detailed analyses concerning which building typologies could meet such stringent criteria. Subsequently, this study aligns material profiles derived from Environmental Product Declarations (EPDs) with modified Life-Cycle Inventory (LCI) data that reflects future Integrated Assessment Models (IAMs) scenarios. This approach was intended to provide a detailed understanding of how various building typologies might align with (or deviate from) evolving environmental performance benchmarks.
3. The final aspect of this research concentrated on new construction, developing a methodology that marries a data-driven analysis of building typologies with prospective LCA techniques. Leveraging the French RE2020 building LCA database, this approach was designed to evaluate

the environmental performance of various building typologies against both current and anticipated future performance levels, determined in the previous chapter. A particular emphasis was made on the integration of sophisticated building stock aggregation methods, including association rule mining and clustering, to identify buildings that are representative in terms of material composition and geometric characteristics. Subsequently, the material composition of these selected buildings was analysed through their lists of Environmental Product Declarations (EPDs) which provide a detailed account of their constituent materials. This analysis facilitated a direct comparison with Life-Cycle Inventory (LCI) data, enabling the incorporation of prospective modifications based on scenarios assessed by Integrated Assessment Models (IAMs).

Building on these analyses, the following key findings summarises the central outcomes and implications of each research phase:

1. The French building stock emitted 162 $MtCO_2eq$ in 2019, with embodied GHGE accounting for 36% of this total. 20% of total emissions occurred outside national borders, indicating that existing climate policies are overly narrow and should incorporate a broader spectrum of emissions. In the future decades, embodied GHGE are projected to become the predominant scope of emissions by 2040 under the current decarbonisation policies.

2. A significant gap in Greenhouse Gases Emissions (GHGE) can result from different targeting strategies for renovation. In particular, policies targeting fossil fuel prove most effective in reducing operational GHGE than those focusing only on energy performance label. In ambitious scenarios with high renovation rates, embodied GHGE become predominant by 2040. A combination of sufficiency (e.g. through lower square meter per *capita*) and deep decarbonisation of energy carriers and construction materials is necessary to achieve the most ambitious carbon budgets.

3. Prospective LCA modelling of new construction suggests a high decarbonisation potential from upstream sectors, with reductions of around 60% in the most ambitious scenarios, in terms of emissions per square meter at the building level. When extrapolated to the national level, these findings seem to indicate that current market share between different building typologies do not enable alignment with ambitious carbon budgets, pointing to the need for further deployment and modelling of additional demand-side mitigation strategies.

9.2 Contributions and implications

The contributions of this study span both the scientific community and policy-making spheres, reflecting the applied facet of the research undertaken. It underscores the importance of recognising buildings as cross-sectoral activities, both in accounting frameworks and in decarbonisation pathways. By employing a diverse array of methods, this research harmoniously integrates top-down and bottom-up approaches, offering a contribution to enhance linkages across scales, from building components (micro scale) to national building stocks and sectoral roadmaps (macro scale).

Initially, the thesis presents a novel approach to extending carbon budgets applicable in EU countries and potentially worldwide. This method offers an opportunity to integrate such extended carbon budgets into broader climate planning across all sectors, for example in the revision of the Low-Carbon National Strategy (SNBC) in France. This aspect not only enriches policy discussions but also lays the groundwork for more integrated sectoral decarbonisation strategies. Furthermore, the initial effort to link carbon budgets with the decarbonisation of upstream sectors marks a step in this research domain. Although this represents an initial implementation, such advancements promise to deepen the scientific understanding of sectoral inter-dependencies in carbon budgeting. The research also demonstrates the capability to calculate WLC emissions based on a robust bottom-up baseline augmented by extensive scenario-based assumptions. This approach not only broadens the analytical capabilities for both scientists and policymakers but also facilitates a nuanced exploration of trade-offs between operational and embodied impacts. Such investigations, which are seldom conducted, are crucial to prevent the displacement of impacts to upstream industrial sectors Moreover, the research leverages a comprehensive dataset of building LCAs, mitigating the risk of reliance on limited data sets that may not accurately represent current practices. This significant data foundation supports the identification of building archetypes, offering a method that could be generalised across different building stock databases, despite challenges related to data gaps. The prospective analysis initiated in this part serves as a foundational step towards bridging the gap between building stock level assessments and product-level analyses. From a policy perspective, the insights into which building typologies can meet stringent environmental performance criteria equips policymakers and industry stakeholders with the necessary information to set realistic, impactful environmental standards.

Collectively, these contributions underscore the thesis's relevance and potential impact, offering both theoretical advancements and practical applications that bridge the gap between scientific research and policy-making in the context of building activities and decarbonisation pathways in general.

9.3 Perspective and outlooks

The methodologies employed and the diverse scopes explored in this doctoral dissertation lay the groundwork for numerous future research opportunities.

- **Top-down modelling enhancements:** There is a significant opportunity to strengthen the linkage between Input-Output Analysis (IOA) and prospective models, aiming for a more nuanced understanding of how scenarios impact supply-chain effects. Additionally, the concept of environmental budgets could be expanded beyond the current focus on greenhouse gas emissions (GHGE), although this exploration is not without its challenges.

- **Advancing stock dynamics understanding:** Enriching the modelling and comprehension of building stock dynamics, especially by including more socio-economic drivers and sufficiency levers, emerges as a crucial area for future research. This advancement is paralleled by the need to effectively integrate quantitative and qualitative dimensions of prospective assessments. Furthermore, the regionalisation of these dynamics promises increased relevance for stakeholders and policymakers, albeit contingent upon the availability of data.

- **Building stock modelling developments:** The growing availability of raw data is set to support the development of robust and widely applicable methods for assessing the environmental impacts of buildings, from the meso to macro scale. This data enables a holistic yet precise bottom-up perspective of operational and embodied impacts. There is also a potential to more effectively marry explorative and optimisation approaches, facilitating the planning of trajectories that optimise the chances of meeting climate objectives.
- **Bridging gaps in prospective analysis:** A primary barrier to expanding prospective analysis from the component scale to the macro scale is the widespread availability of LCI data. Future research should focus on bridging this gap, fully leveraging advanced methods across scales, and incorporating consequential approaches to explore the broader effects of specific policies.
- **Interdependencies among decarbonisation levers:** The intricate web of interdependencies between decarbonisation strategies across different sectors presents both challenges and opportunities. Future work should adopt integrated models that consider the demand and supply dynamics of low-carbon solutions, critically assessing the feasibility of meeting ambitious decarbonisation goals within the limits of available resources and technologies.

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9.4 Appendix A: Supplementary information to Chapter 5

9.4.1 Supporting data

The supporting data for this Chapter can be found at: https://github.com/marpellan/French_WLC_budgets.

9.4.2 SECTEN format

The *residential and tertiary* sector in the Secten format includes emissions from residential and non-residential buildings use phase including:

- Heating, domestic hot water and cooking
- Air conditioning
- Refrigeration
- Use of products (e.g. paints, aerosols)
- Domestic machinery (e.g. gardening)
- Burning and sewage
- Other domestic activities

For non residential buildings, subsections include:

- Heating, domestic hot water and cooking
- Air conditioning
- Refrigeration
- Use of products (e.g. paints, aerosols)
- Other tertiary activities

They do not take into account emissions associated with the use of electricity and heat from district networks, which are included in the *energy* sector.

9.4.3 Emission factor of electricity

In France, the Base Carbone provides emission factors by usage for electricity consumption in residential and non-residential buildings. Table 9.1 summarises them, both D-EF and LC-EF for the year 2019.

9.4.4 Concordance matrices

Due to the large number of sectors and regions in Exiobase, the concordances matrices used to aggregate them are available as Excel files in the Github repository. Additionally, in Table 9.2 the concordances between the 19 sectors aggregation and the IEA scenario pathways is given.

Table 9.1: Emission factors of electricity by usage in 2019 in $kgCO_2eq/kWh$ in the Base Carbone (ADEME, 2020)

Usage	D-EF ($kgCO_2eq/kWh$)	LC-EF ($kgCO_2eq/kWh$)
Average	0.0418	0.0607
Heating	0.0524	0.0717
Hot water	0.0414	0.0595
Lighting	0.0447	0.0631
Air conditioning	0.0407	0.041
Other usages	0.0414	0.0587

Table 9.2: Concordances between the 19 sectors aggregation and the IEA scenario pathways

IEA Pathways	Sectors
Oil	Petroleum products
Natural gas	Gas
Final consumption	Agriculture, hunting, forestry & fishing; Electrical & machinery
Industry	Construction; Manufacturing & recycling; Metal & metal products; Mining & quarrying; Other non-metallic products; Others
Iron & Steel	Iron & Steel
Cement	Cement
Transport (road)	Transport
Services	Public administration; Financial intermediation & business activity

9.4.5 Cement and concrete value chain decarbonisation lever

Although this study does not aim to develop a detailed mitigation roadmap, it offers an overview of mitigation opportunities within the cement and concrete value chains sector due to the significant role of the *'Cement, lime and plaster'* in embodied GHGE as illustrated in Section 5.5.1. The global cement sector, responsible for 7% of CO_2 emissions, faces challenges in decarbonisation, with two-thirds of its GHGE stemming from the inherent process of limestone calcination (IEA, 2021). Previous research has often focused narrowly on production stages, resource use, or cement's end-of-life, predominantly examining fuel switching and production efficiency (Miller et al., 2021). Notably, upstream energy and emission efficiencies have been more thoroughly quantified than downstream and material efficiency strategies (Pamenter and Myers, 2021). Yet, the value chain reduction's importance is increasingly recognised, with strategies ranging from clinker, cement, and concrete levels to structural applications (Favier et al., 2018). At the clinker production stage, shifts towards energy efficiency and alternative fuels, including biomass and waste, are crucial for CO_2 reduction. Cement production's move towards supplementary cementitious materials (SCMs) like fly ash, slag, and calcined clays reduces emissions and promotes a circular economy by utilising waste materials. The concrete production phase highlights the need for optimised mix designs that incorporate SCMs, enhancing strength and durability while minimising cement content. These approaches are integral to structural design and building activities, advocating for durability, material efficiency, and recycling principles. This strategy aligns with the reduction ethos promoted by (Habert et al., 2020a): less clinker in cement, less cement in concrete, less concrete in structure and fewer structure replacements.

In the French context, the Sectoral Transition Plan for the cement industry (ADEME, 2021c) outlines a detailed decarbonisation roadmap, identifying five emission reduction levers: plant upgrades, fuel mix changes, clinker content reduction in cement, incremental changes, and carbon capture and storage (CCS). It presents a reference scenario predicting a 54% CO_2 emission reduction by 2050 (compared to 2015 levels) alongside a 13% demand decrease, and two decarbonisation scenarios focusing respectively on demand-side shifts and technology advancements, projecting up to an 83% CO_2 reduction.

9.5 Appendix B: Supplementary information to Chapter 6

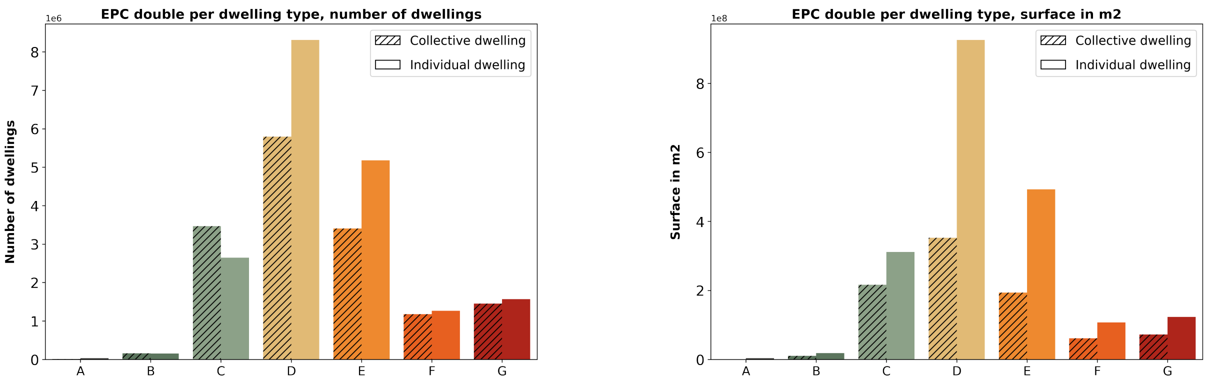
9.5.1 Supporting data

The supporting data for this Chapter can be found at: https://github.com/marpellan/Scenario_explorer.

9.5.2 Stock in 2020 from the BDNB

General figures

In Figure 9.1, the repartition of EPC label is given in number of dwellings (left side 9.1a) and by surface in m^2 (right side 9.1b).



(a) Number of dwelling

(b) Surface in m2

Figure 9.1: Number of dwellings and surface (in m^2) per dwelling type and EPC double label

A substantial portion of the dwelling stock falls under the C, D, and E labels. The D label is notably prevalent, encompassing 41% of dwellings and 44% of the total surface area. Meanwhile, F and G labels collectively account for approximately 5.5 million dwellings, which represents about 16% of the entire dwelling stock. In contrast, A and B labels are extremely scarce.

It is also insightful to examine the energy mix within each category of dwelling type and EPC label. An analysis conducted by dwelling type and EPC labels reveal that electricity and natural gas are the most dominant energy vectors in the dwelling stock. Electricity prevails in dwellings with the highest energy performance certificates (EPCs), such as A and B labels. Besides, district heating also has a significant role in collective dwellings. Natural gas, on the other hand, is predominantly used in dwellings with C to F labels and is the major contributor of operational emissions (Pellan et al., 2023b). The usage of oil products is mainly found in dwellings with the poorest EPCs, particularly in individual dwellings.

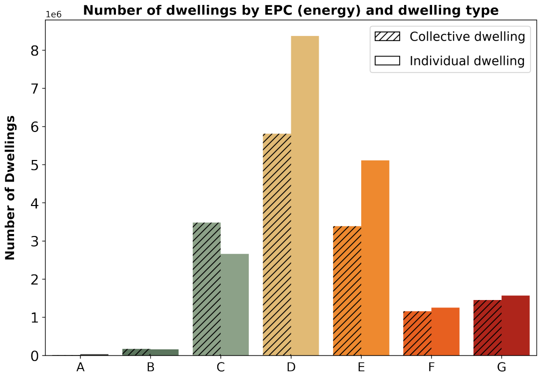
EPC energy vs GHGE

Under the new EPC labeling method, dwellings are now categorised based on the inferior of two labels: either for energy consumption or GHGE (MTES, 2021). Table 9.3 details the values for both labels given by by the legislation.

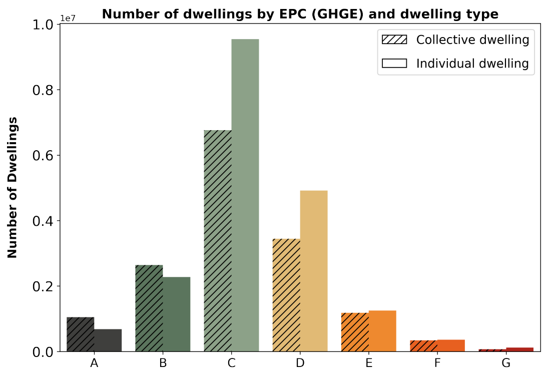
Table 9.3: EPC regulation

Rating	EPC Energy (kWh/m^2)	EPC GHGE (kgCO$_2$eq/m^2)
A	0-70	0-6
B	70-110	6-11
C	110-180	11-30
D	180-250	30-50
E	250-330	50-70
F	330-420	70-100
G	>420	>100

Using data from the BDNB, it's possible to assess the distribution of dwellings for both EPC energy and EPC GHGE. Figure 9.2 presents this information, with EPC energy data on the left (9.2a) and EPC GHGE on the right (9.2a).



(a) Dwelling type per EPC (energy) label in number of dwellings



(b) Dwelling type per EPC (GHGE) label in number of dwellings

Figure 9.2: Dwelling type per EPC label in number of dwellings and m2

The distribution varies significantly between the two labeling systems. Specifically, EPC energy labels indicate poorer performance compared to EPC GHGE. While D and E labels predominate in the EPC energy category, C and D labels are most common in the EPC GHGE classification. Furthermore, there is a contrasting pattern regarding the best (A and B) and worst (F and G) labels. The number of dwellings in A and B categories for EPC energy closely mirrors those in F and G for EPC GHGE, and vice versa.

To better understand, Figure 9.3 features a Sankey diagram illustrating the transition of dwellings from their EPC energy label to their EPC GHGE label.

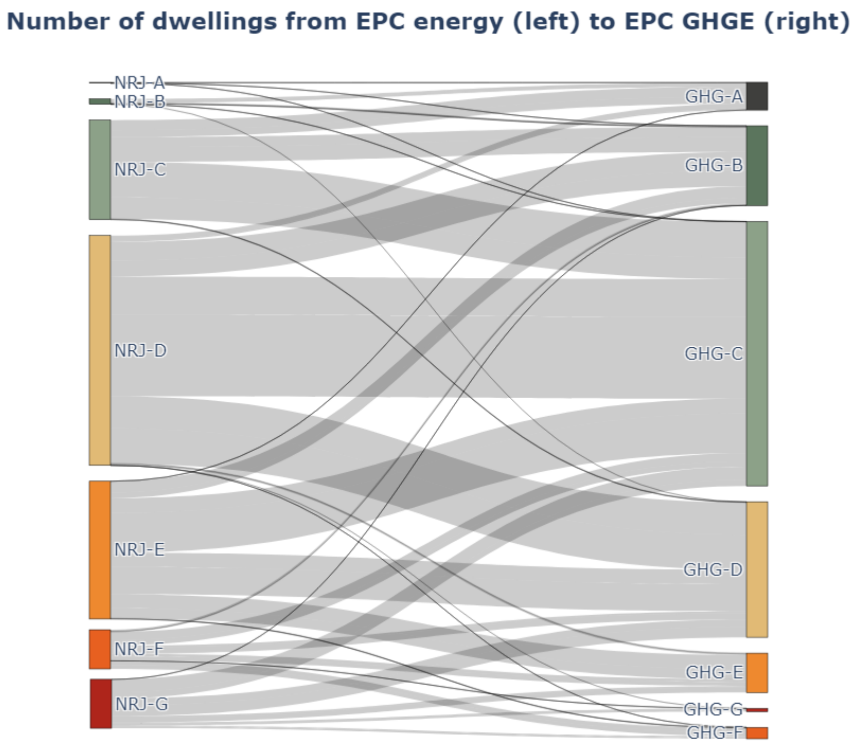


Figure 9.3: Number of dwellings with EPC energy and GHGE

This diagram highlights the considerable disparity between the two systems. Indeed, a significant portion of dwellings deemed relatively energy-inefficient (e.g. D and E labels, and even F and G) are categorized under the C label in terms of GHGE.

Surface per EPC label

It has been observed that dwellings with poorer performance ratings typically have smaller surface areas compared to those with better ratings. Figure 9.4 illustrates the average size of dwellings by their double-labelled EPC label and dwelling type.

The data clearly shows that dwellings with higher efficiency tend to have larger surface areas. Consequently, demolishing an equal number of dwellings across different EPC labels does not result in a uniform reduction in surface area. In this study, the emphasis is on demolishing highly inefficient dwellings, predominantly those with a G label and, to a lesser extent, F labels in the High-Demolition Scenario (HDS). Therefore, the total surface area impacted by these demolitions is not as extensive

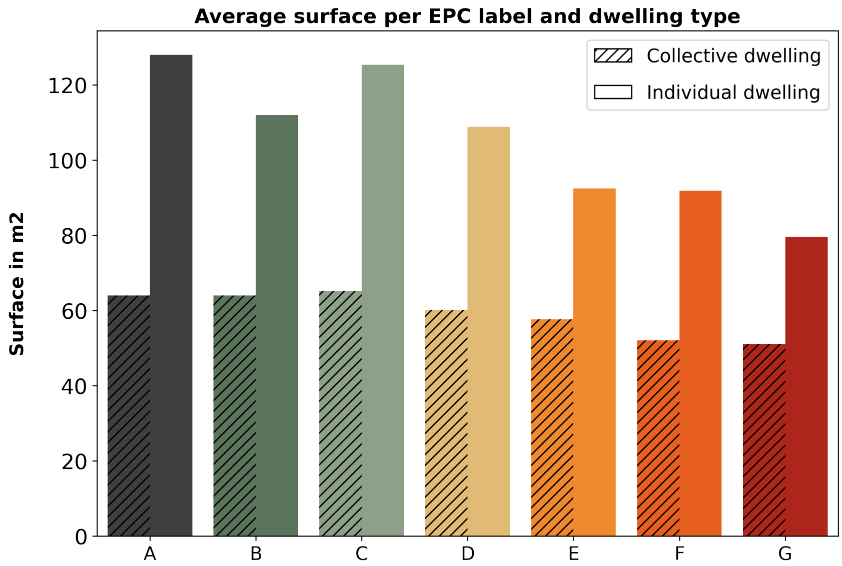


Figure 9.4: Average surface per EPC label and dwelling type in m^2

as it would be if calculated by simply multiplying the average surface area per dwelling type by the number of dwellings.

9.5.3 Limit values in France

The recently introduced environmental regulation RE2020 establishes limit values for both embodied and operational Greenhouse Gas Emissions (GHGE) in new buildings. These threshold values are designed to progressively decrease over time, with specific targets set until 2031. Table 9.4 outlines these limit values, expressed in $kgCO_2eq/m^2/year$.

Table 9.4: Limit values in the RE2020 in $kgCO_2eq/m^2/year$

	2022-2024	2024-2027	2028-2030	2031-
Embodied GHGE - Individual	640	530	475	415
Embodied GHGE - Collective	740	650	580	490
Operational GHGE - Individual	4	4	4	4
Operational GHGE - Collective	14	6.5	6.5	6.5

The diminishing values for embodied GHGE provide a baseline scenario for the evolution of limit values by 2031.

9.5.4 Statistical analysis of the RE2020 database

The RE2020 regulation also mandates the creation of LCA for buildings. As a result, an increasing amount of data is becoming available to assess the environmental performance of buildings, including their components and systems. In this study, building LCA from August 2023 to November 2023 are selected, for individual and collective dwellings. The analysis considers only the values for 'Building Components and Equipment' and 'Construction Site', while data pertaining to energy consumption and water usage are not included. The selected ranges for the different life-cycle stages are as follows:

- A1-A3: 0 - 1000 $kgCO_2eq/m^2$
- A4-A5: 0 - 200 $kgCO_2eq/m^2$
- B: 0 - 600 $kgCO_2eq/m^2$
- C: 0 - 100 $kgCO_2eq/m^2$

Table 9.5 provides the median values from the statistical analysis that are used as baseline in the study.

Table 9.5: Median values per dwelling type and life-cycle stages in $kgCO_2eq/m^2/year$

Dwelling Type	Life-cycle Stage	$kgCO_2eq/m^2$
Collective	A1-A3	413
Collective	A4-A5	97
Collective	B	260
Collective	C	49
Individual	A1-A3	330
Individual	A4-A5	67
Individual	B	223
Individual	C	60

9.5.5 Embodied GHGE of renovation

The RE2020 decomposes building components and equipments in 13 groups:

- Group 1: Roadwork and diverse
- Group 2: Foundations and infrastructure
- Group G3: Structure and masonry
- Group 4: Roof and cover
- Group 5: Interior partitions, suspended ceilings, components and joineries
- Group 6: Exterior surfaces (facades), components (doors and windows) and joineries
- Group 7: Interior coatings (floors, walls and ceilings)
- Group 8: HVAC equipment
- Group 9: Sanitary installations
- Group 10: Electrical equipment
- Group 11: Special electrical equipment (systems, controls and communication)
- Group 12: Interior transport equipment (elevators etc.)

- Group 13: Local electricity production equipment

More information is available from INIES, the French database for building components LCA:https://www.inies.fr/inies-pour-le-batiment/lacv-batiment/

In the study, the values for embodied emissions are derived from the median values per group obtained from the database. Depending on the performance level of the renovation, which is determined based on the number of EPC label jumps, a specific set of groups are affected. This approach is similar to the methodology used in the French *Quartier Energie Carbone* study (CSTB et al., 2022). Table 9.6 provides the median values used per EPC label jump, as well as the groups considered.

Table 9.6: Embodied GHGE per m^2 per EPC label jump

EPC Label Jump	Renovation Category	Groups	Individual Values	Collective Values
1	Small	8	105	105
2	Medium	5, 8	170	147
3	Medium	Method from CSTB et al. (2022)	210	195
4	Deep	Method from CSTB et al. (2022)	330	330
5	Deep	All, except 123	450	470
6	Deep	All, except 123	450	470

9.5.6 Renovation scenarios

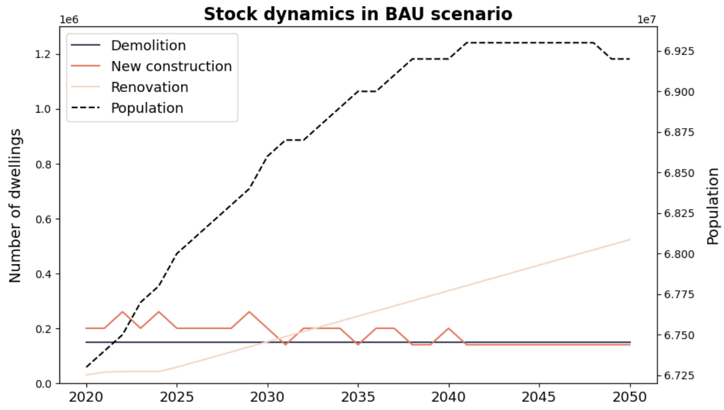
This study uses renovation scenarios as outlined by the developers of the BDNB. Given the extensive volume of data, encompassing around 35 million dwellings in the database, it is impractical for the author to implement alternative strategies.

The renovation assumptions made in this study focus on both the building envelope and the systems for heating and hot water. For the building envelope, the assumed heat transfer coefficient values are:

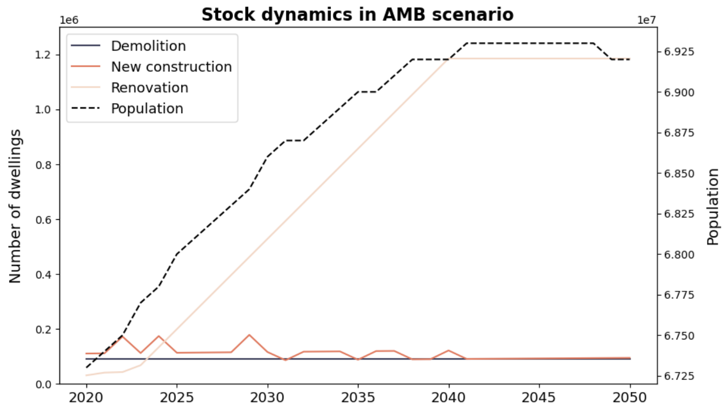
- Walls: 0.23 $W/(m^2{\cdot}K)$
- Roofs: 0.14 $W/(m^2{\cdot}K)$
- Floors: 0.23 $W/(m^2{\cdot}K)$
- Bays (e.g., windows, doors): 1.6 $W/(m^2{\cdot}K)$

For heating and hot water systems, a set of predefined rules (dictionaries) was implemented to replace existing systems based on their known characteristics and performance.

9.5.7 Stock-level activities



(a) Stock dynamics in the 'BAU' scenario



(b) Stock dynamics in the 'AMB' scenario

Figure 9.5: Stock-level activities and population growth in the 'BAU' and 'AMB' scenarios

9.6 Appendix C: Supplementary information to Chapter 7

9.6.1 Supporting data

The supporting data for this Chapter can be found at: https://github.com/marpellan/Prospective_RE2020.

9.6.2 RE2020

Following a five-year trial of the voluntary E+/C- label, the RE2020 regulation was officially enacted in January 2022 (CEREMA, 2024). It mandates the completion of a building LCA in accordance with the EN15978 standard, encompassing the production stage (A1-A3), construction stage (A4-A5), in-use stage (B1-B7), end-of-life stage (C1-C4) and the beyond building life cycle stage (D). Carbon calculations are conducted across four areas: building components and equipment, construction site activities, energy consumption, and water usage. The regulation details 13 categories of building components and equipment outlined in Table 7.1.

For each category, Environmental Product Declarations (EPDs) from the INIES database [1] are employed to model the life-cycle impacts of products, including their lifespan. The INIES database serves

[1] https://www.inies.fr/

as the primary source of EPD data for construction materials in France, featuring both collective EPDs (representing multiple manufacturers) and individual EPDs (specific to a single manufacturer). In instances where an EPD is not available, modelers may resort to 'default data' which incurs a 30% penalty that serves as a security coefficient.

Lastly, the RE2020 introduces a semi-dynamic method for calculating GHGE, introducing a simplified approach by applying a time-dependent correction factor to the static GWP100 indicator based on the timing of emissions. This correction factor decreases over time but varies between CO_2, with a value of 0.58 at year 50, and fluorinated gases (F-Gases), which have a correction factor of 0.88 at the same time point (CEREMA, 2024).

The RE2020 introduces is a simplified version approach of the dynamic LCA method (Levasseur et al., 2010) with a fixed observation period (in years). The simplification consists in applying a correction factor that depends on the timing of emissions to the static GWP that takes a time horizon of 100 years.

$$GWP_{dynRE2020}(t) = F_{RE2020}(t) * GWP_{stat} \tag{9.1}$$

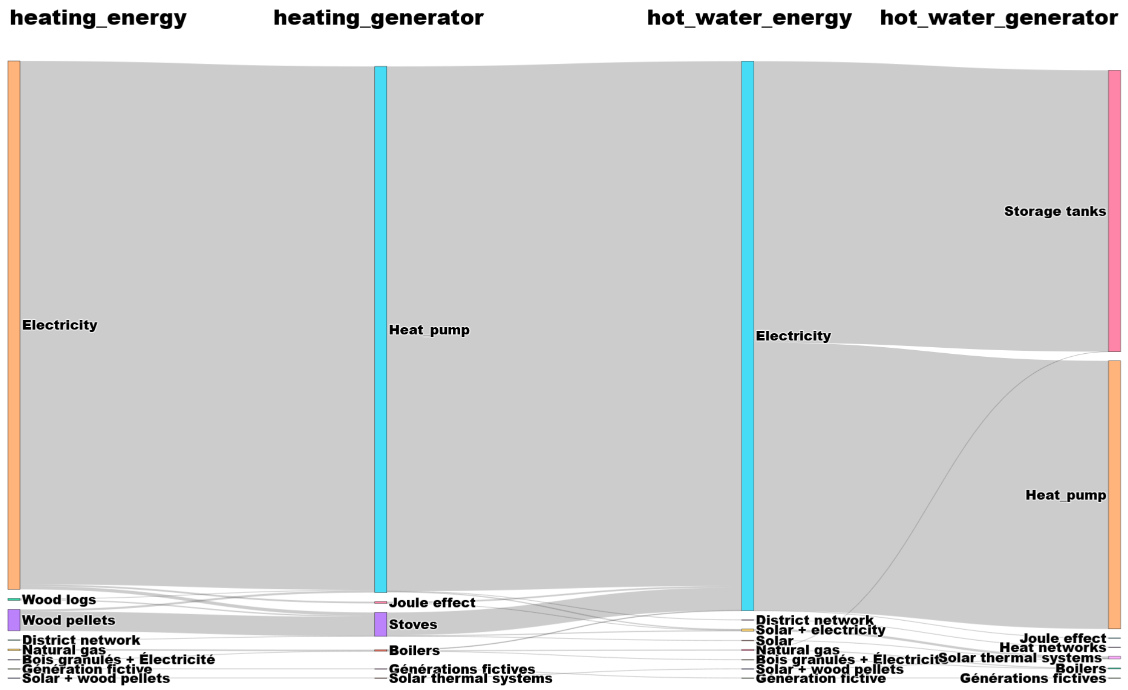
Where $F_{RE2020}(t)$ is the time-dependant correction factor. Weighting coefficient based on the year of emissions, different for CO_2 (0.58 at year=50) and FF (0.88 at year=50)

The $GWP_{dynRE2020}(t)$ is only applied during the use phase of buildings, e.g. from year=1 to year=50.

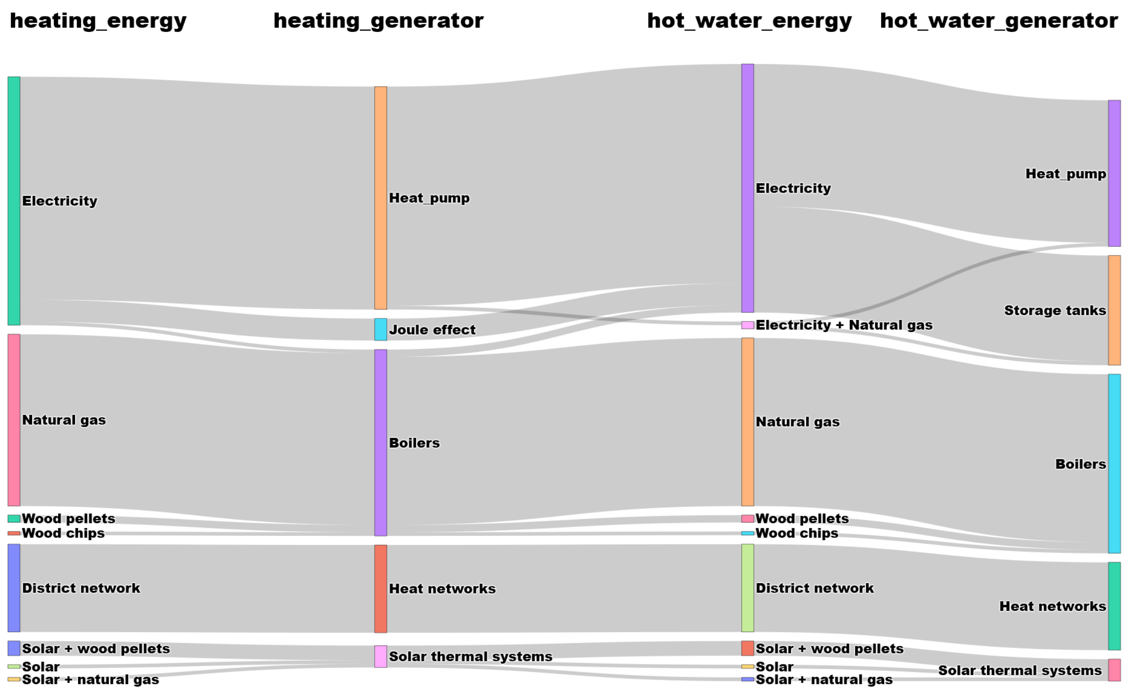
In practice, changes most of all the results for emissions that happen at end of life (e.g. wood).

9.6.3 Energy carriers, heating and hot water systems

The following Sankey diagrams reveal distinct preferences for energy carriers and systems for both heating and hot water systems, differentiated between individual and collective housing.



(a) Individual housing



(b) Collective housing

Figure 9.6: Energy carrier and generator type used for heating and hot water

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Summary

As a PhD student, I am engaged in researching the interaction between climate and sectoral policies within the building sector. I have a keen interest in prospective life-cycle assessment, input-output analysis, scenario analysis, and building stock modeling.

My goal is to engage in projects that bridges the gap between scientific research and practical policy application, aiming to develop science-based policies that drive sustainable and impactful changes both in policy frameworks and industry standards.

Education

ETH Zürich — **2021 - 2024**
Civil & Environmental Engineering — PhD

INSA Lyon — **2019 - 2020**
Environmental Engineering & Sustainability — Advanced Master

University College Dublin — **2015**
Academic Exchange

Grenoble School of Management — **2014 - 2018**
Technology, Economics & Management — MSc

Champollion High School — **2012 - 2014**
Mathematics, Economics, Geopolitics — Preparatory classes

Experience

Scientific and Technical Center for Buildings (CSTB) — **Feb 2021 - 2024**
PhD Candidate

"Downscaling the French low-carbon national strategy for the building activities" - a 3-year PhD project conducted with the CSTB and the Chair of Sustainable Construction at ETH Zürich, led by Prof. Guillaume Habert.

The main objective of the research is to integrate life-cycle thinking into net-zero national policies and quantitatively assess exploratory scenarios by 2050. This involves applied modelling using life-cycle assessment, input-output analysis and scenario analysis combined with data-driven methods.

Scientific and Technical Center for Buildings (CSTB) — **Sep 2020 - Feb 2021**
Environmental Engineer

Collaborated on various projects centered around Life-Cycle Assessment (LCA) and Material-Flow Analysis (MFA), with a particular focus on building renovations. Key contributions include:

- *Integrating embodied impacts of retrofitting archetypes into the Menfis model.*
- *Collecting data for an MFA model in the Ile-de-France region.*
- *Researching the influence of carbon taxation on construction practices.*

Scientific and Technical Center for Buildings (CSTB) — **April 2020 - Sep 2020**
Research Assistant

Collaborated with a PhD candidate on Consequential Life-Cycle Assessment, in particular:

- *Analyzing industrial and economics data to construct a stock-flow consistent model.*
- *Participating in the case study on residential buildings retrofitting in the context of the pandemic economic subsidies.*

Schneider Electric — **Sep 2018 - Sep 2019**
Market Analyst Apprentice

Conducted market studies for low-voltage products with product engineers and organized focus group in Madrid and Barcelona.

Publications

From limit values to carbon budgets: assessing comprehensive building stock decarbonisation strategies — **March 2024**
Building & Environment (in review)
http://dx.doi.org/10.2139/ssrn.4676635

Pellan, M; Almeida, D; Louërat, M; Habert, G

Beyond sectoral carbon budgets for the building activities: a French case study — **Jan 2024**
Energy & Buildings (in review)
http://dx.doi.org/10.2139/ssrn.4633977

Pellan, M; Almeida, D; Louërat, M; Habert, G

Decarbonisation roadmap for the building activity: LCA modelling of the renovation lever — **Sep 2023**
Journal of Physics: Conference Series
https://iopscience.iop.org/article/10.1088/1742-6596/2600/15/152010

Pellan, M; Almeida, D; Dubois, F; Louërat, M; Habert, G

A holistic perspective on the French building and construction GHG footprint — **Sep 2022**
IOP Conference Series: Earth and Environmental Science
https://iopscience.iop.org/article/10.1088/1755-1315/1078/1/012049/meta

Pellan, M; Louërat, M; El Beze, J; Habert, G

Languages

French
Mother tongue

English
Fluent

Spanish
Professional proficiency

Skills

Python

Brightway

SQL

LaTeX

Courses

Brightway Autumn School — **Oct 2023**
Départ de Sentier

Open Science Summer School — **July 2022**
EPFL

Prospective Environmental Assessment — **May 2021**
ETH Zürich

Teaching

Universite Grenoble Alpes — **2021-2022**

Introduction to the environmental impacts of the building activities (bachelor civil engineering students)

Practical courses on 'Elodie' building LCA software (master civil engineering students)

References

Prof. Guillaume Habert
PhD director

Dr. Mathilde Louërat
PhD co-supervisor

Dr. Denise Almeida
PhD co-supervisor

Marine Vesson
Manager

Interests

Outdoor sports
Cycling , Trail running, Mountaineering

Guitar player and music lover

Cinema

Open source and sustainability